Francisco Rodrigues Andriolo

The use of Roller Compacted Concrete

oficina de textos

is gaining popularity in the industry of dam construction. Its advantages have been confirmed and acknowledged through reduction of costs and time for completion of civil works. Small to medium dams can be completed between two flood seasons. Today higher and larger RCC dams are being designed and built throughout the world. The technology and methodology for design and construction of Roller Compacted Concrete (RCC) Dams has developed rapidly during the last thirty years.

Eng. Andriolo, earnestly committed to Civil Engineering's mission, actively contributed towards the developments in concrete technology during the past three decades. From now on, RCC dam engineers may rely on this treatise, a comprehensive state of art on RCC technology. The author presents useful guidelines derived from his extensive practical experience comprising over 20,000,000 cubic meters of actually built CVC and RCC dams. With a sound practical approach the book shows abundant data and pictures from over twenty completed dams in which the Author has been directly involved, beside many others throughout the world.

This 14 chapters book is a reference in research, design and construction of RCC works. It covers a variety of topics ranging from the history of RCC, construction materials and selection, concrete mixture, principles of the RCC design to the economic analysis, the technology of construction and quality control of the works and the performance of completed RCC structures. The book concentrates on dams, but the subject really concerns a new material, for whatever optimized uses

The Use of Roller Compacted Concrete

Francisco Rodrigues Andriolo

The Use of Roller Compacted Concrete

de textos

Capa: Francisco Rodrigues Andriolo
Revisão: Analy C. Uriarte Somagino e Shoshana Signer
Diagramação: ARS Visualis - arsv@uol.com.br

Dados Internacionais de Catalogação na Publicação (CIP)
(Câmara Brasileira do Livro, SP, Brasil)

Andriolo, Francisco Rodrigues
The use of roller compacted concrete /
Francisco Rodrigues Andriolo. - São Paulo:
Oficina de Textos, 1998.

Bibliografia.

1. Barragens 2. Concreto compactado a rolo 3. Represas de concreto

98-4638 CDD-627.81

Índice para catálogo sitemático:

1. Barragens de concreto: Uso de concreto compactado a rolo: Engenharia de barragens 627.81
2. Concreto compactado a rolo: Uso de concreto compactado a rolo: Engenharia de barragens 627.81

Oficina de Textos
R. Augusta, 1371 lj. 107
Telefax: (011) 283.2932 tel: (011) 284.1741
01305-100 - São paulo - SP - Brasil
email: ofitexto@uol.com.br

List of Contents

Preface I

For some of us long-standing professional colleagues of Eng. Andriolo, earnestly committed to Civil Engineering's mission, it is a privilege and honor to be prefacing such a book. Amidst the fantastic developments that the world has witnessed in all technological fields during the past three decades, and that will expand exponentially, it is exhilarating to see, and signal, that age-old everybody-knows Civil Engineering also rises up to the podium.

RCC embodies an exemplary reminder that engineering is a challenge of creativity: and this book renders it fruitful down to every practical detail of design, construction, inspection, and performance, proven through thorough experience. In rejecting the "engine engineering", that prevails but numbs, and seeking the fertility of "ingenious engineering" the solution is found, as often can be, by straddling across the tracks of competing sub-disciplines. And the competing breakthrough stimulates both the conventional solutions, the compacted embankments and the concrete structures. The book concentrates on dams, but the subject really concerns a new material, for whatever optimized uses can be conjured, with even greater freedom than has been used.

For Brasil, Latin America, and the developing world, it is heartening to receive such contributions favouring shortcuts to development. Water resources properly harnessed is the ominous worldwide need. Conscious combinations of the optimized principles from such embankment dams as the CFRD and ECRD, and from such slimmer structures as the concrete gravity and buttress-shape dams, not only improve safety, logistics, economy and performance of the dams themselves, but, above all, greatly enhance layouts for handling the three hydraulic circuits (diversion, operational, and flood spilling).

The coverage of RCC in the book, historic, updated, and complete, is self-evident; so are the extensive references. Should one confess, on the contrary, to the fear that many a young colleague may take as definitive the book's literal teachings, presently recommended, rather than the stimulating examples portrayed, of research and development? There is much to be done yet, and always : the notorious example is given, regarding the innovative use of rock-flour fines, a very important regional solution for Brasil's geology.

Eng. Francisco R. Andriolo is, himself, an example to the younger colleagues entering our field of service to humanity. Curiosity and enthusiasm know no closed doors, no needs for formal sponsorships. Within the day-to-day obligations to bide by conventions, fertile investigative testing is produced by theoretical intuitions, and the generous cooperation of on-site engineers during construction, enthusiastically induced to cooperate in the development foreseeable.

Andriolo is deeply committed, and proven effective. He has produced previously, and now, remarkably. For additional books, further optimizing, we will bide our time eagerly. The stage is set for further optimizing, both design principles and zoned construction : one might but remember that earth-core impervious sections can be as narrow as 40% of a conventional concrete gravity section. It is the unfettered developing world, stimulated by crusaders like Andriolo, cooperating symphonically with other specialist colleagues, that will further open the vistas of Dam Engineering.

Victor F. B. de Mello
Prof. Dr. (M.I.T.), Past-Pres. ISSMFE
São Paulo-Brazil

Preface II

The technology and methodology for design and construction of Roller Compacted Concrete (RCC) Dams has developed rapidly during the last thirty years. Today higher and larger RCC dams are being designed and constructed throughout the world. RCC is also being successfully and economically employed for rehabilitation of old conventional concrete, masonry and embankment dams and for protection against flow over existing dams of various type.

This comprehensive treatise on the subject gives a preview of the historic development of the modern day RCC, which can be as good as the conventional concrete (CVC) placed and vibrated in situ in the forms. The phisical properties of well-engineered RCC in strength, durability and impermeability are similar, and sometimes superior to that of comparable CVC. The two big advantages of RCC over CVC particularly for large dams, are the speed of construction and lower unit cost of completed concrete.

In the chapter on design of RCC dams, the author, appropriately, stresses the need for prevention of cracks and leakage through the dam. A cracked and leaking RCC dam is not as durable as an uncracked concrete dam. Also, both these conditions cause public apprehension regarding its safety, and consequently expensive repairs may be required to alleviate public concern.

Large RCC dams, without full transverse ungrouted contraction joints are essentially three-dimensional elastic monolithic structures. The degree of lateral transfer of stresses would depend upon curvature of axis of the dam and the shape of the dam site. Therefore, for high RCC dams, whether straight or curved gravity, or arch type, it is necessary to ensure a high degree of monolithicity and adequate bond over the entire surface of the construction or layer joints. As in CVC dams, high tensile stresses on the upstream face of a RCC dam, and particularly at the dam foundation contact, can be conducive of structural cracking, increase in hydraulic uplift pressures and reduction in effective shearing resistance.

In the chapters on selection of materials, design of RCC mixes and quality control, the author has presented useful guidelines derived from his extensive practical experience comprising over 20,000,000 cubic meters of actually built CVC and RCC dams. The excellent quality of 13,000,000 cubic meters in the binational Itaipu Dam and structures where Eng. Andriolo was responsible for quality control, is a testimonial to the depth of his experience in concrete technology. The exhaustive list of references includes almost all the literature on RCC published in the world to date.

It is a privilege for me to introduce and recommend this excellent book to professional engineers engaged in the engineering of dams.

Gurmukh Sarkaria
Consulting Engineer- California- USA

Preface III - Prologo

El mundo de las presas ha evolucionado desde las construidas por los romanos hasta nuestros días teniendo siempre como premisas tres factores primordiales: durabilidad, impermeabilidad y economía. En este siglo, en la década de setenta, surge una nueva tecnologia nacida bajo los auspicios de una construcción más rápida y económica de presas de fabrica que desemboca en la técnica denominada "Roller Compacted Concrete". Esta nueva forma de concebir las presas de fabrica, no es sino una consecuencia lógica de la evolución de los sistemas convencionales hacia materiales y medios constructivos conformes a la técnica actual.

Denominamos hormigón RCC al utilizado en el procedimiento de construcción que utiliza las técnicas de puesta en obra de los materiales sueltos en la colocación y consolidación del hormigón. De esta forma se aúna la rapidez de ejecución y economia de la puesta en obra de los materiales sueltos con las características del hormigón.

A primera vista podria considerarse que la evolución técnica de las presas de RCC en el mundo se ha producido de forma descoordinada y heterogeneidad conceptual. Sin embargo, la lectura del libro de F. Andriolo pone de manifiesto que la situación no es tal, y nos muestra como desde una visión y concepción integral del problema se incorporan y supeditan las demás.

En el libro se tratan todos los temas con profundidad y compromiso y se desarrollan, con fundamento en un extenso y completo tratamiento bibliográfico, razonamientos comparativos entre lo expresado y lo sostenido por otros autores.

Expone la necesidad de conciliar la economia en el diseño del material y puesta en obra con la obtención de una fábrica durable, impermeable y resistente, y como una supuesta mejora en la calidad del material puede traer consigo la disfunción del sistema y el posible desarrollo de problemas en las estructuras. Es decir, se señala en forma certera la necesidad de adecuar el hormigón a los materiales disponibles, a las caracteristicas exigidas, a la puesta en obra y a las condiciones económicas, y se pone de manifiesto la importancia del papel que juegan los finos en el diseño de hormigones RCC.

Plantea de forma clara las distintas opciones de que se dispone en el diseño de las presas de RCC, formas de construcción y puesta en obra. Como consecuencia de establecer la existencia de una única concepción del hormigón R.C.C., sitúa el problema en su verdadera dimensión: el proyectista debe buscar la armonia entre el material de construcción y el diseño estructural y funcional con el cumplimiento de los condicionamientos de seguridad, durabilidad y economia.

El autor, F. Andriolo, es ingeniero con vasta experiencia en el campo de las presas e intensa dedicación en cuanto se refiere al diseño, construcción y control de presas RCC. Es por ende uno de los especialistas más claramente capacitado para sensibilizarse con el tema planteado en este libro.

A partir de este momento los profesionales pueden contar con una obra en la que se trata desde el diseño de las presas y material de construcción hasta el análisis económico y control de las obras. El carácter eminentemente practico del libro, con abundante información gráfica, no le resta interés para el investigador, que encontrará en él la actualidad y rigor exigibles. No cabe, por lo tanto, sino felicitarse por la elaboración de esta obra.

Joaquín Díez-Cascón Sagrado
Ph.D- Ingenieria Civil Prof. Universidad Cantabria-Santander-España

Preface IV

Since the initial introduction of RCC as a construction material for repair work at Tarbela Dam during the 1970's, the first all-RCC Willow Creek Dam in Oregon, USA, followed in 1982. Over the last 16 years RCC's growth as a recognised method for constructing dams has been phenomenal. This period has seen gravity dams constructed, or currently being constructed, rise in height from Willow Creek's 52m to China's Longtan Dam of 192m. Several weirs ranging from 5m to about 15m have also been built. From 1988 onwards RCC has also been applied for arch dams with examples such as South Africa's Knellpoort (50m high), Wolwedans (70m high) arch/gravity dams, China's 75m high Puding massive arch and the 63,5m high Xibin thin arch dam now under construction and the 131m high Shapai thin arch under design. At the same time similar advances were made in the materials field where consideration had to be given to economic design, heat generation of the concrete mix, use of waste products such as fly-ash and rock powder as pozzolanic materials to replace cement, etc. By the end of 1996 more than 158 RCC dams have been built internationally and the numbers are ever increasing This is mostly because of their general good performance as well as their competitiveness with other dam types.

However, this did not come about without the faith, innovation, serious research and the will to succeed of the many designers and contractors who have contributed towards this technology.

In this book Francisco R. Andriolo has not only presented the current practices in RCC dam design, based on a vast amount of publications and personal experience, but has also captured the spirit and essence of the RCC technology. Not only does he elaborate on the latest research, but he also stands back and draw the reader's attention to past research for conventional concrete dams. An example is for instance his reference in Chapter 7 to past research on joint strengths at the Ross Dam which were conducted for the raising of that dam. Suddenly the reader has the comfort of being provided with a solid base for understanding not only the differences between conventional mass concrete and RCC construction, but also those things which are both common and similar. Probably the most important statement made in the book is the fact that RCC is *"concrete"* and nothing else but just that.

The book also covers a wide range of statements and answers to questions normally raised by both uniformed clients and uninformed consulting engineers. Many RCC designers, if not all, have been confronted by these very same questions. Francisco Andriolo has been successful in addressing almost all of these issues and thereby served his fellow RCC designers in a great way. Thank you Francisco!

He has also been very successful to show that the RCC designer should have a good knowledge of both RCC design and construction and that both aspects should be considered simultaneously during the design process. The RCC dam designer who is capable of doing this, MUST BE SUCCESSFUL!.

Johann Geringer
Chief Engineer Project Planning
Department of Water Affairs and Forestry, South Africa

Preface V

Roller Compacted Concrete (RCC) is a new tendency in the industry of dam construction. Its advantages have been evidenced through reduction of costs and time for completion of civil works, especially for the dams with small to medium size that can be completed between two flood seasons. Because of this, river diversion engineering can be reduced to the minimum.

RCC dams have been developed rather rapidly over recent years. More than 200 dams (higher than 15 meters) from 26 countries have been accomplished or under construction. As we known, several additional countries are joining the RCC ally and using the RCC technology to design their dams. Some RCC dams of a hight over 100 meters have been successfully constructed while others are under construction. These completed RCC works comprise different types of structures from gravity dams to arch dams, manifesting that since the first emergence of RCC dams in 1980, this damming technique has made a significant progress.

The development of RCC dams in Brazil was earlier than other countries in Latin America. Through the experimental RCC blocks used in Itaipu, São Simão and Tucurui projects from 1976 to 1982, experiences were obtained in the earlier RCC practices. The RCC knowledge were further enriched through a large amount of scientific research and by the experts who spent much time on consultancy for the projects in Latin America and Africa, such as Conception and Capanda projects. These practices demonstrated their leading position in the RCC technology during that time in the world.

RCC dams show a very bright in respect to modify and simplify the RCC construction technology. It will provide more benefits to clients and contractors in the ways of decreasing the percentage of conventional concrete in a structure, finding the best mixture from using local materials, improving the durability of concrete and enhancing efficiency of equipment. It can produce high quality of concrete and conduct high speed of construction. Therefore, it is the main direction of RCC development in the near future.

Apart from using RCC in dam construction, in other engineering fields such as road paving and rehabilitation of civil works, this method can also be considered a powerful means. There have already been many successful cases to show an aggressive progress of the technology in different engineering aspects.

There are few books talking about RCC, which is not well-matched with the fact that the RCC technology has being developed very fast. Hence it is encouraged to have a new book published that reports the newly development of the technology on time.

Mr. ANDRIOLO, Francisco Rodrigues, the author of this book, is a consulting engineer at Andriolo Engenharia S/C Ltda in São Paulo, Brazil, and has engaged in this field for many years. From 1976, he worked in the laboratory of the Itaipu project and carried out experiments on the dam site for the first block of RCC in Brazil. In this book, he collected a wide range of information from real dam projects worldwide and summarized the experiences and his own contributions to RCC are presented to all of us in English, hence the book will be the best gift to those who work in this field.

This book consists of 14 chapters covering a variety of topics ranging from the history of RCC, construction materials, concrete mixture, principles of the RCC design to the technology of construction and the performance of completed RCC structures. It describes most the aspects of RCC from different approaches and, therefore, I believe it will be of a very high value of reference in research, design and construction of RCC works.

Shen Chonggang
Dr. Prof. Senior Engineer IWHR. Vice President CHINCOLD-China

Preface VI

This book is an out standing contribution for the roller compacted concrete technology.

For such an important contribution, Andriolo allies several virtues to do so qualified literature: perseverance, competence, organization and expertise.

Perseverance to collect all literature about RCC published up to now.

Competence to select the main important aspects related to the different subjects of RCC, since the discussion of materials, mix design concepts and approaches, properties, construction practices, quality control and quality assurance, cost, and other uses, besides to dam construction and finally the performance of the RCC.

Organization in the careful presentation of all above subjects with numerous illustrations and cases.

Expertise to analyze all the different aspects related to RCC, mainly the design of RCC dams and their construction problems, so clearly shown in the 14 chapters of the book.

This book will enable to open discussion for all the professionals involved with the RCC construction and practice.

This book shows that the concrete dam construction division between RCC or CVC is not a matter of concern anymore.

There is no reason for the artificial division of several RCC types because RCC is becoming narrow and narrow.

If one take care of a suitable project, with a well known concrete materials with a proper mix design program and the knowledge of all the concrete properties, a well planned construction equipments and construction procedures, there is no reason for keep going with differentiation between RCC or CVC. This is an stimulating challenge arised with the knowledge reported in this book.

The correct alternative in the choice of concrete materials, mainly the cementitious ones, including the aggregate particles fines than # 200 sieve, will enable to produce a watertight parent concrete. If one takes care of the bond between the concrete lifts, with a suitable mortar placed and spread between the lifts ones, the monolithic concrete will be as equal as conventional concrete, like was brilliantly expressed in the Chapter 4, item 4.2.1:

"A complete RCC dam structure should function as a monolithic elastic structure, integrally bonded to its rock foundation, that is its structural performance should be equivalent to that of a CVC dam with a similar configuration. For the two types to be equal in quality, safety and durability, they should have equivalent margins of safety against cracking, rupture, overstressing, shearing-sliding and leakage through the concrete and construction or joint layers".

Andriolo, you stimulate all the people engaged in the RCC construction of dams to do so, with this book.

Andriolo, last but not least, I wish to express my admiration and congratulation to Sandra, your devoted wife, for her patient and competent support, to enable you to give us this important contribution for the civil engineering.

Success is my sincere wish.

Walton Pacelli de Andrade
Brazil

Preface VII

The book presented by F.R- Andriolo is the encyclopaedia on the roller-compacted concrete technology, the most brilliant engineering achievement in the field of construction of the mass concrete structures.

The mass concrete structures like gravity dams since the time of the Boulder Dam in USA used to be constructed employing a rather complex techniques with cutting the structures into sections, columns and blocks. Special low-heat cements, grading of aggregates, cooling of the concrete mix by flaky ice to replace part of the mixing water and cooling of the mass concrete by built-in coils through which chilled water is pumped are used to avoid thermal cracking.

All these measures used to bring to a considerable increase in cost of the concrete placed in the structures. As a result the concrete dams were not competitive compared to embankment dams which were constructed faster and at a lower cost due to complete mechanization of their construction.

The dam construction technologies with implementation of low- cement concrete mixes to be compacted by the state of the art vibrating rollers have been developed in a number of the countries over the last two decades and all stages of this work were reflected in the book.

That's why it's so valuable!

The book consists of several chapters in which consequentially the aspects of selection of concrete mix ingredients, the specific features of design process, staged construction methodology and the results of operation of the dams constructed are being reviewed.

F.R- Andriolo, the author of the book, has been studying the subject of the book for many years and due to his systematic work and enormous practical experience is an acknowledged authority in the field of concrete

Dam engineering.

I congratulate F.R. Andriolo with completion of this fundamental work and I do hope that all the engineers will study this work with interest. Specialists in engineering of concrete dams will use this book as a manual book in their every day work.

Albert D. Osipov
Russia

The Use of Roller Compacted Concrete

Patrocínio:

Explanatory note from the author

The objective of this text is to carry out a general review of my 4th book - *"CONTRIBUIÇÕES PARA O CONHECIMENTO E DESENVOLVIMENTO DO CONCRETO ROLADO"* edited (in Portuguese) in March-1989, including the new approaches, current data and to study essential points of the Roller Compacted Concrete - RCC - technique.

Cover page of the "Contribuições Para o Conhecimento e Desenvolvimento do Concreto Rolado"

In this decade, since the edition of that book, the progress of the RCC technology had let it to become more Rapid, Diverse and Safe – as demonstrated in several seminars and congresses. This aspect can be recognized by the influence of this methodology on dam construction that requires rationalization of the adoption of others construction technologies and costs.

Stimulated by the remarkable progress achieved by the RCC methodology, and "kindly challenged" by friends, this text book intends to be a "reference tool" to professionals that might be involved with the RCC technique.

It is well known that [0.01] mankind is crying for water, food, and clean sustainable energy all over the planet. Total water use doubled between 1940 and 1980, and is expected to double again by the year 2000. There are many countries in the world with scarcity of water. There is neither a water supply system for 65% of the world's rural population, nor for 35% of the urban population. In addition, more than 1,5 billion people are deprived of sanitary facilities.

The pressure on water resources in the world has increased dramatically in the last decades as a result of:

- Exponentially growing in the world population;
- Rising expectations for economic development, and improved standards of living;
- Large expansion on irrigated agriculture, associated with the inefficiency in controlling water losses;
- Increasing use of natural resources, requiring enormous quantities of water;
- Increasing use of energy;
- Discharging of waste products requires large volume of water for treatment.

Early civilizations developed along major rivers (Tigris/Euphrates, Nile, Ganges, and Yellow), and the same phenomenon occurred in the contemporary era in developing countries, due to water abundance and availability for transportation, consumption, food production, and more recently for industrial development.

Many developing countries emphasized the need of infrastructure, such as dams, power projects and reservoirs on large scale.

For more than 5000 years, dams that have impounded reservoirs have enabled civilizations to flourish by assuring dependable supply of water for domestic purpose and irrigation. Later dams were used to control flood and/or to provide a renewable, non-pollutant source of electric energy as well as for recreation, fishing and navigation benefits.

It is well known that about 30% of the fresh water available, in terms of km^3/annum, is in South America, but the ratio between stable and unstable portions river runoff can be affected by man through management of land surfaces and change in the vegetation, or by withdrawals and artificial storage.

Prior to 1900, there were [0.02] less than 500 dams. An enormous increase in the number of dams in the world took place after the second half of the 20th century. There are now more than 36.000 dams over 15m high, and the total number increases each year.

Further technology development in all these areas is important. Problems to be addressed include costs, effectiveness, and magnitude of increased demand for water. In addition, long term social and cultural adjustments are required to bring about conservation and improve efficiency.

It is very important to mention that the RCC technique is not the ***"unique methodology"*** available to build a dam, as sometimes it can be heard. Of course it is an alternative that must be considered and analyzed, as a global way to look for the best, the simplest, the cheapest, and also a safe solution.

Acknowledgments

I express my gratitude to all friends, professionals, and "hundreds" of other persons that directly or indirectly contributed to the development of my book.

Special thanks to the professional technical team from :

- COPEL where I have been working since 1994, and that permited the publication of the large amount of data included in this text;
- CESP, friendly Flávio Moreira Salles,
- FURNAS, friendly Walton Pacelli de Andrade;
- CHESF, friendly Alberto Jorge Cavalcanti;
- DNOCS, friendly Thereza Léa Monteiro;
- ABCP, friendly Marcio Rocha Pitta;
- Planservi Engenharia Ltda, friendly Carlos Yukio Suzuki;
- IECA- Spain, friendly Carlos Jófre;

Special thanks to José Eduardo Moreira, Marco Antonio Juliani Camargo and José Luis Stephan.

Special thanks to Antonio Fernando Krempel who, friendly, challenged me to write this text.

Special and great thanks to those ones that would like to help me, but couldn't carry it out.

It is very important to express my gratitude to all the sponsors that directly contributed to the patronage of this book, making it available to many Brazilians and other technicians elsewhere.

I express my gratitude and excuses to my family whon I deprived from many moments to write this text.

Summary

This text presents a sequence of data and details concerned with the "Roller Compacted Concrete", for Dam and others constructions, that includes a few words about Design, Materials, Proportioning, Properties as Material, Uses, Quality Control, Costs and Performance.

Keywords

Admixtures; aggregate gradation; aggregates; aggregate size; air entrainment;

cement pastes; cementitious material; cements; coarse aggregates; compacting; compaction ratio; compressive strength; concrete construction; concrete dams; concretes; consistency; consolidation; construction joints; conveying; Conventional Vibrated Concrete (CVC); creep properties; crushed powder; curing; dams;

density (mass/volume); durability; elastic properties;

elastic properties; elastomeric membrane; electric pole tamper; erosion abrasion resistance; extended layer construction method; external compaction equipment;

facing system; factor of safety; filler; fine aggregates; fissures; fly-ash; fog spray; formwork (construction); foundation; fullscaled field test; fully restrained;

gap-graded aggregates; gravity dams; green cutting;

handling; hauling; high fines content; high paste; homogeneity; hydration heat; hydro blasting;

impermeable barrier; inspection; instrumentation; internal friction;

joint cutter machine; joint surface; joints (junctions);

leakage; lean; lean mixture; lift joint; lift thickness;

mass concrete; mix design; mix efficiency; mixers; mixing; mixing water; mixture proportioning; modulus of elasticity; moisture adjustment; monolithic; mortar bedding layer;

non plastic fines; no-slump concrete; nuclear test;

overtopped flow; overtopping

peak; performance; permeability; placing; planning; pneumatic pole tamper; Poisson's ratio; pore pressure; pozzolanic activity; pozzolanic material; pozzolans; precast block; proportioning mix; pugmil;

quality; quality assurance; quality control; quality control actions; quality control plan; quality control system; quarry;

random samples; retarder; roller; Roller Compacted Concrete (RCC) shear properties;

safety; safety factor; sand aggregate ratio; sand blasting; saturated surface dry; seepage; set time; shear; shear properties; shearing; silica fume. single probe; sliding

slope compactor; smoothed spillway; soil-cement; soil sandy cement; specific gravity; specific heat; specimen; splitting tensile; stability; stability analysis; standard deviation; statistical concept; stepped spillway; strain capacity; stress analysis; structural design; sublayer; surface preparation; systematic error;

temperature; temperature crack; tensile strain; tensile stress; thermal analysis; thermal control; thermal effects; thermal properties; thermal stress; three point loading; training; transverse joint; triaxial shear; triaxial strength;

uniformity; unit weight; uplift pressure;

vacuum chute; variability; VC device; VeBe apparatus; vibration; vibratory roller; voids; volume change;

water blasting; water-cement ratio, water content; water measure device; waterstop; watertight; workability.

Glossary

References cited [0.03] contain further explanations, but not necessarily the definition given.

as dug — granular material recovered from natural deposits and utilized for aggregates with little or no processing. Term is used in British practice, equivalent to "pit run" in US practice;

BaCaRa — Barrages en Béton Compacté au Rouleau - the Projet National, a French organization devoted to the development or RCC;

Cannon test — a name sometimes applied to a modified VeBe test developed at TVA in the 1970's by R. W. Cannon;

CFRD — concrete faced rockfill dam- an impervious facing on a pervious embankment. It considers a rockfill dam with an impervious concrete upstream face slab, that shows thickness from 70cm (at the deepest level) to 50cm at the crest;

CIRIA — Construction Industry Research and Information Association, London;

composite dam — a water barrier consisting of abutting segments of different types such as an RCC gravity segment abutted by a rockfill, for example, the Ryumon dam in Kyushu;

concrete — a composite material that consists essentially of a binding medium within which are particles or fragments of aggregate embedded, usually a combination of fine and coarse aggregate; in Portland cement concrete, the binder is a mixture of Portland cement and water;

concrete approach — mix design in accordance with conventional concrete design principles, one of two approaches or philosophies with respect to RCC mix design methods, the other being the soils or geotechnical approach;

concrete fill — a name given to the idea of using dry lean compacted concrete placed in thin lifts to build concrete dams by several innovating engineers;

CVC — conventionally vibrated concrete - as opposed to RCC;

dry lean concrete — a term used in road pavement base applications, preceding use of RCC in dams;

elephant trunk — a vertically suspended heavy rubber hose often 20 cm in diameter used to drop wet concrete from a conveyor or a hopper 2 to 15 m on to the lift surface controlling segregation of the mixture. The term "tremie" is also used but, strictly speaking, a tremie is a pipe for placing concrete under water;

fines content – the finer material than 0,075mm, with low or without cohesion, introduced in the RCC mixes;

FSHD — faced symetrical hardfill dam. A steep sided RCC gravity section with bonding between lifts disregarded, having a reinforced conventional concrete upstream face for watertightness;

geotechnical approach — see soils approach.

hardfill — mass of lean RCC placed with no special treatment of lift surfaces or attempts to develop tensile strength;

hearting concrete — in British practice, interior part of mass concrete in a dam as differing from facing concrete;

high-fine-content mix — RCC of high density with few voids, leading to increased strength properties and a more fluid mix while still having zero-slump; generally less than 100 kg/m³ cement content with high fine content (over 100 kg/m3) material, that can be silt, pozzolanic material, fly-ash, or crushed powder rock ("Rock Flour");

high-paste-content mix — RCC of high density with few voids, leading to increased strength properties and a more fluid mix while still having zero-slump; generally exceeds 150 kg/m³ cementitious content;

lean paste mix — RCC which incorporates the maximum density philosophy commonly associated with the principles of soil compaction developed by Proctor, but does not produce a paste content sufficient to fill all voids; ranges from 45 to 100 kg/m³ of cementitious material;

mass concrete — any volume of concrete with dimensions large enough to require that measures should be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking;

MSA – maximum size aggregate, that is the maximum dimension of the aggregate used for the concrete mixes;

medium paste content mix — RCC designed with paste content somewhere between mixes designed by the soils approach and the concrete approach;

pugmill — high speed concrete mixers both "batch" and "continuous" types with a horizontal mixing chamber and double rotating shafts having inter-acting paddles attached. The batch type loads the chamber with raw materials for a given volume and discharges out the bottom after mixing. The continuous type introduces materials at one end in the proper proportions where the paddles mix and direct it to the discharge end in a continuous operation. Other general type is drum mixer;

RCC — roller-compacted concrete, except for pavements, is mass concrete with mixture components in such proportions as to allow for zero-slump consistency in the unhardened state thereby allowing placement and compaction using methods similar to earthfill construction. However it requires special provisions for impermeability in hydraulic structures;

RCD — roller-compacted dam - Japanese method of roller-compacted concrete having significant special requirements such as always forming and build both faces of CVC, cutting transverse contraction joints at about 15 m spacing, and extensive treatment between lifts;

RCCD — roller-compacted concrete dam - term used in China to refer to Chinese dams built generally according to the Japanese method;

rollcrete — a term for "roller-compacted concrete" coined at the Shihmen cofferdam construction in 1960 and used during the extensive repair work at Tarbela dam in the 1970's. In general use in South Africa, but it has come to mean a lean RCC using pit run or lightly processed aggregates in the USA;

soils approach — concrete mix design in accordance with the maximum density principles of soil compaction developed by Proctor. Also called geotechnical approach. See concrete approach;

soil-cement — a mixture of soil and measured amounts of Portland cement and water, compacted to a high density by rolling. Cement content usually is in the range of 3 to 15 percent by weight with the soil particles ranging up to coarse sand size of 4.75 mm;

swinger — horizontal rotating jib boom (or conveyor) often 15-20 m in length mounted on a large diameter pipe tower embedded in the concrete mass; used to distribute wet concrete to the surface of the fill from a conveyor system extending along the boom. The swinger is generally fed by a conveyor and has the ability to swing 360°, raise, lower, extend and retract;

VC consistency test — VeBe test using larger samples, resulting in **VC** values of recorded time to bring paste to the surface by a standard vibration system;

VeBe test — measures workability of concrete by establishing a correlation between water content and consistency of the sample using a vibrating table in conjunction with a weighted surcharge, recording the time required for excess cement paste to rise to the surface of a standard sized container. Various modifications have been made to this test procedure to adapt it for larger-scale RCC tests - see Cannon test and VC consistency test.

References

0.01 USCOLD- United States Committee on Large Dams- "The Role of Dams in the 21st Century"- Denver, June 1992;

0.02 ICOLD- International Commission on Large Dams- "World Register of Dams – 1988 Updating" Paris, June 1989;

0.03 USCOLD- United States Committee on Large Dams- "Annotade Bibliography on Roller-Compacted Concrete Dams"- Denver, June 1994;

1

Introduction

The term "roller compacted concrete" describes concrete used in the construction process, which combines economical and rapid placing techniques of embankment material with those excellent mechanical properties of concrete, such as strength and durability. This technique is best suited to multi-layer constructions with a high ratio of surface to thickness, that is to say, pavements and dams.

Since the 70's, different laboratories have done many studies in Brazil showing RCC properties and its potentiality, although the first dam constructed with RCC technology occurred only during the 80's.

It was during the 90's, mainly by the adoption of RCC technology for the Jordão and Salto Caxias Dams Projects that this technique reached its peak and became very popular. The bid system adopted by COPEL (Companhia Paranaense de Energia, the energy government agency for Paraná State - Brazil), for the "Jordão Dam" allowed the Contractor to chose between a Rockfill embankment faced with concrete or a RCC Dam (see chapter 10) pointed out to time and costs as outstanding advantages for RCC technology

Figure 1.01 Saco de Nova Olinda RCC Dam, built in 1986

Today, roller compacted concrete dams are being discussed, designed, and constructed in many of the developed and developing countries throughout the world. Its use in arch dam construction has increased mainly in China and South Africa. It is evident that conditions and dimensions of Brazil's territory will challenge the engineers to adopt such a solution in a large number of projects.

Interest in this type of dam has increased for several reasons, the most prominent being economics and construction speed. In many countries the costs of conventional concrete dams have increased significantly faster than corresponding costs for embankment dams. But the fact that concrete is such a good and long-lasting construction material, has stimulated designers to seek new ways of using it in dam construction. They succeeded with the adoption of RCC technology.

Better understanding of RCC lately, led it to become based on aggregate grading and provided the best use of fines and filler materials in an "engineering" concept - in terms of ***quality, safety, and economy***. What brought RCC technology to its ***simplicity*** is the use of available materials at the Project site and since the operations of proportioning, mixing and hauling are performed by adequate and planed equipment, the construction is done ***rapidly***.

It is very important to consider, specially in Brazil, that dam construction practice, established mainly in the 70's and 80's, had optimized the use of low cementitious content for concretes in gravity dams, as a MSA 152mm conventional mass concrete with **84kg/m^3** of cementitious content (**61kg/m^3** Type II cement + **23kg/m^3** Calcined Clay Pozzolan) poured during the construction of Ilha Solteira Dam in 1972 [1-1].

This book is meant to be useful for RCC dams with volumes ranging from 1,000m^3 to over 1,000,000 m^3. RCC technology can be used in dam construction under climates ranging from tropical to arctic, and in those climates having major seasonal changes. RCC construction is suitable in developing as well as industrialized countries, with labor wages ranging from some of the lowest to some of the highest in the world. The secret of efficient RCC construction is to keep it as continuous, repetitive, and simple as possible.

Figure 1.02 Jordão RCC Dam, constructed during 1994-1995

Figure 1.03 Salto Caxias Dam, during construction – around 1,000,000 m^3 RCC, in a 1,240,000 KW Hydroelectric Power Plant.

Figure 1.04 Ilha Solteira Hydroelectric Project – 3,620,000m3 CVC concrete, finished by 1974.

References

1.01 ANDRIOLO, F.R. *Construções de Concreto - Manual de Práticas para Execução e Controle.* São Paulo: Editora Pini, 1984

2

Concept of RCC

Roller ***C***ompacted ***C***oncrete - **RCC** - is a technology characterized mainly by the use of rollers for compaction.

Roller compacted concrete (RCC) is a construction technology, not a design criterion nor a design technology, that uses a concrete (concrete as material) of no-slump consistency in its unhardened state which is transported, placed, and compacted using earth and rockfill construction equipment.

Properties of hardened RCC are similar to those of conventionally placed concrete. This text applies to the use of RCC in structures and thus require measures be taken to cope with the generation of heat of hydration of the cementitious materials and volume change control to minimize cracking. Mixture proportioning, physical properties, mixing, transporting, placing, consolidating, curing, protection, testing, inspection, design, and construction will be considered along the chapters.

Figure 2.01 RCC – a concrete of no-slump consistency

Figure 2.02 Soil (Gravel+Sand) Cement used as slope protection

The terms "roller compaction" and "roller compacted concrete" can be understood as follows:

Roller compaction: A process for compacting concrete using a roller, often a vibratory roller;

Roller compacted concrete: Concrete compacted by roller compaction; concrete that in its unhardened state will support a roller while being compacted.

RCC is concrete proportioned to support external compaction equipment. Though related to granular soil-cement, which may use similar placement methods, it contains larger amount of coarse aggregate and develops properties similar to conventionally placed concrete. RCC encompasses a broad range of mixtures with properties that primarily depend on the quality of used materials, the cementitious materials content, the degree of compaction and the degree of control exercised.

Materials referred to in the past as "rollcrete" and "rolled concrete" and some materials previously referred to as soil-cement or cement-treated base may be considered RCC.

The resulting material is denser with lower amount of water than usual Conventional Vibrated Concrete ("CVC" will be used in this text to identify Conventional Concrete).

This technology has been successfully used in a number of major dams in the world. The use of RCC in the construction of gravity and arch dams continues to increase. The mix is spread in thin layers over the whole or part length of the dam, enabling the construction to proceed very quickly.

As RCC concrete mix designs are conventional and lead to high strengths and densities, it can be useful for pavements, rehabilitation works and replacement or protection of structures.

Its lower cost compared to CVC derives mainly from the possibility of continuous mixing and hauling, as well as obvious planning simplifications and economy due to shorter construction period.

The RCC concept as a construction method was born, in theory and in practice, at the Asilomar Conference [2-01] – California, USA, in March/1970. Raphael's paper [2-02] entitled *"The Optimum Gravity Dam"* postulated the optimum gravity dams as being the most economical solution between the extremes of the high-volume earthfill (containing no cement) and the small volume conventional concrete gravity dam. Raphael noted that the increase in shear strength of a cement-stabilized material would result in a significant reduction of the cross section compared with a typical embankment dam. Also, the use [2-03] of continuous placement methods similar to those used for earth dams would generate savings in time and money compared with traditional concrete dam construction methods.

References

2.01 "Rapid Construction of Concrete Dams", in: Proceedings of the Engineering Foundation Research – Conference, American Society of Civil Engineers. Asilomar, California, 1970.

2.02 RAPHAEL, J. M.: "The Optimum Gravity Dam,", in: Rapid Construction of Concrete Dams, ASCE. New York, 1970. p. 221-244;

2.03 RAPHAEL, J. M.: "Construction Methods for the Soil-Cement Dam", in: Economical Construction of Concrete Dams, ASCE. New York, 1972. p. 217.

3

Historical Development of RCC

3.1 Historical Background

3.1.1 Summarized Development

At the Asilomar Conference in California (1972), the need for a faster and more economical construction method of concrete dams was first addressed. The same question was later discussed during the XIth International Congress on Large Dams (ICOLD Madrid, 1973). After this, many symposiums, congresses and technical meetings concerning RCC technology emerged around the world.

Obviously, previous work done had opened the way suggesting alternatives to a faster and less costly concrete dam construction. The idea of combining placement advantages of dams built with loose materials (using lorries for transportation from the mixer to the work face, spreading the material in layers and using external compaction) to the advantages of concrete as a construction material developed in the 60's.

RCC was first placed in a dam in 1960-61 [3.01], at the core of the Shihmen Cofferdam in Taiwan. The same continuous grading aggregates used in conventional concrete were employed. The maximum size was 76 mm and the RCC was made in the same plant used for conventional concrete production. The binder mix proportion was 107 kg/m^3. Dumpers were used to transport the material, which was spread in 0.3-m thick layers by bulldozers. The material was compacted by the transit of the dumpers and the D-8's used in spreading the concrete. The water content was based on that defined by the optimum moister obtained following the Modified Proctor Method.

The 172- m high Alpe Gera Dam was built in Italy between 1961 and 1965 [3.02]. Using loose material methods, lean concrete was placed in 0.7-m thick layers from one side to the other (in this way avoiding traditional block construction). Batteries of vibrators mounted on dozers were used for compaction and transversal joints were defined by cutting each layer. Impermeability of the dam was assured by covering the entire upstream dam face with metal sheets. An analogous methodology was applied in the construction of the Quaira Della Miniera Dam, also in Italy.

Another early hybrid was developed by concrete dam designers at Hydro Quebec in Montreal [3.03]. Their ideas were incorporated in two 18m high gravity wing walls at the Manicougan

I Dam in Quebec in 1965. Here, lean mass concrete was placed by dozers for the core of the dam and was internally vibrated. A richer mix was used for the upstream face of the wing dams. The facing concrete was slip-formed vertically. Joints with waterstops were spaced at 15m intervals. Precast blocks were used for the downstream face. Hydro Quebec estimated that the system saved 20% of the cost and two-thirds of the time that would have been required to build the concrete wing walls using conventional methods.

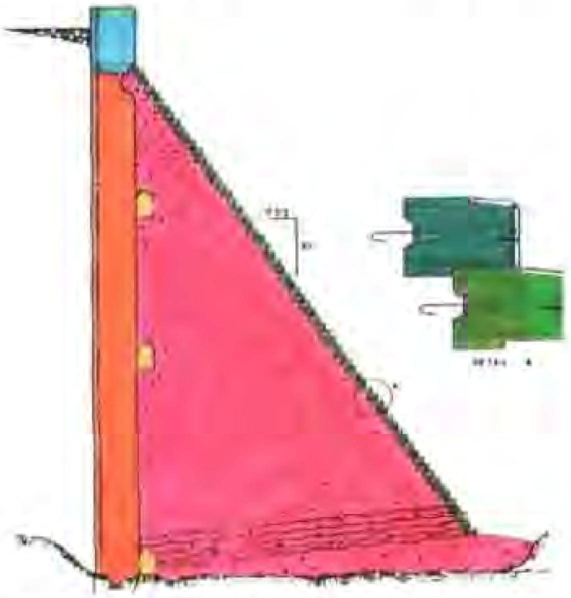


Figure 3.01 Concrete class zoning scheme for Manicougan I Dam (1965).

John Lowe III described the application of lean concrete to the Shihmen Dam in a 1962 conference organized by ASCE in Omaha, Nebraska. Lowe suggested the possible use of rubber or metallic compactors to compact the concrete. He invented the English word **"rollcrete"** as an abbreviation of **roll**er compacted con**crete**. His project, however was never published. A copy was later presented at the meeting sponsored by CIRIA in June 1981.

An important milestone in the outset of this new trend is the RCC used at Tarbela Dam in Pakistan [3.04 to 3.10]. Between 1974 and 1982 more than 2.5 million cubic meters of RCC were placed. It was initially used for replacement of a rockfill protection wall destroyed during the collapse of a tunnel in the first filling of the reservoir. This repair was followed by the reinforcement of the stilling pool and the cofferdam. River aggregate with a maximum size of 150 mm was used. The initial Portland cement content was 133.5 kg/m^3. Dumpers and scrapers were used for transport and vibratory rollers for compaction.

In the spillway rehabilitation works, the aggregate was relatively well graded with a maximum size of 150 mm and approximately 10% of fines which passed through ASTM sieve number 200. The aggregate was divided into two sizes, the cut being made at the 19mm sieve, combined with 110 kg/m^3 of Portland cement and water and mixed in a continuous mixer.

In Japan, research on RCC started in 1974 [3.11; 3.12] under the auspices of the Committee on Rationalized Construction of Concrete Dams. The first projects done in this country using the technology called RCD (**R**olled **C**oncrete **D**am), are the 89-m high Shimajigawa Dam, completed in 1980, and the Ohkawa Dam foundation slab, started in 1979.

The RCD mix proportions for these two dams contained 130 kg/m³ of binder, Portland cement mixed with 30% of fly-ash, and an aggregate with a MSA of 80 mm.

In 1974, the US Army Corps [3.13] developed an alternative RCC gravity dam for the Zintel Canyon reservoir in Washington to substitute the earth dam type.

Zintel Canyon Dam was not built with RCC technology, but its concepts served as a basis for building the Willow Creek Dam in Oregon, completed in 1982 [3.14 to 3.18]. This became the first dam in the world to be completely built with RCC, and stands side by side with the Shimajigawa Dam, the first to [3.19] use the RCC concept.

The Willow Creek Dam is 51m high, has an RCC volume of 300,000 m³, a vertical upstream slope and a downstream slope of 0.8H/1V. The RCC was designed with a crushed aggregate of MSA of 76mm and 4 to 10% of fines which passed through sieve number 200. The quantity of binder varied depending on the part of the structure. For example, for the internal RCC, 47 kg/m³ of cement and 19 kg/m³ of fly-ash were used. The thickness of the layer ranged from 24 to 34 cm and was controlled by laser.

In Great Britain, the investigation sponsored by CIRIA ended with a full-scale test during the construction of the Winbleball Dam in 1979 [3.20]. This was the first step towards an alternative construction method for the Milton Brook Dam. The RCC designed during this experiment had a high paste content.

In Spain, RCC was first used at the Erizana Dam [3.21], the construction of the Bayona Dam dike and the Castilblanco de los Arroyos Dam in 1985.

In Brazil, this new technology was first used in 1976 to build a concrete floor at a storage building, for the contractor's camp facilities, at Itaipu Dam site [3.22].

Figure 3.02 RCC used in the floor of a storage building at Itaipu Dam site facilities (1976)[3.22].

In the 80's, the use and development of RCC dam construction technology increased progressively.

As a general conclusion, it can be said that all the ideas involved in RCC dam construction methods have already been used in isolated cases in the past, the only novelty being their association and harmonizing in order to obtain a quicker and more economical dam construction.

To understand the development of RCC construction technology it is important to notice that at the end of 1980, there were only 02 completed RCC dams and at the end of 1986, there were 15 completed RCC dams in the world. By the end of 1996 there were more than 150 RCC dams, completed or under construction, in the world, as shown in Figure 3.03.

Country	RCC Dams (completed or under construction)			
	1986	1990	1993	1996
Africa	**2**	**7**	**15**	**17**
Angola	-	1	1	1
Morocco	-	2	6	7
South Africa	2	4	8	9
Asia	**3**	**11**	**24**	**50**
China	1	3	10	24
Japan	2	7	13	24
Kyrgyztan	-	1	1	1
Thailand	-	-	-	1
Europe	**1**	**6**	**20**	**27**
France	-	1	3	6
Greece	-	-	1	1
Italy	-	-	-	1
Romania	-	-	1	1
Spain	1	5	15	17
North America	**6**	**15**	**26**	**32**
Canada	-	-	-	1
Mexico	-	1	2	5
USA	6	14	24	26
Oceania	**2**	**3**	**6**	**7**
Australia	2	3	6	7
Central & South America	**1**	**3**	**5**	**23**
Argentina	-	1	1	1
Brazil	1	1	3	17
Chile	-	-	-	1
Colombia	-	-	-	1
Cuba	-	-	-	1
French Guyana	-	-	-	1
Honduras	-	1	1	1
Total	**15**	**45**	**96**	**156**

Figure 3.03 RCC Dams throughout the world [3.23].

3.1.2 General Development

Of the total number of dams built worldwide [3.24] until 1950, excluding China, 38% of the dams equal or greater in height than 15m had been built in concrete. Between 1951 and 1977, this number dropped to 25%. Between 1978 and 1982, this number decreased even more, dropping to 16.5%.

The decline in the construction of concrete dams took place in a time when the number of arch dams in narrow valleys was increasing. The reduction happened, however in dam sites situated in wide valleys, where concrete gravity dams were substituted by embankment or fill type dams, with a lower construction cost. This cost reduction originates basically from a greater efficiency in the equipment used.

Nevertheless, in contrast to a greater economy, the fill types dams presented - and still present - a greater probability of failure as mentioned in [3-24]. In the United States, there has not been a failure of a concrete dam higher than 15 m since 1928. Outside the United States, the most recent failure of a concrete dam was that of Malpasset Dam, in France in 1959. This was a 61-m high arch dam, in which sliding of one of the abutments occurred over the length of a fracture plane. On the other hand, during the last 60 years, hundreds of failures have happened with fill type dams. The main causes are the overflowing during a flood (as was the case in Tous Dam) and the internal erosion of the fill material (as at Teton Dam).

As a result, it became necessary to find a new type of dam that combined the superior safety of concrete dams with the efficiency of the construction method of fill type dams. From this basic idea, and by way of several different methods, RCC dams were developed.

The RCC construction method evolved not only from the efforts of some influential concrete dam designers but also from the work of geotechnical engineers who traditionally design earth and rockfill embankments. Their combined efforts have produced a concrete dam built with methods usually associated to earth dam construction. The product is a low-cost dam with the same inherent safety as a conventionally placed concrete dam.

An authentic forerunner of this dam type is the Alpe Gera Dam, completed in 1964 in Italy [3-02]. Here, an attempt was made to reduce the cost of construction while maintaining the cross section of concrete gravity type dams. Part of the economy was obtained by reducing the cement content in the concrete used in the interior of the dam body, where stresses are lower and demands for durability, minimal. Most cost reduction however, came from the use of embankment construction methods. Concrete was extended in horizontal layers [3-25; 3-26], a method currently called [3.27] "**E.L.C.M.**- Extended Layer Construction Method" by the Japanese. It was used at Nunome Dam – 72m high, volume of 330,000 m^3 in 1989. The difference between construction methods used at the Alpe Gera Dam and known as "E.L.C.M.", and those used in a roller compacted concrete dam, is that the lean concrete was consolidated by internal needle vibrators mounted on tractors, instead of using external compacting with rollers.

In the 1970's, the evolution of the concept of RCC dams followed different roads:

- Dams built with lean mixtures, with a content of cement paste of 70 to 100kg/m^3, and with the placing of mortar between layers. This alternative was developed by the United States Army Corps of Engineers and other researchers and their first important work was the Willow Creek Dam (United States), completed in 1982;
- Dams with high-paste contents of binding material from 150 to 270kg/m^3, with a high proportion of fly-ash. An example is the Upper Stillwater Dam (United States, 1987) with more than 1,125,000m^3 of concrete with a mix of 247kg/m^3 of binding material.

· Dams of average content of paste, with mixes between those of the two previous groups. Les Olivettes Dam (France, 1987), with 130kg/m³ of a special cement, and Craigbourne Dam (Australia, 1986), with 170kg/m³ of binding material, are examples of this type.

· Japanese dams known as **RCD**: **R**oller **C**ompacted **D**ams. The difference with the previous types is not the content of binding material (until now, it has oscillated between 120 and 130kg/m³), but basically, the method of placing on the job. Layers 50 to 100cm thick are extended in several sublayers and are all compacted in one operation, instead of compacting each sublayer. Before compaction, cuts are made in the fresh concrete every 15m using a vibrating cutting tool and crack or fissure inducers are inserted. Bonding or union between layers is assured by way of careful cleaning of the surface and the extension of a thick layer (15mm) of mortar. The first application of this technique occurred at the Shimajigawa Dam (1980); to date, more than twenty works have been carried out. The most remarkable examples are the Tamagawa Dam (1986), with a total volume of 1,154,000 m³ and the Miyagase Dam (1994), with 1,930,000m³ of compacted and conventional concrete.

· Brazilian Dams, with a cement content of 70 to 100 kg/m³, with high fine content (8% to 12% finer than 0,075mm) and the placing of mortar between layers and a conventional mass-concrete upstream membrane face. The fine material used can be silt (as used in Saco Nova Olinda Dam) without pozzolanic activity or can be crushed powder filler, from a certain rock, as used in Jordão and Salto Caxias Dams, with low pozzolanic activity.

Other than the Italian precedent, the Alpe Gera Dam, and other cases of embankment type dams such as the repair of Tarbela Dam (Pakistan, 1974), the first dam was the Shimajigawa Dam (Japan, 1980) mentioned above.

RCC technology evolved considerably afterwards and numerous examples of RCC dams emerged in countries such as United States, Japan, South Africa, Australia and Spain. The ample approval of RCC dams can be explained by the great advantages of this technology, among which can be emphasized:

Figure 3.04 Saco Nova Olinda Dam - the first Brazilian RCC dam and the first (in plan) arched RCC dam in the world.

· as compared with conventional concrete dams:

⇒ superior rate of construction (can reach 2-2,5m per week);

⇒ large-scale use of conventional equipment (dumpers, bulldozers, rollers);

⇒ as a consequence of the previous point, reduced costs;

⇒ less impact on the environment.

· as compared with embankment or fill type dams:

⇒ shortening of the time for completion, by placing with similar rates reduced volumes (ratio from 1:4 to 1: 5);

⇒ may perform as a spillway over the dam;

⇒ shorter outlet conduits and intakes. Intake tower abutting against the dam and not freestanding;

⇒ shorter river diversions during the construction;

⇒ as a consequence of the aforementioned, a considerable construction cost reduction;

⇒ less impact on the environment due to less quantity of materials required, which also results in a reduction in traffic problems, dust and scars in the zones of borrow pits;

⇒ they support floods or spilling not only in service but also during construction.

Most RCC dams are gravity dams, although in some countries (South Africa, China) there are some examples of arch - gravity dams.

For many years [3-25], the so-called "rolled concrete" was used as sub-base of roads and airfield pavements where it has generally been referred to as "lean concrete" or "dry lean concrete". Mainly, it has been used as a 150 to 250-mm thick base under bituminous surfacing.

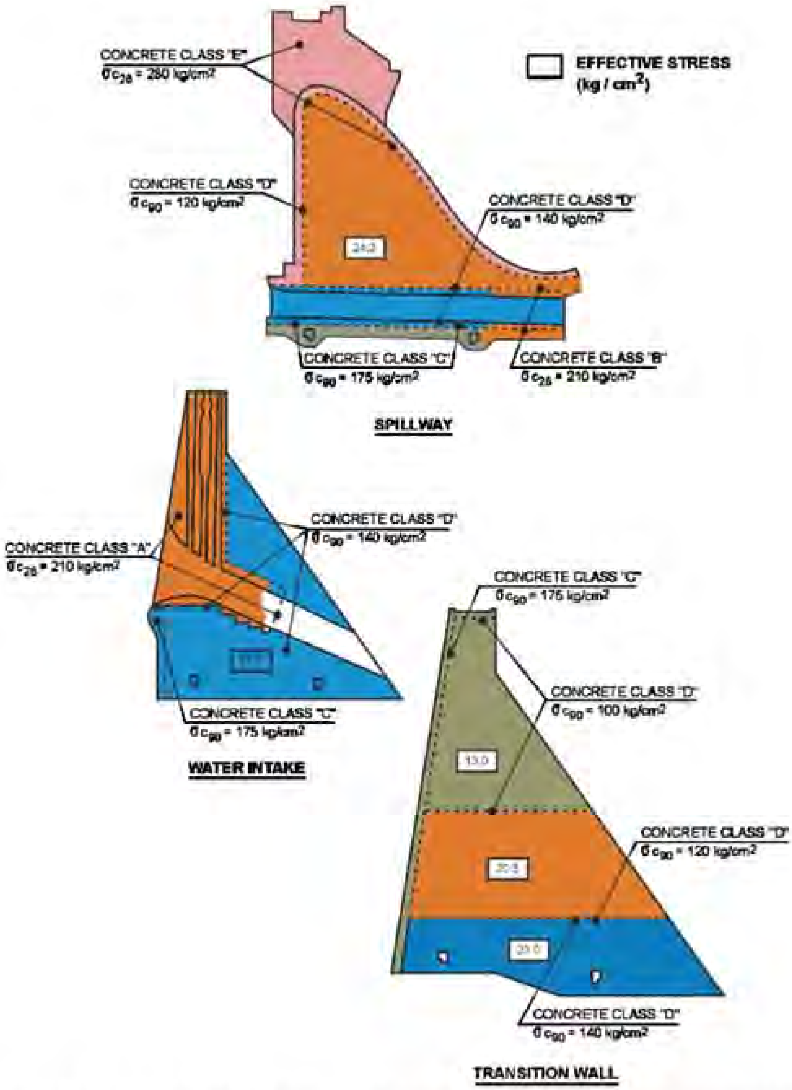
The popularity of rolled concrete for this use has been attributed to a number of factors, primarily that it is a simple material to produce and place, and it requires no unique construction facilities or equipment. The mixtures for paving work usually have low cement content, about 110 to 120kg/m^3, and involve the use of washed aggregates suitable for plain concrete. The water content is chosen to produce no-slump concrete to suit compaction by rolling, and the material is laid without contraction joints. The main deficiency, from a performance point of view, has been the occurrence of transverse cracks. This undesirable characteristic has had a major influence on mixture proportioning and pavement design.

Figure 3.05 Paving works at Congonhas Airport (São Paulo, Brazil 1950). No-slump concrete [3-28].

During the construction of the Congonhas Airport in São Paulo, Brazil [3-28] a dry mixture was compacted with vibratory plate for paving work.

As mentioned before, the Alpe Gera Dam is an important milestone in the development of new construction methods for concrete dams.

The possible merits of dry lean concrete as an interior concrete for gravity dams were suggested by Paton [3-29; 3-30] in a contribution to the International Commission on Large Dams (ICOLD).



Note: It is important to point the concept of an upstream concrete membrane used as impermeable barrier and a massive zone at downstream.

Figure 3.06 Concrete Class zoning for some Brazilian Dams[3-34].

Although mass sections using large aggregate RCC were not new, Raphael's paper [3-31] was the first to recognise that these construction methods could be used to produce a large dam. Sly Creek Dam for the Oroville-Wyandotte Irrigation District was designed as an 18-m high solid soil-cement dam in 1967. The California Division of Safety of Dams approved the design by a private consulting firm for construction, but it was not built due to a funding problem [3-32]. RCC (called "rollcrete" at the time) containing coarse pit-run aggregate was used for the mass foundation to support the outlet conduit for Cochiti Dam in New Mexico in 1968 [3-33].

During the 70's, similar ideas for interior lean mass concrete were adopted by Brazilian dam designers and government agencies, for massive structures using **CVC** as schematic shown on Figures 3.06 [3-34]

Cannon (1972, 1974), from the Tennessee Valley Authority (TVA), presented papers entitled "Concrete Dam Construction Using Earth Compaction Methods"[3.35] and "Compaction of Mass Concrete with Vibratory Roller"[3.36] in which he showed results from tests conducted by the TVA on concrete compacted by vibratory roller. These results were obtained in part from the first full-scale trial of roller compacted concrete in the USA which took place at Tims Ford Dam in 1970.

In Japan, the Ministry of Construction of the Japanese Government organized a committee formed by specialists in concrete dams headed by Dr. Kokubu, and since 1974, this committee has been promoting research concerning construction of concrete dams. Part of this research is the work being done on the Roller Compacted Dam (RCD) construction method which has been investigated independently in Japan [3-11; 3-12; 3-19; 3-37 and 3-38]. A full-scale test conducted at the cofferdam of Ohkawa Dam (volume = 10,000m^3)[3-11 and 3-39] in 1976, and the results of basic research and studies proved the RCD method applicable to the dam body.

Shimajigawa Dam [3-37; 3-40], the world's first RCD dam (volume = 317,000m^3) was completed in 1980, followed by Tamagawa Dam [3-40; 3-41; 3-42; 3-43], the world's largest and highest RCD dam (height=100m, volume= 1,150, 000 m^3, completed in 1987).

In the UK, Price (1977) conducted a comprehensive laboratory investigation and design study at the University of Newcastle [3-44]. Trials with lean concrete which contained fly-ash pozzolana were carried out in 1976 at the Tamar Treatment Works in Cornwall, and the results were reported by Dunstan (1977) of the South West Water Authority [3-45]. Subsequently, Dunstan played a major role in the CIRIA - Construction Industry Research and Information Association-sponsored research project in 1978-80, which included two large and three small full-scale trials reported in two notes [3-46; 3-47]. In these trials, rolled concrete with a low cement content and a high fly-ash content was investigated. A method of using an offset slipform paver to form the face of a dam was also investigated. The experiments culminated in construction of a small section of dam using materials and a production plant, which would be available for the future construction of the Milton Brook Dam, UK.

The remedial work on Tarbela Dam, Pakistan [3-04 to 3-10], during 1975-83, was also significant in the historical development of roller compacted concrete.

One of the first effective uses of RCC in the United States was in 1976 at TVA's Bellefonte Nuclear Plant [3-48], where 5,800 m^3 were used to raise the supporting base under the turbine building by approximately 3m. Between 1978 and 1980, the USCE used RCC on the floodway sill adjacent to the Tanana River, [3-49] on the Chena River project in Alaska, [3-50] and for rock protection in the tailrace of the second powerhouse at Bonneville Lock and Dam in Washington.

Based on data developed in its early research and test sections, the Corps designed an alternate RCC for Zintel Canyon Dam near Kennewick, Washington, in 1974. The concept of a more economical gravity dam took a big step forward when it was found that the "rockfill" section could be reduced to a typical gravity dam section with a vertical upstream face [3-13; 3-51]. Although Zintel Canyon Dam was not built due to lack of funds, many of its concepts were carried through at Willow Creek Dam, Oregon. This dam, completed in 1982, became the world's first major dam built almost entirely of RCC. A large amount of RCC was used for roads and runways at Ft. Drum Army Base in New York State in 1980.

The 53-m high Willow Creek Dam confirmed the economy and rapid construction possible with RCC. More than 315,000 m^3 of RCC were placed in less than 5 months at an approximate cost of US $\$30/m^3$, including the precast concrete panels that formed the vertical upstream face and all incidental costs for the RCC mass [3-52].

The experiments at Tamar Treatment Works (Cornwall, 1976), reported by Dunstan, included two large and three small full-scale tests with low cement and high fly-ash content using an offset slipform paver to form the face of a dam. These did not lead to the use of RCC in a major dam in the UK, but were the basis for the U.S. Bureau of Reclamation's (USBR) design for Upper Stillwater Dam, Utah. [3-53]. The 92-m high Upper Stillwater Dam, completed in 1987, contains 1,080,000 m^3 of RCC placed within horizontally slipformed, air-entrained concrete facing elements.

Canada was also an early user of RCC technology: the cofferdam for Revelstoke Dam in British Columbia was completed in 1980 [3-54].

The Japanese and Canadian projects are also worthy of note for using forced mixing rather than conventional concrete batch drum mixing.

Since these first projects, RCC has rapidly gained popularity and has been used in a number of completed structures in Brazil [3-55], Spain, France, Australia, and South Africa as well as in the United States and Japan. RCC is being used in other structures that are in various stages of concept, design, and construction. As with conventional concrete, there does not appear to be a limit to the size of the structure that can be designed and built with RCC.

RCC is also used as dam facing for erosion protection on new and existing embankment dams.

Figure 3.07 RCC placed at the Navigation lock of Tucurui Dam - Brazil.

3.2 State of the Art of RCC Dams

The conventional method of constructing concrete gravity dams relies on the casting of a series of monoliths divided by contraction joints. The method has the advantage of preventing temperature cracks, but the necessary equipment for concrete cooling and joint contraction makes this method less economical than conventional embankment dam construction. Another disadvantage of concrete dams is the limited use of large machinery, possible in embankment dam construction, because of the small construction area.

On the other hand, embankment dams have some structural disadvantages when compared to concrete dams, the main one being the lack of resistance of their materials when overtopped by floods.

As pointed out before, roller compacted concrete dams combine advantages of both technologies: the economical and rapid construction of embankment dams and the structural reliability of concrete dams. In RCC and RCD construction methods, concrete is placed in long and continuous layers and consolidated by vibrating rollers or by a combination of crawler tractors with nonvibratory rollers, while conventional concrete is placed in isolated monoliths and consolidated by immersion vibrators. RCC and RCD methods are characterized by reduced labor costs, continuous construction, shortened construction periods, and cement content savings for the concrete. There is however, a need to develop techniques to prevent temperature cracks in the concrete. A successful technique is that used in RCD technology [3-56 to 3-65].

Extremely lean mixtures of no-slump material are used reducing the cost and heat generation of the concrete. The construction of Willow Creek Dam (USA) in 1982, for example, is widely known to have permitted a substantial economy, although watertightness was later improved by grouting because of leakage through the dam.

Following the Willow Creek experience, a number of RCC dams have been built, but with modified designs:

- most have used adequate cement content;
- measures have been taken in all cases to control leakage at the horizontal joints and/or through the upstream face;
- transverse joints and concrete performances have been adjusted to the new design concept.

These improvements, while keeping the structural qualities, benefit from a better cost-effectiveness.

In Japan, the RCD method of dam construction using roller compacted concrete has evolved somewhat differently than in the USA. RCD is a cautious but steady movement from traditional mass concrete design and construction to the inclusion of roller compacted concrete in a dam. The Japanese, like many nations, hold that roller compacted concrete dams should have structural reliability (e.g., strength, watertightness, durability and integrity) similar to that of traditional concrete dams, and that such properties should not be slighted just for the sake of cost reduction [3-59].

RCD was considered a new construction method, but RCD dams were not considered a new dam type nor was their design philosophy different from that of conventional dams. Elaborate studies have been made on the design of the mixture proportion in order to achieve a similar strength, watertightness, and other performances of conventional concrete, in addition to a greater construction efficiency and economy.

Transverse contraction joints, commonly provided in the dam body, make the dam free of temperature cracks. Mortar spread between layers makes the dam watertight and the outside surfaces of RCD dams, consistently formed and built of conventional concrete, make the dams as durable as conventional concrete dams.

The RCD method is flexible enough to be applied to dams of any height and purpose, and RCD dams are completed free from visible temperature cracks, water leakage, and other structural deficiencies. Shimajigawa Dam, completed in 1980, was the world's first roller compacted concrete dam, achieving the same quality of concrete of a conventional concrete dam, as well as a better economy and construction speed.

Figure 3.08 Sakaigawa RCD Dam, during construction, with contraction joints.

3.3 Development of Roller Compacted Concrete in Brazil

3.3.1 First Trials

Brazil's background in concrete technology, design of concrete structures and construction methods, previously described, played a major role in the development and rise of RCC.

***ITAIPU*:** The first known use of the new technique was to build a concrete floor in a storage building at Itaipu dam site in 1976. After almost 20 years this floor is still being used (see Figure 3.02).

In 1978, 26,000 m^3 of RCC, with a peak of 3,054 m^3/day, were placed at Itaipu Dam site, to form a backfill downstream access ramp for the diversion structure [3.66; 3-67]. This concrete, with a content of 91kg/m^3 of cement and 26 kg/m^3 of fly-ash would have to be removed later according to the construction planning. However, ten years later, when the second powerhouse in the diversion channel was under construction, extracted cores indicated that the material had a compressive strength of almost 21 MPa, was in a very good condition and could remain there thus forming a small part of the world's largest hydroelectric power plant.

SÃO SIMÃO: In 1977/78, CEMIG, a state owned power company (Minas Gerais State), placed at São Simão Dam almost 40,000 m^3 of RCC in 0.5 meters lifts to:

- build a concrete base (11,800 m^3);
- smooth and fill an access tunnel floor (2,000 m^3);
- plug diversion galleries (20,300 m^3);
- build a concrete gravity wall (4,300 m^3).

TUCURUI: In 1982, about 12,000 m^3 of lean RCC were placed in 0.25m lifts at the right gravity guide wall (see Figure 3.07) navigation lock [3-55]. The concrete mix contained 65kg/m^3 of cement and 38kg/m^3 of pozzolan (calcined and grinded clay). Extracted cores showed compressive strength of about 10 MPa.

TRÊS MARIAS: RCC was also used at Três Marias Hydroelectric Project when the spillway profile had to be modified. Lifts of 0.25m were used to place a total of 14,600 m^3 of RCC in an area of 8,500 m^2.

In those early days of RCC studies in Brazil, some full-scale tests were performed such as a 250 m^3 testfill at Itaipu, and a 450 m^3 at Tucurui, among others. Inspection carried out in those testfills included construction methodology, construction equipment, mixes design, determination of the main characteristics of the concrete such as compressive and tensile strength, thermal properties (coefficient of thermal expansion, specific heat, difusivity, adiabatic temperature rise) modulus of elasticity, Poissons ratio, permeability and density.

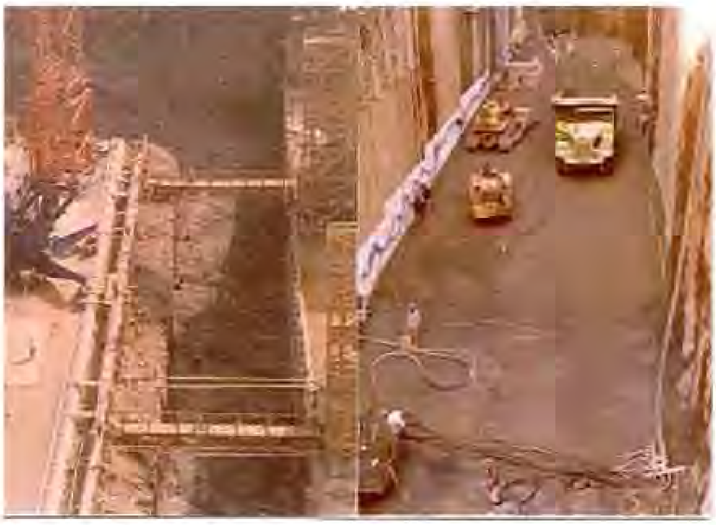


Figure 3.09 RCC used as backfill of an access ramp at Itaipu Project- 1978

3.3.2 First Projects

In the early 80's, Brazilian consulting engineering companies began to consider RCC as a good alternative for dam construction. Most feasibility studies initially compared RCC to traditional mass concrete and finally, to earthfill and rockfill dams. At that time, several large hydroelectric projects were having their feasibility studies developed like, for instance:

- Barra Grande (183m high), and;
- Capim Branco (108m high).

The RCC solution was studied in great detail but was not chosen as the best alternative because:

· the real cost of roller compacted concrete was still undetermined in Brazil, and there was a tendency to increase the final prices to overcome unknown factors;

· some engineers questioned the technical feasibility of building high dams and did not want to bet on the new technology.

Important facts that helped change this situation are:

· visits of Brazilian engineers to RCC dams completed or under construction abroad, mainly in the USA (Willow Creek, Galesville, Upper Stillwater, Monksville, etc) and Japan (Shimajigawa, Tamagawa, Pirika, Sakaigawa, etc);

· presentation of technical papers on RCC ([3-66]. The first one - "Concreto Adensado com Rolo Vibratório") was presented at a Brazilian seminar held by the Brazilian Committee on Large Dams and the Brazilian Concrete Institute;

· lectures given to owners, contractors and consulting engineering companies about the advantages of using RCC.

Major contributions to the development of RCC however were the construction of Saco de Nova Olinda Dam, in the state of Paraiba, and the construction of Urugua-i Dam in neighbouring Argentina.

SACO DE NOVA OLINDA: Built in 1986, mainly for irrigation purposes, it is 56m high and its 138,000 m^3 of RCC were placed in only 110 days with a production peek of 2,500 m^3/day. The construction method used was widely advertised and several papers about the dam were published in the country and abroad. The easiness of the method and its potential became obvious at Saco Dam. Pugmills were used to batch the concrete, small trucks (4 to 6 m^3) to transport the mix to the site, very simple formwork was applied at the upstream and no forms at the downstream face, stricking the sceptics that were not yet sure about the feasibility of RCC. A cost of about US$ 40/m^3 also testified in favour of the technique.

It is important to notice that the mix of this first Brazilian roller compacted concrete dam contained 70 kg/ m^3 of Portland Pozzolan cement.

URUGUA-i (Argentina): This project was built in Argentina from 1987 to 1989, not far from the Brazilian border at Foz do Iguaçu. For this 78-m high dam about 600,000 m^3 of RCC were placed in approximately 270 days reaching a peak of almost 6,000 m^3/day.

Several concrete tests were [3-68 to 3-70] performed at Itaipu laboratories for this dam including, among others: thermal properties, creep, triaxial and compressive strength, strain capacity, modulus of elasticity, Poisson's ratio, autogenous strain and permeability. It is important to notice that triaxial tests made on lean concrete, with 60kg/m^3 of cement, resulted in 2.5MPa of cohesion and a friction angle of 48°.

One of the greatest features of this dam was the low cost of the RCC: US$ 32.1/m³ were paid for a 60kg/ m³ concrete and US$ 35.7/m³ were paid for the 90 kg/m³ mix, despite long transportation distances (more than 1,000 km). No pozzolanic material was used in the mixes but researches made at Itaipu laboratory showed that the use of fines originated from the crushing process could greatly improve the quality of the concrete and even impart some pozzolanic activity.

Figure 3.10 RCC at Urugua-i Dam in Argentina, during construction

3.3.3 Special Uses

***SERRA DA MESA Cofferdam*:** In 1989, FURNAS - a federal government owned power company- decided to use RCC for the cofferdams of Serra da Mesa Hydroelectric Project. The 17,300 m³ of the upstream cofferdam, 22m high, and the 11,300 m³ of the downstream cofferdam, 13m high, were placed in 72 days of construction.

Several laboratory tests and full-scale trials preceded these applications because it was the first time that FURNAS would try to use RCC. A high cement paste content mix was used: 60 kg/m³ of cement and 133 kg/m³ of grinded blastfurnace slag. Because of financial problems construction of the dam was postponed and the cofferdams were overtopped five times.

The structural behaviour is being monitored with instrumentation and visual inspections. Periodically, concrete cores are extracted and tested at FURNAS laboratory. The first cores were obtained when the material was 450 days old; later, six years after construction, another series of cores were equally tested for: density, compressive strength, tensile strength (splitting test and direct test), modulus of elasticity and permeability. Compressive strength increased from 22.6 MPa at 365 days to 25.5 MPa at six years. Direct tensile tests performed on cores taken from joints between two lifts showed an increase in strength from 1.19 MPa at 450 days to 1.63 MPa at 6 years while cores from the concrete with no joints presented at 6 years a direct tensile strength of 1.73 MPa [3-71].

The cofferdams were overtopped with flows of:

Rain Period (High Flow)	River Maximum Flow (m^3/s)	Maximum Overtopped Flow (m^3/s)	Maximum Height over the Cofferdam (m)
1989-1990	9171	6671	12
1990-1991	3403	853	7
1991-1992	6701	4151	11
1992-1993	3907	1220	8
1993-1994	4601	1850	9

The structure behaved according to what was expected in the design and showed a remarkable strength against erosion.

***PORTO PRIMAVERA wave protection*:** Another special use of RCC was developed by CESP, São Paulo state government power company, at Porto Primavera Hydroelectric Project (1800 MW).

The material was placed in a 26-m high rockfill embankment that protects the earthfill dam as a barrier against high waves that occur annually during the operation of the spillway gates.

The RCC barrier was chosen instead of "rip-rap" due to a lack of large stones at the site (natural gravel is the coarse aggregate for concrete). It is 10-m high, 5 m in width. The first stage was 200m long and was built in 1993. Concrete was placed in continuous 0.35m lifts with no provision for construction joints.

The design correctly predicted that the opening of joints caused by thermal cracking would not affect the behaviour of the structure. The downstream water level has already reached the RCC and its behaviour is considered very good.

A lean RCC with 100 kg/m³ of Portland Pozzolan cement was used and tests were performed to examine the mix, the equipment and the method: laboratory tests, small-scale compaction tests and a full-scale field-test (185 m³). Cores were extracted and tested at CESP's central laboratory at Ilha Solteira.

The RCC and the rockfill are being monitored by instruments and periodical visual inspections. Installed instruments include rod extensometers, inclinometers, electrical resistance, thermometers and reference marks.

XINGO ROCKFILL DAM Protection: The 150-m high concrete faced rockfill dam of Xingó Hydroelectric Project required protection to reduce the risks caused by eventual overtopping during construction. RCC was chosen as the best alternative and a mix containing 100kg/m³ of Portland cement plus 30kg/m³ of artificial Pozzolana (from calcined clay) was used for the 44,155 m³ of concrete. RCC was placed in successive layers of 0.4 m.

Prior to its actual application, CHESF, a federal government owned power company, decided to test the methodology and for this purpose, built a full-scale test fill, with a volume of 719 m³, in one week.

3.3.4 Projects of the 90's

In the first half of this decade, six dams were built using the RCC method: Caraibas, Gameleira, Cova da Mandioca, Várzea Grande, Juba I and Juba II, and five others were (1998) under construction: Jordão River Deviation, Salto Caxias, Canoas, Traíras, Pelo Sinal, Jucazinho, Belo Jardim and Rio do Peixe.

3.3.5 Completed Dams

Some features of the completed dams are summarised below.

CARAÍBAS: Caraíbas dam, initially designed as an homogeneous earthfill dam with a volume of 140,000 m³ and a morning-glory spillway, had its design changed to a concrete gravity dam built with RCC, incorporating a stepped spillway in the dam body. The RCC volume is 17,800 m³, and 57 days were spent to place it initially in 0.3m lifts and later in 0.4m lifts. Portland Pozzolan cement was used in the RCC mix and a cement content of 66kg/ m³ was deemed necessary. No additional fly-ash was used.

The dam, owned by CEMIG, a state power company, was built in 1990 mainly to increase water supply, and also for irrigation and rash breeding.

GAMELEIRA: Gameleira dam, owned by CODEVASF - a federal government owned company- was also initially designed as an embankment dam and later changed to RCC. The dam is 29-m high with 150m of crest length, a total volume of 29,289 m³ and 27,000 m³ of RCC with a cement content of 70kg/m³ with no fly-ash added. It provides water for the neighbouring population and for irrigation and the reservoir is also used for flood control.

An interesting feature of this dam is that it was overtopped during construction without presenting any concrete damage. The spillway operates every year with no wearing of the stepped spillway.

COVA DA MANDIOCA: CODEVASF also owns the Cova da Mandioca dam, initially designed as an embankment dam (420,000 m³) and later replaced by an RCC dam, 32m high with a volume of 75,200 m³ with 71,400 m³ of RCC. A cement content of 80kg/m³ was used with no fly-ash and lifts were 0.4m high. Compressive strength reached 7.5 MPa at 90 days.

JUBA: Juba I and Juba II belong to Itamarati Norte S.A., a private company, and their main purpose is power generation, totalling 42 MW each. RCC was placed to form the stepped spillways and the cement content of the mix was 70kg/m³ with no addition of fly-ash.

Figure 3.11 Jordão RCC Dam .

JORDÃO: The purposes of the Jordão river derivation dam are, first to connect its reservoir to the neighbouring reservoir of Segredo Hydroelectric Project assuring specified levels of power generation, and secondly, to generate 6,5MW in the unit that will be set up. The derivation tunnel with 9m of diameter is about 4,700m long.

The total concrete volume is 647,000 m^3 of which, 547,000 m^3 correspond to RCC. The dam is 95m high and the crest length, 546m long. A Portland Pozzolan cement was used and the cement content varies from 70 kg/m^3 to 100kg/m^3 of RCC.

One of the most important features of this dam, the first of its kind in Brazil, was the bidding process: two basic designs were available to the contractors. One was a concrete face rockfill dam and the other, an RCC dam. Each contractor could choose only one type of dam to bid for and the lowest price would win. The winner, as well as the second and the third places in the rank chose the RCC option. The cost of the RCC was approximately US$ 21/m^3 of concrete [3.72].

3.3.6 Dams under Construction

The success of early RCC trials and dams in Brazil along with the enormous development of this technology all over the world became the main force of Brazilian RCC projects in the 90's.

The most remarkable event was COPEL's approach to the tender of Jordão Dam. The outcome of this first bidding was later emphasised when the power company, owned by the state of Paraná, tendered the Salto Caxias Dam. The results for the bidding of Salto Caxias dam were disclosed by the end of 1994. This 66-m high dam with a crest length of 1,082m has an RCC volume of 912,000 m^3 out of a total concrete volume of 1,438,000 m^3. Construction started in January 1995 and the main purpose of this project is hydroelectric generation with an installed capacity of 1,24OMW.

Figure 3.12 Salto Caxias Hydoelectric Project, during construction in 1997 (Courtesy from COPEL).

3.4 RCC Design and Construction-Brazilian Practices

3.4.1 Design

Design for RCC dams in Brazil follow the same procedures as for traditional concrete dams. However, some characteristics of the method demand more attention be given to certain topics, such as thermal stresses and watertightness.

The use of drainage galleries and the shape of uplift diagrams have been much discussed in RCC dams less than 40-m high [3-73]. Several Brazilian RCC dams under construction or still being designed have one line of internal drains as a supplementary guarantee against seepage.

Thermal stress analysis has been performed in Brazil since the late 60's, when HEATRN software, derived from Wilson's initial studies at the University of California, Berkley, USA, began to be used. However, because of the low cement content of most RCC mixes, thermal stress analysis has verified that up to now, cracking is not a problem in Brazilian dams.

Several Brazilian RCC dams, either built, under construction or being designed, were previously embankment dams. Change in the dam type owes much to the flexibility of designers:

· usually taking into consideration the special requirements of the construction methodology, trying to avoid embedded parts;

· maintaining a close link with those responsible to the layout and planning of the project thus adapting the design to the construction phases;

· taking advantage of the characteristics of concrete.

3.4.2 Materials

The installed capacity for power generation in Brazil is 55x10^3 MW. About 8% come from thermoelectric powerplants moved by diesel, coal and nuclear energy. Coal is responsible for only 2% of the total and is used in powerplants located in the south of the country.

Consequently, the use of fly-ash is almost impossible in the North and Northeastern parts of the country, because of the high cost of transportation that may increase the cost of the material, sometimes exceeding the price of cement.

Therefore it is easy to understand why most of Brazilian RCC dams use low cement content mixes, and when pozzolanic material is considered necessary, its amount is as low as possible. The use of low cementitious contents presents the following main advantages:

· reduced risks of thermal cracking,

· reduced material for alkali-aggregate reactions;

· lower cost of the mix,

Silt has also been used in Brazil for some RCC mixes. One of the major breakthroughs in the concrete mix design however, refers to the use of stone dust or crushed powder as a filler. The first experiments began at Itaipu laboratories [3-74] where it was proved that certain types of rocks, when finely crushed, could also have some pozzolanic properties. For this reason there is a trend in Brazil, nowadays, to carefully study the crushing plant scheme in order to include a quaternary crusher, if tests prove it to be cost-effective. The use of silica-fume in RCC mixes has not yet proven economical in this country.

3.4.3 Construction

Up to now, small projects have used unsophisticated equipment for RCC production and placement in Brazil; ordinary batching plants or pugmills, small trucks (4 to 6 m^3), dozers (D4 and D6 types) and rollers commonly available.

Lift heights that initially started at 0.25m in the first trials have increased to 0.40m in some projects.

Construction of galleries embedded in the RCC has varied widely according to the need of each design. Several methods have been used, such as: placing coarse or fine aggregate in the part of the RCC lift where the required gallery will be and then mining out this material; use of wood separators or small precast concrete elements between the RCC and fill as each layer is placed; precast concrete sections; conventional forming.

Experience has shown that the use of loose sand as fill material can contaminate the surrounding concrete surface thus requiring extra cleaning. However, good results were obtained at Canoas Dam where wet sand was used and removal was easy. The use of wood separators or small precast elements has proven to be a good solution and improves the aesthetics. A coarse aggregate used after compaction becomes difficult to remove and consequently, time consuming.

Procedures to build the upstream face, the downstream face, contraction joints as well as other constructive details such as waterstops embedment, lift cleaning and use of bedding mixes are very similar to what is being done in other projects around the world.

3.4.4 Instrumentation

Monitoring has always been a matter of concern in dams in Brazil, and therefore, almost all projects include some type of instrumentation, such as thermometers, piezometers and rod extensometers. Reduction of the number of instruments embedded in the RCC is taken into consideration as a way of avoiding construction stops.

3.5 RCC Focused as material

3.5.1 Soil-cement

Sly Creek Dam [3-32; 3-33] in northern California was designed in 1967 as a l8-m high solid ***soil-cement*** dam. The entire section had to be erosion-resistant because the dam was designed to be overtopped and ultimately inundated during high-flow conditions. The increased shear resistance of soil-cement over earthfill construction allowed both the upstream and downstream slopes of Sly Creek to be steepened to 1H:1V. The design [3.31;3.32;3.75] by California engineering consultants St. Maurice, Helmkamp and Musser (MHM Engineers), was approved for construction by the State Department of Water Resources' Division of Safety of Dams. The project was never built because of a lack of funds. At the same time (1964), Sarkaria, G.S., at IECO- San Francisco- proposed the same concept for the 50-m high New York Flat Dam, in the same area. Both dams were discussed with California DSOD, but DSOD approves only when the bid documents are prepared.

Erosion resistance also was the key criterion for the design of a 6.7-m high, 10-km long embankment to enclose a 445-hectare cooling-water reservoir for the Barney M. Davis power station in Corpus Christi, Texas. The long, low ring-dike had to withstand wave action from within and erosion by floods and heavy rain from without.

A solid soil-cement cross section with a 3.7-m crest width and 1.5H:1 V slopes on both faces was one of the alternatives considered by engineering consultants, Sargent & Lundy, in 1971. It proved to be the most economical option when it was bid two years later as an alternative to a more conventional sand-fill embankment with soil-cement slope protection on both sides.

Besides being the only large dam constructed entirely of soil-cement, the Barney M. Davis reservoir embankment marked the first recorded use on a dam of vibratory rollers to compact soil-cement. No joints were incorporated in the 268,000 m^3 of soil-cement used to construct the long, low dike. Transverse cracks occurred in the soil-cement section as anticipated, but they were not of sufficient width to allow passage of water.

Also at the 1972 conference, Raphael reported on a major installation of soil-cement for upstream slope protection at Castaic Dam in California. A placement rate of 382 m^3/hour was achieved on that project. Raphael also noted in 1972 that techniques were available to take the next step of building an economical soil-cement dam. Apparently, he was not aware of the earlier Sly Creek Dam design or the solid soil-cement alternative proposed, and eventually built, for the Barney M. Davis powerplant's cooling-water reservoir ring dike.

In Brazil, Ilha Solteira Laboratories owned by CESP (São Paulo state government agency) developed a large study concerning the use of soil-cement as a material for construction of the dam body, as reported in [3-76].

3.5.2 Different Paths Taken in RCC Mix Design

RCC mix design was evolving in three different directions during the 1970's.

⇒ In the United States, a ***lean-concrete*** alternative based on soil technology was being developed by the Army Corps of Engineers and other investigators;

⇒ British engineers were focusing on the so-called ***high-paste*** alternative, a hybrid of conventional concrete mix design and earthfill dam construction methods;

⇒ The Japanese research team, set up to explore rationalized concrete dam construction methods, was developing the third approach, which was called ***roller-compacted dam*** concrete method, or **RCD**.

3.5.2.1 Development of the Lean RCC dam

The United States Army Corps of Engineers began a concentrated effort to develop RCC for use in building concrete dams in the early 1970's. The Corps built field test sections at Jackson, Mississippi, in 1972 [3-77] and at the site of Lost Creek Dam in Oregon in 1973 [3-78]. The field tests confirmed the basic construction method and provided information on material properties and the strength of the bond between successive layers of RCC. In fact, the name "roller-compacted concrete" may have been first used by Corps investigators Hall and Houghton in reporting on the Lost Creek test section[3-78].

3.5.2.2 Development of the High-Paste RCC dam

After initial work in the early 1970's by the Tennessee Valley Authority on a concrete mix with a low-Portland-cement and high fly-ash content, the development of this so-called high-paste RCC alternative shifted to the United Kingdom. The properties of the material were demonstrated in 1976 following field trials in Cornwall, England[3-45 to 3-47].

The high-paste RCC dam evolved along the same lines as the Japanese RCD method, in that both started out with the basic cross section of a concrete gravity dam. The volume of RCC at Upper Stillwater was reduced even further by taking into account the tensile strength of the bond at the joints between successive lifts of the high-paste RCC mix.

3.5.2.3 Development of RCC in Japan

At the same time that considerable progress was being made toward the development of RCC for dams in the United States, Japan also was working independently to develop a rationalized method for building concrete dams that would speed the placement of concrete and lower the cost of construction.

Because of seismic, hydrologic, and topographic problems associated with most dam sites in Japan, designers there have taken a more conservative approach to RCC dam construction. Their aim is for a product with the same quality and appearance as that of conventionally placed mass concrete gravity dams [3.11;3-12;3-19;3-37 to 3-43;3-59].

3.5.3 Development of the "Fines Content Practice"

The use of continuous grading for the RCC based on a cubic-type (or similar) curve takes into consideration a substantial quantity of fines, finer than 0.075 mm, for the adequate cohesiveness of the mix (see Chapter 6).

In stiff RCC mixtures, increased quantities of these materials may actually be used to reduce water requirements so that higher limits may be used without adverse effects.

These fines may be of various kind as previously mentioned: fly-ash, blast furnace slag, natural or calcinated clay Pozzolans, diatomaceous earth, silt and also "crushed powder" or "rock flour" (called "pó de pedra" in Brazil), byproduct of rock crushing obtained during the aggregate production process.

The use of this "stone crushed powder" (fines lower than 0.075 mm) in the RCC composition has considerable advantages. It not only improves the cohesiveness of the mixing while fresh but also reduces the expansions resulting from the reactions with the cement alkali, which depends on the Silica mineralogical form and content.

Natural sand resources of Brazil's southeast and south regions (next to the Paraná River basin) were becoming scarce. This forced the production of crushed sand by crushing rocks, normally of the basaltic type.

At first sight (see Chapter 5), the visual observation of these rejects did not indicate the presence of cohesive materials that could be considered damaging.

This gave rise to the evaluation of that reject with views of incorporating it to the CVC and RCC mixes [3-68 to 3-70], during the construction of the Urugua-i RCC Dam (in Argentina). A cubic grading curve (see Chapter 6) was used for the basaltic aggregates, requiring a certain amount of fines. The mixing studies for the Urugua-i Dam, carried out at Itaipu Laboratory, suggested the incorporation of the basalt "Stone Crushed Powder" to the mixing, which was successfully adopted.

3.6 Most Significant Events in RCC for Dams

1964 **Alpe Gera Dam**, a 172-m high concrete gravity dam in the Italian Alps, was built like an earth embankment, using dumper trucks, dozers, and tractor-mounted immersion vibrators to place lean concrete in horizontal lifts;
1970 ***Jerome Raphael*** presents a paper **"The Optimum Gravity Dam"** in which he proposes the concept of an embankment made of cement-enriched, granular pit-run material placed and compacted with high-speed earth-moving equipment;
1970-1973 Research in the United States by the **Tennessee Valley Authority** at **Tims Ford Dam** and by the **Corps of Engineers** at Jackson, Mississippi, and at **Lost Creek Dam** helped to prove the economic feasibility of RCC and to develop the construction methods for its mass placement;
1974-1975 The emergency repair of a collapsed outlet tunnel at **Tarbela Dam** in Pakistan using RCC demonstrated the rapid placement rates possible: 460,000 yd^3 (350,000 m^3) of RCC were placed in 42 working- days;
1978 Research started four years earlier by **Japan's Committee on Rationalized Construction of Concrete Dams** led to the start of RCC placement for the body of **Shimajigawa Dam**, a 89-m high gravity dam;
1978 A full-scale trial of the use of high-fly-ash-content RCC together with laser-controlled slip-formed facing elements was successfully completed at **Wimblehall Dam** in England. This work on **High-Paste** RCC contributed significantly to the design in the early 1980's of the **U.S. Bureau of Reclamation's Upper Stillwater Dam** in Utah;
1980 **Shimajigawa** became the first dam in the world to be built using RCC for the main portion of the dam.
1982 The placement of 331,000 m^3 of RCC in less than five months for the **U.S. Army Corps of Engineers' Willow Creek Dam** in Heppner, Oregon, confirmed the rapid construction rates and economic viability of dams built entirely of RCC;
1983 Construction started at **Tamagawa Dam**, the first RCC dam to reach 100m in height, in Japan;
1984 RCC came to the southern hemisphere with the design and construction of Australia's 40-m high **Copperfield Dam** in only 10 months.The construction of the 21-m high **Winchester Dam** in Kentucky using precast concrete panels and an attached polyvinylchloride (PVC) membrane to both form the RCC and provide an impervious upstream face initiated a concept that may be called a "concrete-faced RCC dam";
1985 The erosion resistance of exposed RCC was proven in the field when **Chervil Ponding Dam** in Texas, a 6.1-m high RCC dam, was overtopped by 4.4m during a flood, 30 days after construction was completed. It was overtopped by 4.9m due to an even greater flood two years later, with no considerable wear of the RCC crest and downstream slope;
1986 The construction of the 56-m high **Saco de Nova Olinda Dam** in Paraíba state- Brazil, the first RCC arched dam in the world and the first RCC Dam in Brazil and South America;
1988 Construction started at the 115-m high **Sakaigawa Dam** site, in Japan. The first RCC dam higher than 100m;
The construction of the 77-m high **Urugua-i Dam** in Argentina, the first RCC with ("Pó de Pedra") crushed powder filler to adjust the grain size curve;
1991 The construction of the 155-m high **Myagase Dam**, in Japan, the first RCC dam higher than 150m;
1992 The construction of the 75-m high **Puding Arch-Gravity Dam in China**, using the conceptual criterion of arch dam.

Figure 3.13 The Most Significant Events in RCC for Dams.

3.7 References

3.01 LOWE, J. III. "Discussion: Utilization of Soil Cement as Slope Protection for Earth Dams", in: First ASCE Water Resources Engineering Conference–Omaha. Nebraska, May 1962.

3.02 GENTILE, G. "Study, Preparation, and Placement of Low Cement Concrete, with Special Regard to its Use in Solid Gravity Dams", in: VIIIth ICOLD Congress, International Commission on Large Dams. Edimburg, 1964. vol. 3.

3.03 WALLINGFORD, V. M. "Proposed new Techniques for Construction of Concrete Gravity Dams", in: Transactions, Tenth International Congress on Large Dams. Montreal, Q39, June 1970. vol. VI.

3.04 "Repairs at Tarbela dam race spring snowmelt", in: Engineering News - Record. New York. vol. 193, nº 19, October 31, 1974.

3.05 MARSHALL, T. "Tarbela rescue: 380,000 m^3 plug beats the flood", in: New Civil Engineer, Institution of Civil Engineers. London, 27 April 1975.

3.06 "Repair and Reconstruction of the Tunnels at Tarbela.", in: Water Power & Dam Construction. United Kingdom, June-July 1975.

3.07 HAYWARD, D. "Indus River Contractors win race to protect Tarbela's eroded plunge pool", in: New Civil Engineer, Institution of Civil Engineers. London, March 6 1978.

3.08 JOHNSON, H. A., and CHAO, P. C. "Rollcrete Usage at Tarbela Dam", in: Concrete International, ACI. Detroit, Michigan vol. 1, nº 11. November 1979.

3.09 CHAO, P. C. "Tarbela Dam - Problems Solved By Novel Concrete", in: Civil Engineering, ASCE. New York, vol. 50, nº 12, December 1980.

3.10 LAVILLA, G. C. "The Technique of Placing Rollcrete as Experienced at Tarbela Dam During 1978 - 1981 for the Construction of Additional Works at the Spillway", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

3.11 SHIMIZU, S. and TAKEMURA, K. "Design and Construction of a Concrete Gravity Dam on a Weak Bedrock", in: Transactions, Thirteenth International Congress on Large Dams. New Delhi, vol. I, Q48, November 1979.

3.12 HIROSE, T.; SHIMIZU, S. and TAKEMURA, K. "Studies on Construction of Dams by the RCD Method", in: Transactions of the Japan Society of Civil Engineers. Tokyo, nº 303, 1980.

3.13 SIVLEY, W. F. "Discussions: Zintel Canyon Optimum Gravity Dam", in: Transactions, Twelfth Congress on large Dams. Mexico City, vol. V. Q44, April 1976.

3.14 SCHRADER, E. K. "Willow Creek Dam - An Optimum Gravity RCC Dam with Vertical Upstream Face", in: Rolled Concrete for Dams, Proceedings of the International CIRIA. Conference. London, June 1981.

3.15 *Willow Creek Design Memorandum, Supplement to GDM 2 - Phase 2, Main Dam, Spillway, and Outlet Works.* U.S. Army Engineer District. Walla Walla, Washington, December 1981.

3.16 SCHRADER, E. K. and THAYER, H. J. "Willow Creek Dam A Roller Compacted Concrete Fill", in: Transactions, Fourteenth International Congress on Large Dams. Rio de Janeiro, vol. IV. Q55, May 1982.

3.17 SCHRADER, E. K. "The First Concrete Gravity Dam Designed and Built for Roller-Compacted Construction Methods", in: Concrete International, ACI. Detroit, vol.4 nº10, October 1982.

3.18 SCHRADER, E. K. "World's First All-Rollcrete Dam", in: Civil Engineering – ASCE. New York, vol. 52, nº 4, April 1982.

3.19 HIROSE, T. and YANAGIDA, T. "Some Experiences Gained in Construction of Shimajigawa and Ohkawa Dams", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

3.20 MAYNARD, D. P. "Fullscale Trial at Wimbleball", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

3.21 GOMEZ LAA, G. "Rollcrete in the Erizana Dam", in: Transactions, Fifteenth International Congress on Large Dams. Lausanne, vol. II, Q57, June 1985.

3.22 Relatório C-09/96- "Atividades da Divisão em Junho/76", in: Technical Report from Concrete Control Division - Itaipu Binacional, June/1976.

3.23 HANSEN, K. D.; REINHARDT W. G. "Roller Compacted Concrete Dams", in: *Water Power & Dam Construction*. McGraw-Hill, Inc, 1997. Yearbook RCC dams > 15m.

3.24 HANSEN, K. D.; REINHARDT, W. G. "Roller Compacted Concrete Dams", in: McGraw Hill. 1991.

3.25 "Bulletin 75 - Roller Compacted Concrete For Gravity Dams" in: ICOLD International Commission on Large Dams. Paris, France, 1989.

3.26 GENTILE, G. "Notes on the Construction of the Alpe Gera Dam", in: *Rapid Construction of Concrete Dams*. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California: ASCE, March 1970.

3.27 "Nunome Dam", in: Nunome Dam Construction Office - Water resources Development Public Corporation. Nara, Japan, 1991.

3.28 "Aspectos da História da Engenharia Brasileira Civil em São Paulo 1860-1960", in: Companhia Brasileira de Projetos e Obras – CBPO. São Paulo, Brazil, 1989.

3.29 PATON, J. "Discussion: Recent Development in the Design and Construction of Concrete Dams", in: Transactions, Tenth International Congress on Large Dams. Montreal, vol. VI, Q39, June 1970.

3.30 PATON, J. "Discussion on Concrete Dams - Methods for Rapid Construction and Economies", in: BNCOLD Journal nº 10 (Institution of Civil Engineers). London, 1971.

3.31 RAPHAEL, J. M"The Optimum Gravity Dam", in: *Rapid Construction of Concrete Dams*. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California. ASCE, March 1970.

3.32 RAPHAEL, J. M. "Construction Methods for Soil-Cement Dam", in: *Economical Construction of Concrete Dams*. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California. ASCE, May 1972.

3.33 THOMAS, D. A. "Artificial Bedrock for Outlet Structure." Rocky Mountain Construction. Denver, 16 July 1968.

3.34 "Concreto Massa no Brasil - Memória Técnica – 1 Registro Histórico", in: CBGB - Eletrobras-IBRACON. Rio de Janeiro, Brazil, 1989.

3.35 CANNON, R. W. "Concrete Dam Construction Using Earth Compaction Methods", in: *Economical Construction of Concrete Dams*. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California. ASCE, May 1972.

3.36 CANNON, R. W. "Compaction of Mass Concrete with Vibratory Roller", in: ACI Journal, Proceedings. Title nº 71-34. Detroit, vol. 71, nº 10, October 1974.

3.37 MINISTRY OF CONSTRUCTION. *Construction of Shimajigawa Dam with Roller Compacted Dam Concrete.* Japan: Chugoku Regional Construction Bureau, 1981.

3.38 MINISTRY OF CONSTRUCTION. "Design and Construction Manual for RCD Concrete". Tokyo: Technology Center for Land Development, 1981.

3.39 SHIMIZU, S.; TAKEMURA, K. "Test Fill of RCD at the Upstream Cofferdam of Ohkawa Dam". Japan Concrete Institute, Concrete Journal, April 1978.

3.40 HARADA, J.; SHIMADA, S. "Measuring of Concrete Temperature at Tamagawa Dam", in: Engineering For Dams. Japan Dam Engineering Center, vol. 3, nº 2, 1985.

3.41 HARADA, J.; SHIMADA, Y. "Design and Construction of Tamagawa Dam", in: Journal of Jancold, nº 107, March 1984.

3.42 HARADA, J.; TAKAHASHI, F. and YAMADA, K. "Incline Facilities at Tamagawa Dam", in: Engineering For Dams. Japan Dam Engineering Center, vol. 3, 1985.

3.43 YAMAUCHI, T. et al. "Construction of Tamagawa Dam by the RCD Method", in: *Transactions*. Lausanne, Fifteenth International Congress on Large Dams, vol. II, Q57, June 1985.

3.44 PRICE, A. C. *The Engineering characteristics of Dry Lean Concrete as Applied to the Construction of Gravity Dams*. Newcastle, England: University of Newcastle upon-Tyne, 1977. (Ph. D. thesis.)

3.45 DUNSTAN, M. R. H. *Trial of Lean Rolled Concrete at the Tamar Treatment Works.* Report to the South West Water Authority. England, June 1977.

3.46 DUNSTAN, M. R. H. "Relationship between properties generated by cement and by flyash", in: Rolled Concrete or Dams, Proceedings of the International CIRIA Conference. London, June 1981.

3.47 DUNSTAN, M. R. H. *Rolled Concrete for Dams - Construction Trials Using High-Flyash-Content Concrete.* CIRIA Technical Note 106. London, May 1981.

3.48 CANNON, R. W. *Bellefonte Nuclear Plant - Roller Compacted Concrete – Summary of Concrete Placement and Evaluation of Core Recovery.* Report nº CEB- 76-38. Knoxville, Tennessee: Tennessee Valley Authority, 1977.

3.49 HANSEN, K. D. "Roller Compacted Concrete, Water Control Applications in U.S. and Canada", in: Portland Cement Association. Denver, July 1979.

3.50 RICHARDSON, P. "A First in Alaska... Roller - Compacted Concrete", in: Alaska Construction & Oil, Vernon Publications, Inc. Seattle. vol.19, nº 11, November 1978.

3.51 SCHRADER, E. K. "Roller-Compacted Concrete." The Military Engineer, The Society of Military Engineers. Washington, D. C., vol.69 (451), September-October 1977. (Skokie, Illinois: Portland Cement Association, 1978.)

3.52 SCHRADER, E. K. and MCKINNON, R. "Construction of Willow Creek Dam", in: Concrete International , ACI. Detroit. vol.6, nº 5, May 1984.

3.53 OLIVERSON, J. E. and RICHARDSON A. T. "Upper Stillwater Dam: Design and Construction Concepts", in: Concrete International, ACI. Detroit, vol.6, nº 5, May 1984.

3.54 BUSH, E. G. W. "Rollcrete in Revelstoke Cofferdam", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

3.55 ANDRIOLO, F. R.; DE VASCONCELES G. R. L. and GAMA H. R. "Use of Roller Compacted Concrete in Brazil", in: Concrete International , ACI. Detroit. vol. 6, nº 5, May 1984.

3.56 HIROSE, T. and TAKEBAYASHI S. "Present State and Problems of Rationalized Construction of Concrete Dams", in: Concrete library of Japan Society of Civil Engineers. Tokyo, vol. 2, nº 2, December 1983.

3.57 HIROSE, T. "Experience in the use of Rollcrete", in: International Water Power & Dam Construction United Kingdom, vol. 35, nº 3, March 1983.

3.58 *"Development in Japan of Concrete Dam Construction by the RCD Method 1984"*, River Development Division, Ministry of Construction, 2-13, Kasumigaseki, Chiyoda - ku. Tokyo, 1984.

3.59 KOKUBU, M. "Development in Japan of Concrete Dam Construction by the RCD Method", in: Technical Lecture, 52nd ICOLD Executive Meeting. Tokyo, June 1984.

3.60 MINISTRY OF CONSTRUCTION. *Tamagawa Dam - Omono River System*. Tamagawa Dam Construction Office. Tohoku Regional Construction Bureau, Tazawako Town, Senboku District, Akita Prefecture, Japan, March 1984.

3.61 FUJISAWA, T. and NAGAYAMA, I. "Cause and Control of Cracks by Thermal Stress in Concrete Dams", in: Transactions, Fifteenth International Congress on Large Dams. Lausanne, vol. II, Q57, June 1985.

3.62 KOKUBU, M.; SHIMIZU S. and JOJIMA, S. "Present State and Problems of Rationalized Construction of Concrete Dams in Japan", in: Transactions, Fifteenth International Congress on Large Dams. Lausanne, vol.II, C7, June 1985.

3.63 KOKUBU, M. "Development in Japan of Concrete Dam Construction by the RCD Method", in: Technical Lecture Given at 52nd ICOLD Executive Meeting. Tokyo, June 1, 1984 and published in Engineering for Dams, Japan Dam Engineering Center. Tokyo, vol.3, Special Issue, 1985.

3.64 "*Development* in *Japan of Concrete Dam Construction by the RCD Method 1986*", in: River Development Division, Ministry of Construction, 2-13, Kasumigaseki, Chiyoda - ku. Tokyo, 1986.

3.65 NAGAYAMA, I. and YAMANAKA, T. "Watertightness of the RCD Dam - Monitoring Shimajigawa Dam", in: Engineering for Dams. Japan Dam Engineering Center. Tokyo, vol.4, nº 1, 1986.

3.66 BETIOLI, I.; SCANDIUZZI, L.; ANDRIOLO, F. R. "Concreto Adensado com Rolo Vibratório", in: Proceedings of the XIII Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, April/1980.

3.67 KRAUCH, H. W. "Rolled Lean Concrete at Itaipu Dam", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June/1981.

3.68 ANDRIOLO, F. R.; GOTTARDO, G.; BRAGA, J. A. "O Desenvolvimento e Uso do Concreto (Betão) Adensado com Rolo Vibratório, em Obras Hidráulicas em Países da América do Sul", in: Proceedings of the Conferência Ibero-Americana sobre Aproveitamentos Hidráulicos. Lisbon, Portugal, June/1987.

3.69 GOLIK, M. A.; ANDRIOLO, F. R. "Uruguai (CCR) – Controle de Qualidade do Concreto Lançado no Tramo Principal da Barragem", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Paraná, Brazil, April/1989.

3.70 ZANELLA, M. R.; BRAGA, J. A.; ROSÁRIO, L. C.; AYALA, A. C.; ANDRIOLO, F. R.; GOLIK, M. A. "Concreto Rolado – Ensaios Especiais", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Paraná, Brazil, April/1989.

3.71 GUERRA, E. A.; OLIVEIRA, J. C. F.; GRAÇA, N. G.; ANDRADE, W. P. "Análise do Desempenho das Ensecadeiras Galgáveis em CCR de Serra da Mesa Após Cinco Períodos de Galgamento", in: Proceedings of the I Simpósio de Obras em Concreto Compactado com Rolo. São Paulo, Brazil, April/1995.

3.72 BLINDER, S.; TONIATTI, N. B.; KREMPEL, A. F. "CCR * EFC Comparativo de Custos", in: Proceedings of the I Simpósio de Obras em Concreto Compactado com Rolo. São Paulo, Brazil, April/1995.

3.73 GOLIK, M. A.; JULIANI, M. A. C.; ANDRIOLO, F. R. "Inspection Gallery and Drainage in Small Dams: Problem or Solution?", in: Proceedings of the International Symposium of Roller Compacted Concrete Dams. Santander, Spain, October/1995.

3.74 BRAGA, J. A.; ROSÁRIO, L. C.; DUARTE, J. D. C.; LACERDA, S. S. "Utilização de Finos -Subproduto de Britagem nos Concretos Rolado e Convencional", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Paraná, Brazil, April/1989.

3.75 PORTLAND CEMENT ASSOCIATION. *Fact Sheet on Sly Creek Dam*. Sckokie, 1973.

3.76 ANDRIOLO, F. R.; OLIVEIRA, P. J. R.; SALLES, F. M. "Solo-Aglomerante - Disponibilidade para Uso como Elemento Estrutural em Barramentos", in: Proceedings of the XXI Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, December/1994.

3.77 TYNES, W. O. "Feasibility Study of No-Slump Concrete for Mass Concrete Construction", in: Miscellaneous Paper C-73-10. Viksburg, Mississippi: US Army Corps of Engineers, Waterways Experiment Station, October/1973.

3.78 HALL, D. J.; HOUGHTON, D. L. *Roller Compacted Concrete Studies at Lost Creek Dam*. Portland District, Oregon: US Army Corps of Engineers, June/1974. Report.

4

Design of RCC Dams

4.1 General

The use of vibratory or other rollers to compact concrete instead of immersion vibrators does not change the basic design concepts for dams, locks or other structures; however, it does affect construction procedures. Roller-compacted concrete has been used primarily for gravity-type dams, and nowadays for arched-gravity type dams, and the design of gravity and arched-gravity dams will be emphasized in this chapter. The design of these dams using RCC is fundamentally no different from the design of a similar dam built with conventional concrete. Therefore, many of the principles and formulas for these dams design do not need to be repeated here.

The fast construction possible with RCC should be considered during construction planning, structural design layout of appurtenant structures, and treatment of joints. Any structure of sufficient length and width to accommodate the rollers and spreading equipment could benefit economically from the use of RCC.

The designer, in taking advantage of the latitude afforded by RCC construction, must use discretion in balancing cost reductions against technical requirements. The durability and long-term performance requirements of the RCC dam are technical factors to be considered. The acceptance standards of quality and safety for RCC dams should be the same as those currently accepted worldwide for comparable CVC dams. However, the performance of several completed RCC dams has demonstrated the need to improve certain deficiencies with respect to selection of materials for RCC, foundation treatment, structural monolithicity, crack prevention and leakage, when compared to the standards for CVC dams.

Over the 80's the RCC method of dam construction has gained wide spread popularity throughout the world. With a few exceptions, the height of the highest RCC dams has steadily increased over this period.

The question: **How high RCC dam?** - has been asked several times.

The completion of Shimajigawa Dam (75m) in 1980 and Willow Creek Dam (43m) in 1982 demonstrated RCC to be a cost-effective method of dam construction. Based on that experience, since 1984 there has been a gradual increase in the number of RCC dams built around the world. Parallel to its rise in popularity is the use of RCC in progressively higher dams. Figure 4.01 plots the height of RCC dams against time over the past decade. It can be seen that, with the exception of the Japanese dams, and Upper Stillwater (90m in 1987) and La Coruna (86m in 1988) dams, which are above the general trend, the maximum RCC dam height has increased steadily through 1995.

It should be noted that in recent years Chinese engineers have joined the Japanese in pushing RCC dam technology to new heights. Currently, a number of very high RCC dams are finished or under construction throughout the world including Urayama (155m) In Japan; Capanda (110m) in Angola; Dachaoshan (110m) and Jiangya (130m) in China, Rialp (99m) in Spain, and Pangue (114m) in Chile. Other very high RCC dams currently being designed are Longtan (192m) in China; Batoka (180m) on the border of Zambia and Zimbabwe, Miel I (190m) in Colombia; and American River (146m) in the USA.

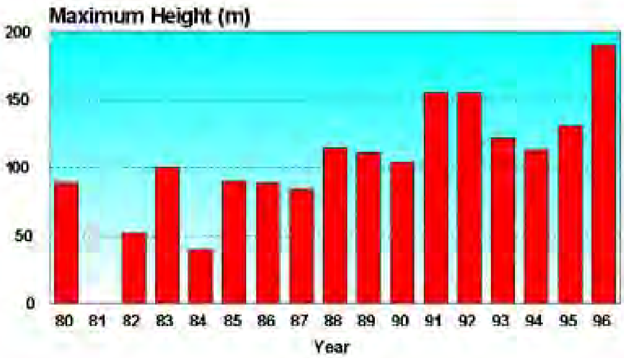


Figure 4.01 Height of RCC dams – from 1980 to 1996.

RCC is being considered on even higher dams such as Pancheshwar (310m) on the border of Nepal and India, and for the second stage of Longtan (216m).

However, in spite of the rise in popularity of the RCC method throughout the world, some dam owners, engineers and public dam safety officials continue to resist the new technology; they are reluctant to design new RCC dams higher than the previous highest dam. On some occasions, RCC dams have even been criticized when compared to other dam types strictly on the basis of precedence.

Frequent comments are *"I don't want a leaky dam"*, *"RCC isn't concrete"*, *"You get what you pay for"*, or *"RCC can be accepted for small dams but I wouldn't risk it on a high dam"*. It is important to address these concerns by summarizing design and construction issues involved and calling upon the 15 years of experience in RCC technology. Only then the fundamental design requirements that will be critical for the design and construction of very high RCC dams can be met [4.01].

The methods of design and the technology for construction of RCC dams have made significant progress during the last ten years. But an objective analyses of the performance of existing RCC dams indicate the need for substantial improvements in some aspects of design, construction techniques and chiefly quality control, to ensure that high RCC dams are equal in long-term quality, safety and performance to conventional mass concrete.

Based on construction experience and the available performance data from completed RCC dams, several high (>100 m) and large (>1 million m^3) RCC dams are currently under design or proposed for construction in the near future. The economic advantages of RCC dams over CVC dams and embankment dams are well known: a shorter construction period due to fast rate of concrete placement and lower costs. However, these advantages are sometimes overestimated, while critical problems that have occurred at RCC dams are either overlooked or their consequences considered acceptable.

During the definition stage of a project, when the dam type is selected, the shortcomings of, or incidents that have occurred at some smaller RCC dams should be carefully evaluated. The consequences of similar mishaps during the lifetime of a high and large dam can be catastrophic.

These requirements include site specific design criteria, a suitable foundation, expeditious use of available construction materials, structural stability, and watertightness.

4.2 Site Selection

4.2.1 General

One of the most important conditions to build a concrete dam - either CVC or RCC - is [4.02] that the foundation presents after treatment by grouting or reinforcement, the necessary strength, permeability and rigidity. Site investigations are always necessary for designing and building dams. Usually a requirement to build a concrete dam is that the foundation is in the rock, even altered or having clay bedding seams or shear zones that could be treated or reinforced. Otherwise, they are not safe. Geotechnical works such as borings, trenches, and galleries and geophysical investigations are needed. Permeability tests are generally carried out in the borings. Shear strength and deformability parameters of the foundation rock mass, especially along the weakest surfaces, are necessary for the design. Instead of tests, appropriate rock mass classifications may also be used to obtain a good estimate of such parameters; in many cases, tests are not necessary.

Interrelated factors that have to be considered when selecting the best dam type for a given site include physiography, hydrology, foundation, schedule (reduction in time), weather, construction materials, construction features, environmental impacts and above all, the intended use of the project and the particular needs of the owner. The fundamental requirements for an RCC dam to be considered for any site or height are an adequate foundation and a suitable source of construction material for processing into RCC aggregate. The remainder of the dam type screening process is an economic comparison of RCC with other types of dams (see Chapter 10). At the screening level of dam type/size selection RCC should not be ruled out because of height alone.

A completed RCC dam should behave as a monolithic elastic structure, integrally bonded to its rock foundations, that is, its structural performance should be equivalent to that of a CVC dam with a similar configuration. For the two types of dams to be equal in quality, safety and durability, they should have equivalent margins of safety against cracking, failure, overloading, shearing-sliding and leakage through the concrete and construction or layer joints.

The degree of monolithicity and elastic isotropy of an RCC dam depends on several factors. If there are vertical transverse cracks or ungrouted contraction joints, the structure's blocks would act as individual cantilever gravity dams, each independent of its neighbors. If no transverse contraction joints are provided, and no transverse cracks occur, the dam will function as a three-dimensional monolithic plug, transmitting load in all directions, including longitudinally to the abutments. If the transverse cracks are inclined or curvilinear, the structural behavior of the dam could be a hybrid between a cantilever gravity dam and a three-dimensional monolithic dam. If longitudinal cracking occurs, it would affect the monolithicity in the transverse direction and cause internal tensile stress concentrations. All cracks alter, in some way, the stress field in the elastic mass with tensile stress concentrations occurring at the end of each crack within the body of the dam. Other factors that could significantly affect monolithicity are the bond, shear and tensile strengths of the horizontal construction joints.

Site selection and foundation requirements for RCC dams are basically the same as those for conventional concrete gravity dams. However, because RCC costs less per unit volume than conventional mass concrete, designers have more freedom in optimizing the site selection. They are no longer strongly tied to a site that minimizes the volume of concrete in the dam structure. Designers can now investigate other sites where a larger-volume RCC dam may be required to maximize the benefits of the entire project. Those benefits could include increased pool storage, greater head power and shorter penstocks for a hydroelectric project.

In preparing preliminary designs and cost estimates for alternative dam types, the optimum location of an RCC dam may be different from the optimum location of an embankment dam. This will depend primarily on the topography and geology of the site.

The design, construction and performance of completed RCC dams indicate several issues that need to be examined if the structural performance of high RCC dams should become equivalent to that of CVC dams. These issues are:

- Quality of the foundations.
- Elastic monolithicity of construction joints.
- Stability against shearing-sliding.
- Structural cracks
- Transverse contraction joints.
- Longitudinal cracks and joints.
- Quality of RCC.
- Large spillways over an RCC dam.
- Drainage and seepage control.

4.2.2 Foundation

Foundation conditions for RCC dams of any height must be equal to those for CVC dams of the same height. If a satisfactory foundation exists there should not be a limit to the height of an RCC dam based on foundation quality.

The structural design of the dam, again as in conventional dams, includes correct interpretation of geology as it will affect stability and deformation of the foundation rock. RCC dams are to be considered three-dimensional structures capable of responding to foundation strengths and weaknesses. Consequently, two-dimensional seepage and stability analyses may not accurately define the total strength resisting the applied loads. If only two-dimensional analyses are made, significant differences in the foundation modulus of elasticity and deformation across the site may cause portions of the dam and/or foundation to be more severely overloaded. This may or may not be acceptable or desirable.

Each project should be evaluated on a site-specific basis. Foundation shape irregularities such as would be seen in a cross-canyon profile could result in load transfer from depressed areas to intrusive areas, again causing variations in stresses and deflections computed from plane strain analyses. Such variations may or may not be significant.

When establishing design criteria for any dam type, including RCC, of any height, the paramount consideration should be the intended use of the structure, the particular needs of the owner and cost. Safety, watertightness, flood frequency, spillway capacity, schedule, seismicity and other site-specific requirements must be established before dam design can begin.

Foundation, loading conditions, safety factor, drainage, stress distribution and thermal cracking potential are all factors which must be considered when evaluating the stability of a very high dam and determining dam configuration and strength requirements.

Sound rock foundations are considered the most suitable for concrete dams because they have high bearing capacity and a high degree of erosion and seepage resistance. RCC dams completed to date have been founded on many different rock types, such as basalt (Jordão, Salto Caxias, Urugua-i, Willow Creek), limestone (Winchester), marlstone (Middle Fork), granite (Copperfield), meta-andesite (Galesville), siltstone (Bucca Weir), quartz sandstone (Upper Stillwater), meta-sandstone (Capanda) and quartzite (Saco Nova Olinda).

Supposing an adequate foundation, there is no structural height restriction for RCC dams. Rock foundations without major faults and shear zones can be most suitable for RCC or CVC dams. Faults and shear zones do not necessarily eliminate a site from consideration, but it may be expensive to treat them in order to ensure an adequately safe foundation.

Because each site is unique, engineers experienced in evaluating foundations should investigate the site and determine possible treatments. A foundation investigation program, usually involving drilling, is essential to evaluate foundation conditions. Characterization from the rock surface down to 10 to 20m is of paramount importance, as it will determine the ability of the foundation to bear loads without unacceptable short-term and long-term deformations.

Foundation investigation and design is probably more important than the design of the dam section itself. History has shown that the failure probability of a concrete dam, while extremely remote, is more likely to happen in the foundation than in the dam itself (see Chapter 3). Special attention should be given to identifying potential sliding planes in the foundation rock.

4.2.3 Foundation rock properties

In the investigation program, five properties of the foundation must be determined, namely:

- ✓ Compressive strength;
- ✓ Shear strength;
- ✓ Deformation modulus;
- ✓ Poisson's ratio, and
- ✓ Permeability.

The compressive strength of the foundation rock is an important consideration in determining the base dimension of the dam. Designers should calculate a minimum base dimension that reduces the maximum allowable bearing stress to acceptable values and is determined by dividing the compressive strength of the foundation material by an appropriate safety factor.

The shear strength of the foundation rock, including any discontinuities, depends upon the cohesion and internal friction properties of the rock, along with the applied normal load. The total strength of the foundation rock can be determined using Mohr-Coulomb's equation in the same way it is used for the RCC material within the dam.

Because joints, shears, and faults have little or no cohesion, the shear strength of a discontinuous rock mass is essentially derived from sliding friction. The shear strength of an existing joint in rock is nonlinear. Shearing resistance of rock with discontinuities should be based on physical tests (mainly "in situ") of the material in order to plot a shear strength versus normal stress relationship. An average shear strength for design can be determined once a range of normal stresses imposed by the dam is calculated. Safety factors are then applied to the sliding friction shear strength depending on the particular load combination being investigated.

When adequate shear strength data are not available for the rock foundation, a conservative approach for preliminary design is to assume no cohesion and a conservative value for the sliding friction shear strength for that type of rock.

The magnitude of the foundation deformation modulus is often not as critical as the variation in modulus across the foundation. Conventional small gravity dams have been successfully built on low modulus materials such as siltstone, claystone, gravel, and sand. Middle Fork, on marlstone, and Bucca Weir, on siltstone, are examples of RCC dams founded on rock with a relatively low (lower than 10,000kgf/cm^2) deformation modulus.

Deformation patterns for complex foundation conditions may be determined with a joint-shear index and shear catalog. Poisson's ratio-the value of transverse strain to its corresponding axial strain-is needed for more thorough mathematical analyses of the dam and its foundation.

Abrupt changes in the deformation modulus can result in differential settlements that can cause cracking in an RCC dam. Therefore, the designer should identify low-modulus zones and plan improvement measures such as grouting the weak material or excavating and replacing it with conventional concrete or RCC.

Although permeability of the foundation rock is the main factor in determining whether a grout curtain is required, most designs for major dams include an upstream grout curtain to reduce seepage under the dam as a matter of course.

4.2.4 Quality of Rock Foundation

Both RCC or CVC high concrete dams require rock foundations, which either in the natural state or after appropriate treatment, have adequate strength to receive the loads imposed upon them by the dam and the reservoir, without undergoing excessive deformations or instability. Invariably, rock foundations for high gravity dams need various types of improvement, and in some cases, foundation treatment can be as important an aspect of design and construction as the dam itself.

It is wrong to think that because in RCC dams concrete is placed in layers and compacted by rollers- in a similar way to earthfill or rockfill embankment dam- RCC dams would have the "flexibility" of an embankment dam to adjust to differential settlement or deformations of the foundation without adverse consequences to its stability. The response of an RCC dam to such foundation behavior and the effects on its stability would be similar to that of a CVC dam. The consequences may include unacceptable reduction in reserve strength against shearing-sliding, cracking at the dam-foundation contact, increase in hydraulic uplift pressures, and cracking and overloading in the dam itself.

At the 90-m high Upper Stillwater Dam [4.03], a transverse crack extending through the entire section of the dam was attributed to movement along a weak layer in the foundation which had been either unanticipated or inadequately treated. While use of a transverse contraction joint in the dam would have "controlled" the cracking, it would not have prevented the other adverse consequences of excessive foundation movement.

For high gravity dams, the weaker foundation features, such as shear zones, faults, contacts filled with gouge or clayey materials, or unfavorably dipping joints, can require extensive, expensive and time-consuming treatment. Often the critical consideration in the design of gravity dams is to assure adequate safety margins against shearing-sliding and excessive non-elastic deformations at the weaker layers or zones in the foundations and abutments. Two pertinent examples of high CVC gravity dams where extensive treatment was necessary to strengthen weaker features in the foundations are the 226-m high Bhakra Dam in India, completed in 1963, and the 196-m high Itaipu Dam in Brazil-Paraguay, which was completed in 1982.

The foundations of Bhakra Dam [4.04] are predominantly sandstone and claystone with several major strata of siltstone and gouge-filled shear zones. Without special treatment of the weaker zones, excessive differential settlements, as well as high uplift pressures would have occurred and impaired the stability of the dam. A typical treatment example was that of a claystone zone, averaging 35m wide and located about 25m upstream of the dam in the riverbed. Extending into both banks and parallel to the axis of the dam, it dipped 70° downstream under the dam. The claystone, when exposed to the atmosphere and submerged in water, weathered and weakened rapidly. The treatment consisted of excavation of the claystone to a depth of 22m, backfilling with concrete, capping it with a 15-m thick concrete slab extending from the dam, and consolidation and contact grouting around the concrete plug.

At Itaipu Dam [4.05], where the foundations for the hollow gravity dam are composed of sound basalt and "breccia", a weak contact zone between basalt flows was found about 20m below the foundations of the highest blocks in the riverbed. The weak contact zone was nearly horizontal and continuous for an area of 170m x 200m and overlaid by sound basalt about 20-m thick, which was suitable for the dam foundations. The weak zone is a few-centimeters to 0.5-m thick layer of fractured dense basalt with a predominance of horizontal open joints, which are sometimes imbricated. Pockets of highly fragmented rock with a film of clay occurred along 60% of the layer. Because of time constraints a plan of underground treatment was adopted. The treatment consisted of mining out the weaker rock from the shear zones and gouge seams through a grid of tunnels and backfilling them with concrete, improving the shear resistance of the weaker zone in the foundation. The total volume of excavation and concrete required for the shear key grid was 20,000m^3, covering 25% of the foundation area.

The special foundation treatment cases at Bhakra and Itaipu dams show that if RCC gravity dams were to be built at those sites, the same amount of foundation treatment would be required to assure the same safety margins and quality as in conventionally built dams. They also show that foundation treatment can be a critical item in the construction schedule, because most of it must be completed before the start of concrete placement. In some cases, in addition to curtain grouting, other supplementary foundation treatments may have to be carried out from the galleries in the dam, sometimes after filling of the reservoir.

The importance of a thorough foundation exploration and treatment in high RCC gravity dams may also be learned from experiences in the design and construction of some relatively smaller ones. For the 68-m high Concepcion Dam [4.06] in Honduras, the selection of an RCC dam type was made before analyses were completed for resolution of such problems as: *"zones of poor foundations; very poor quality cement and Pozzolan; low strength aggregate with high absorption and low density concrete"*.

For non-engineering reasons, construction had to begin before final drawings or specifications were available and *"before the foundation level and axis of the dam were established"*. A similar program would not be appropriate for a high and large RCC gravity dam, posing an unacceptable degree of risk to its safety and durability.

Shaping the foundations and abutments to eliminate site irregularities of the type shown in Figure 4.02, is equally important for high RCC and CVC gravity dams. If not removed or rectified, they would cause internal stress concentrations, resulting in cracking and progressive deterioration of concrete.

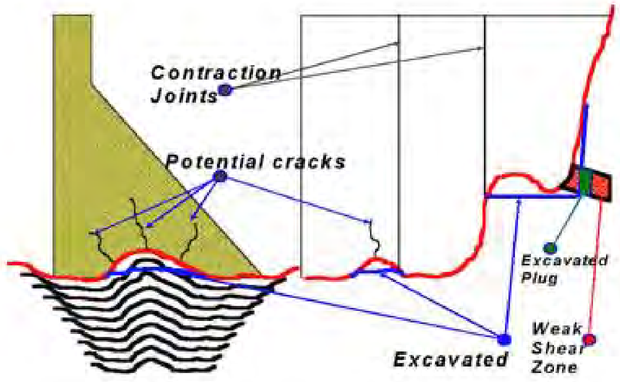


Figure 4.02 Shaping foundation and typical treatment of irregularities.

Figure 4.03 Some typical irregularities in basalt rock foundation - Jordão and Salto Caxias Dams.

Stability of the abutments of a high RCC gravity dam also requires special attention, if there is axial transfer of loads from the dam. Three-dimensional stability analyses of the abutments would be necessary to determine the type of treatment required; it may also influence the structural design of the dam. Even though the stability of a gravity dam depends more on the quality and behavior of the weaker parts of the foundation, the whole stability of the structure and its foundations can be degraded by poor quality and performance of the dam.

Structural cracking, high internal pore pressures, uncontrolled leakage, leaching and alkali-aggregate reaction in the dam concrete can alter the stress patterns in the foundations and abutments to such a degree that the safety margins against failure in the foundations are reduced below acceptable limits. Therefore the stability of the dam-foundation complex must be studied as thoroughly for high RCC dams, as for comparable CVC dams.

4.2.5 Foundation Excavation Guidelines

The amount of excavation required depends on the depth of the overburden and the weathered rock. All overburden covering a rock foundation, such as soil, alluvium, and talus, should be removed. Contract documents should be structured so that payment for unanticipated foundation improvements can be resolved quickly and fairly preventing consequent costly change-of-conditions claims by the contractor.

4.2.6 Foundation Improvement and Drainage

The usual foundation improvement methods are the same used for CVC dams. Curtain grouting is commonly used to control seepage beneath dams, even those founded on tight, low-permeability rock. The spacing can vary depending on the condition of the rock. The depth of the holes also depends on hydrostatic head and foundation rock conditions. The depth of the grout curtain can vary from 40 percent of the head for dense foundations to 70 percent in poorer-quality rock foundations according to USBR criteria [4.07; 4.08].

Foundation grout treatment should ordinarily be developed based on the site-specific needs of each project. Where a complete grouting program is necessary, it will normally be similar to the following:

- standard consolidation grouting at 3-m or 6-m centers across the excavation contact area to 6-m to 15-m depths as determined from the geotechnical analyses; and
- deep curtain grouting at 3-m centers, or less, near and parallel to the dam axis.

Curtain grouting can be performed from the foundation gallery after the structure has reached an elevation so that there is sufficient weight to prevent upward movement of the concrete. Grouting can also be done using angled holes drilled from the upstream heel while RCC placements continue above. This approach has proven to be conveniently effective, and a "timesaver" on some RCC projects.

If needed for stability or seepage control, drain holes should be drilled downstream of the grout curtain. Typically, they are about 76mm in diameter, drilled spaced at 3m interval, from the gallery or downstream face after the foundation grouting has been completed. Generally, depths may vary from 20 to 40 percent of the reservoir depth. Actual spacing, depth, and orientation depend on site conditions.

Foundation or so called "dental" treatment consisting of conventional concrete placements may be required if final excavation has uncovered faults, clay seams, or shattered or inferior rock extending to such depths that it is impractical to remove the areas entirely or to fill them with dental concrete. Most projects have found the use of RCC desirable in any area where it can be placed and compacted, with dental concrete kept to a minimum. Another approach has been to use dental concrete and mass backfill concrete extensively to create a level zone from which to begin placing RCC.

Drain holes are usually provided in rock foundations for all but some low to moderate-height dams to reduce uplift pressures in the foundation and improve the stability of the dam. The role of the drain holes is to intercept and remove any seepage water bypassing the grout curtain and consequently reducing the buildup of hydraulic pressure (uplift) beneath the dam.

Because RCC is always less costly per unit volume than CVC, the designer should maximize the use of RCC in the foundation. However, CVC surfaces are generally built up first to facilitate the start of RCC placement. The size of the starting pad for RCC placement can be as small as one roller in width by two rollers in length.

Hand compactors or small rollers and equipment may be used for compacting RCC or CVC into areas that are inaccessible by large rollers, which are used for the remainder of the dam. Thin lifts usually are required when using such equipment in order to achieve roughly the same density as the RCC for the dam body. CVC should be used at the dam-abutment interface in order to assure bonding to the rock surface and to minimize seepage at this contact.

Figure 4.04 Foundation treatment and preparation at Capanda Dam- Angola

The impact of foundation treatment on costs and the construction schedule of the dam should not be underestimated at the time of selection of type and layout of the dam. The foundations should be shaped to eliminate irregularities that may cause stress concentrations and cracking of the dam.

4.2.7 Very Low Modulus or Non-Rock Foundations

The main concerns for low-modulus rock or non-rock foundations are differential settlement, seepage, piping, and erosion at the downstream toe. Non-rock foundations such as silt, sand, gravel, and granular silt may be acceptable for an RCC or CVC gravity dam. Such foundations are usually considered only for low dams, and a number of factors must be studied first. Foundations of this type may require special measures such as upstream and downstream aprons, cutoff walls, and a drainage system.

Lower Chase Creek (20m high)[4.09] is an example of an RCC dam placed on a very low modulus foundation. The Cedar Falls (9m high)[4.10; 4.11] dam in the State of Washington is an example of low RCC gravity dam built on non-rock foundations. Lower Chase Creek's site consists of a conglomerate overlaid by alluvium. The designers decided to build the 20m dam on top of an RCC foundation mat that extended through the alluvium to the conglomerate. Alternative designs consisting of a cutoff wall to conglomerate or building the dam on compacted alluvium were also considered.

Plate bearing tests helped determine that the conglomerate had a deformation modulus of 0.125 GPa. The analysis concluded "that a dam founded on the conglomerate would be more stable, experience less settlement, have reduced seepage potential, and be no more costly than the cutoff-wall alternative". The RCC foundation mat is 7.6m deep. It extends 3m upstream and downstream from the dam section on a 1H:1V slope, and vertically down to the conglomerate surface.

4.3 Dam Type

4.3.1 Gravity Dams

Gravity structures such as dams [4.08] are designed essentially for stability against overturning and sliding. The compressive strength of concrete is generally not a controlling factor. However, shear strength along the interface between RCC layers can be an influencing factor, especially on high dams and those with steep downstream slopes.

The design of gravity structures is controlled mainly by foundation considerations. Failure of a concrete gravity dam under permanent loading or flood conditions as a result of initial failure in the concrete section above base rock is extremely rare. Historically, concrete dams failure has been by sliding or shear failure of the foundation rock. Knowledge of bedding, orientation of fracture planes in the base rock, and other pertinent foundation information are essential. If there is a potential sliding plane within the foundation, the choice is normally either to excavate below the plane or provide sufficient mass to reduce the sliding potential to a safe limit.

If there are no weak potential failure planes in the foundation rock, then the design normally gives particular attention to the concrete properties of the section and to the foundation preparation for concrete placement. Clean rock with some roughness is essential for bonding of concrete to rock and for minimizing or eliminating leakage.

RCC gravity dams, like CVC dams, are generally analyzed as two-dimensional structures using conventional plane stress analytical procedures based on rigid block or finite element methods. However, three-dimensional analyses can be used for design of straight gravity dams (normally in narrow valleys) and should be used for designing curved structures.

The upstream face is normally vertical for the entire height or for a significant part. The downstream face, at slopes varying between 0.6:1.0 and 0.8:1.0 (horizontal to vertical), or flatter, usually intersects the upstream face at a point near the crest. The downstream face, from a crest thickness of 4.5 to 9.0 m, generally drops vertically to intersect with the slope. A fillet can be added at the intersection to smooth out the face, reducing the probability of stress concentrations developing during overloading such as caused by floods or earthquakes. In highly seismic areas, to fully eliminate stress concentrations, the downstream face should be a constant slope from crest to base. This same constant slope will also simplify construction. To mitigate the subsequent increase in volume, the downstream slope can be reduced without substantial change in stability.

4.3.2 Arched dams

During the XVI Congress on Large Dams, *Lajinha Serafim* pointed out [4.12]:

"RCC presents an economical method of building arched dams, especially high arched dams in wide valleys, where the normal arched dam may not be economically competitive. The RCC arched dam will tend to be a thicker arched dam, because of the nature of the RCC construction process - which requires a minimum amount of space to operate the placing and compaction equipment, as well as for the forming/ facing process. This will probably mean that lower to medium height RCC arched dams will be arch/gravity dams, but higher dams can be true arch dams. It is unlikely that it will be worth introducing double curvature below a height of about 75m. A basic problem will be designing a formwork or facing system that will be able to keep up with the RCC placing, especially with the complication of double-curvature.

Cracking is not normally a structural problem in gravity dams, and is objectionable only in that it can cause unacceptable seepage, with possible deterioration of the concrete if it is excessive. It could also be unsightly. Cracking, however, presents a much more serious problem in arched dams.

RCC is less susceptible to cracking than conventional concrete. This is because the mixes are leaner, and they also contain a higher percentage of pozzolanic material, both of which lead to generation of a lower hydration heat. The higher percentage of pozzolanic material also means slower strength gain, lower modulus of elasticity at the early ages, and thus higher creep which will accommodate some of the tensile strain induced by temperature changes. It can therefore be expected that in a moderate climate RCC will not crack significantly if care is taken to keep the placing temperature down. In extreme climates cracking must be anticipated. Longitudinal cracking is not expected in RCC dams, but transverse cracking primarily initiated by internal restraint may well take place, but will not necessarily extend through the section of the dam".

Whereas cracking is not normally of any structural significance in gravity dams, it can be of major structural significance for an arched dam because the arched dam relies on arch action, which itself depends on continuity throughout the dam. If the dam is not flexible enough to accommodate movement capable of closing the cracks, which could well be the case with the heavier sectioned RCC arched dams, then arch action will suffer, and the dam could effectively be sectioned into monoliths acting in the gravity mode for which they are not designed. This is an extremely pessimistic point of view because it is not expected that transverse cracking will be extensive enough, or continuous enough to be beyond the capacity of accommodation of the dam. However the possibility is there and must be designed for.

The arch-gravity dam is the next step [4.13] in structural effectiveness. This type can usually be built on sites with competent rock and a chord/height ratio of 3.5 to 5.0. The valley chord/height ratio is a guide to assessing a site for its suitability for the different dam types, but this ratio does not consider the shape of the site, that is, whether it is "V"-shaped or "U"-shaped. The canyon shape factor, which is the ratio of the length along the slopes and the bed of the valley, across the valley, to its height, is a better means of comparing valley shapes. The "Canyon Shape Factor" was introduced by Sarkaria, G.S. in an article published in 1952 ("The Influence of Canyon Shape on Design of Concrete Dams"- Civil Engineering & Public Works Review)

The arch dam is the most structurally efficient concrete dam type. This category can be divided into the thin arch dam, the thick arch dam and arch/gravity dam. The peak of structural efficiency is the double-curvature thin arch dam, but the use of double curvature is seldom warranted for dams less than 30m high. The pure arch dam generally requires competent rock and a chord/height ratio not greater than 3.5 [4.13], but many arch dams have been built outside these ratios.

RCC presents an economical method of building arched dams, especially high arched dams in wide valleys where the normal arched dam may not be economically competitive. The RCC arched dam will tend to be a thicker type of arched dam, because of the nature of the RCC construction process - which requires a minimum amount of space to operate the placing and compaction equipment, as well as for the forming/facing process.

A properly designed RCC dam, curved upstream, places the entire upstream face in compression under the usual loading condition, whereas a straight gravity dam can have tensile stresses near the abutments because of the fixed-beam action of the structure across the valley. Curving the structure provides additional resistance to overturning, a potential for a reduction in volume, and the compression of the upstream face can help produce a more impermeable structure.

The use of RCC for a curved plan dam started with Saco de Nova Olinda Dam, completed in 1986 in Brazil. The dam was curved near the right abutment strictly to accommodate local site conditions. No structural credit was taken for the curvature as the 0.8H:1V downstream slope was maintained throughout the gravity structure.

Roller-compacted concrete is a construction method that can be applied to gravity, arch/gravity and arch dams. In South Africa it has been used to build the two (up to 1997) arch/gravity dams: Knellpoort (50m high) and Wolwedans (70m high), sharing the distinction of being the first of their kind in the world.

Completed in 1988, Knellpoort Dam has a maximum height of 50m, a crest length of 200m, an extrados radius of 90m, a vertical upstream face, a 0.6H:1V stepped downstream face, and it contains an RCC volume of $45x10^3$ m^3 with a cementitious content of $203kg/m^3$, of which 70% is fly-ash. The dam has been provided with groutable corrugated sheet-iron crack inducers in crack joints spaced at 10-m intervals. Cracks have indeed formed at these joints, as recorded by crackmeters provided in the RCC.

Contemporary to Knellpoort Dam, the Department of Water Affairs and Forestry-South Africa designed and built the 70-m high Wolwedans Dam, completed in 1989. This dam has a crest length of 270m, an extrados radius of 135m, a vertical upstream face, a 0,5H:1V stepped downstream face, and it contains an RCC volume of $180x10^3$ m^3 with a cementitious materials content of $194kg/m^3$, of which 70% is fly-ash.

Both these dams were provided with various types of instruments to shed more light on their behavior, the results of which could direct more ambitious RCC arch dam designs in the future.

The Wolwedans Dam has been provided with groutable plastic sheet crack inducers in crack joints spaced at 10-m intervals, and cracking has occurred as envisaged in the design. Leakage at the dam varies with the water level in the lake and is roughly 14 l/s, stemming mainly from the crack joints. The crack joints were selectively grouted for the first time in 1993.

Since early 1988, several curved upstream cofferdams have been built using RCC, in China, to provide greater stability during overtopping. Later, RCC was also used for thin-arch dams, and by the end of 1996, two had been built in China (Puding and Wenquanpu).

RCC is concrete, and when properly built it should be superior to CVC mass concrete, due to higher compaction effort applied. Thus, it should produce a denser, more impermeable and more durable mass. There is no reason why it should not be used in any project where conventional mass concrete would be used. As contractors gain experience in RCC and learn to take full advantage of the method, real costs will fall to the benefit of contractor, client and end user. RCC has brought concrete dams back into the competition.

The constant extrados radii of 80m and 135m for Knellpoort and Wolwedans, respectively, have been selected for simplicity of construction rather than effective stress distribution although good stress distributions have been achieved in each case. The maximum compressive principal stress under maximum loading conditions is, however, not more than approximately 5MPa, and very much lower under normal loading conditions due to the large cross-sections. In the case of Wolwedans Dam, arch action only occurs when the water level is approximately 8m below full supply level.

Whenever possible and economical, it always helps to curve or arch a concrete dam. By doing so, one increases the safety of the dam against failure, and improves the use of material. The dam site must be topographically and geologically suitable for the arch type dam. This means that the site must not be too wide and the foundation rock must be adequate; excavation must not be excessive and the arch solution must compete economically with alternative solutions.

RCC extends the use of arch dams because it means that more concrete can be placed at a lower total cost than with CVC concrete. This opens the application to wider valleys where conventional concrete arch dams are less competitive.

Curving a dam also increases spillway capacity, and by confining the spillway to the river section in narrow valleys, may help obtain adequate spillway capacity.

The design of an arch dam using RCC is similar to the design of a dam built of CVC. Because RCC is used in thinner and higher arch dams, there is a greater need for higher strength and a more uniform concrete to bear the higher stresses imposed on the structure. Shear resistance, especially cohesion between successive lifts, takes on added significance in order to maintain proper cantilever action.

The design of an RCC gravity/arch or arch dam does not include full section vertical joints, because joints would have to be grouted to endure proper arch action. Therefore cracking must be minimized if not, eliminated altogether. So special attention must be given to thermal aspects of mix design and construction; construction is very likely to be limited to the cooler months of the year and that the materials will have to be cooled to produce the required low RCC placing temperatures.

The RCC construction method requires sufficient working room to economically place and compact the material. Therefore, RCC should be considered only for dams with true arch action above a certain height and with a crest thickness no smaller than 3.0m, and at least, 5.0m. A minimum height for RCC to be considered for a single-curvature arch dam might be 30m, while 75m might be the lower limit for a double-curved arch dam.

RCC can be made applicable to all but thin arch dams, but its main application is in arch/gravity dams and the heavier sectioned arch dams with little double curvature. There would appear to be little justification in introducing double curvature in RCC dams with a maximum height of less than 75m as the shuttering and layout complications out-balance the economy of material. A double curvature dam however usually means a slimmer and more flexible dam with a greater ability to accommodate movement and this must also be kept in mind.

4.3.3 Other Section Configuration

The use of RCC excites the imagination and other dam configurations have emerged. As suggested by J. Raphael and adapted by P. Londe in the article [4.14], a "new" dam transversal section (as used in the Guadalemar Dam built in 1994, in Spain) can be achieved with:

- a symmetrical cross section;
- a watertight upstream facing;
- no internal drainage of the dam body; and
- use of lean RCC .

This design configuration offers some advantages:

✓ low stresses in the dam body (it is possible to use a very lean RCC or a mix such as gravel-sandy-cement, or a pit run material cement based);

✓ low stresses in the foundation (it is possible to adopt this material in some foundation with low modulus);

✓ low cost of the hardfill;

✓ greater safety than the traditional triangular cross section, specially when subjected to earthquakes.

In this way the friction angle can be lowered, with low shear and compressive stresses and without tensile stresses.

In this case, a soil-sandy-cement as studied in [4.15] can be useful in large countries with few resources or where materials are not readily available as an option for the implementation of dam projects. Strengths between 8MPa to 12MPa, with a low cement and pozzolanic material content have been achieved at one year. Test samples were casted using Normal Compaction Energy showing densities within normal parameters for the types of soils under study. The compressive strength has increased with age. Soils with greater sandy portions in their composition have resulted favorable for mixing with binders. Soil with 10% cement (155,8 kg/m^3) achieved an 18MPa compressive strength at 180 days. The use of pozzolanic material resulted in greater strength at old ages, which increased when contents were incremented from 10% to 15%, becoming stable between 15% and 20%. The relation between the tensile strength through diametral compression and simple axial compression was around 10% with a variation coefficient of 15% in the global universe of test values, with no particular bias for any of the mixes under study. Modulus of elasticity remained between 6,000MPa and 10,000 MPa, and it decreased as the soil became more plastic (greater water content).

4.4 Design Considerations

4.4.1 General

Experience gained in the design and construction of smaller RCC dams indicates that RCC can be successfully employed to build high dams with the same quality of comparable CVC dams, which have been in satisfactory service for several decades.

The quality and safety standards accepted for RCC dams should be the same as those internationally accepted for comparable CVC dams, nowadays. The performance of several completed RCC dams, however, reveal the need to improve certain deficiencies related to selection of materials for RCC, foundation treatment, structural monolithicity, crack prevention and leakage, when compared to the standards for CVC dams.

In order to produce a dam that is structurally efficient and economical, gravity dams are generally triangular in cross section.

The crest elevation of an RCC dam is normally identical to the maximum water surface. A parapet wall is usually added to take care of freeboard. This differs from embankment dam design, where freeboard and settlement considerations raise the elevation of the dam crest.

The upstream face of a gravity dam is usually vertical in order to concentrate the weight of concrete upstream and better resist the reservoir water loading, apart from simplifying construction. It is common practice in Japan (Dodairagawa, Sakaigawa, Tamagawa, and others) and elsewhere (Puebla de Cazalla, Rialb and Val Dams, in Spain) to add a batter to the lower part of the upstream face increasing the base thickness and thereby improving sliding stability at the base. If a batter is used, stability and stresses should be checked at the elevation where the batter intersects the vertical upstream face.

The downstream slope is generally constant from the base to near the crest of the dam. A constant slope is considered efficient from the point of view of both structural design and construction. A curved downstream slope may be used for a high RCC gravity dam in order to minimize volume. It can be built rather easily. As previously mentioned, it is poor practice in seismic areas to locate the point of intersection of the downstream slope with the vertical upstream face below the crest elevation. The obtuse angle formed by the intersection of a downstream vertical face with the slope will create an undesirable stress concentration when the dam is subjected to seismic shaking, as was proven at Koyna Dam in India.

Adequate bonding, uniformly distributed over the entire surface of each construction joint, is essential to obtain the necessary degree of elastic monolithicity in a high RCC gravity dam. Without such bonding, higher than admissible shear stresses and an unacceptable risk of shearing at a weak construction joint may occur. Treatment of the surface [4.16] of each construction joint, comprising a thin layer of bedding mix of suitable strength, regardless of the time intervals between placement of RCC layers, can provide adequate bond and shear strength and monolithicity. It can also reduce leakage through the joints.

Prevention of structural cracks in a high RCC dam should be a mandatory objective. Transverse contraction joints through the full cross-section of the dam, located at intervals not exceeding 20m for the entire length of the dam, effectively prevent transverse cracking.

The risk of longitudinal cracking in the dam body increases according to height and volume of the RCC dam and the cementitious content of the mix. Provision of an inclined longitudinal construction joint would be an effective and practical crack prevention measure, which would facilitate monolithic performance of the dam and also be compatible with the construction schedule.

All materials used in a high RCC gravity dam, including cement, pozzolanic material, fine and coarse aggregates, should be similar in quality to those considered suitable for a comparable CVC dam. Particularly important are physical properties related to specific gravity, susceptibility to AAR, and excessive thermal expansion.

The RCC mix should be designed with the lowest cement plus pozzolanic material content necessary to obtain the desired workability, specified strength in compression and shear at prescribed ages, with the lowest practicable rise in temperature and with the desired durability.

Large spillways with high crest gates, located over a high RCC dam, affect the stability of the dam. During dam design, special attention should be given to the integration of the spillway structures to the RCC dam, particularly the piers supporting large gates, so that the dam is not overstressed.

4.4.2 Loading Conditions and Combinations

Loading conditions for an RCC dam are similar to those for any other dam consisting of a combination of reservoir and tailwater, temperature, hydrostatic, dead load, ice, sediment and earthquake loads. As the dam grows in height, external loads increase and the magnitude and distribution of internal stresses within the dam grow too. The loads that may act on an RCC dam are the same that act on a CVC dam, and include the following:

⇒ **Horizontal Loading :**

· Hydrostatic pressure of reservoir on the upstream face;

· Horizontal silt pressure;

· Impact of waves or seiches against the upstream face. This includes the effect of a potential landslide into the reservoir;

· Hydrostatic pressure of tailwater against the downstream face;

· Inertial force of the reservoir water against the dam during an earthquake;

· Ice load on the upstream face;

· Inertial force of the mass of the dam during an earthquake;

⇒ **Vertical Loading :**

· Gravity dead load of the dam and appurtenances such as gates and bridges. It should be remembered that RCC weighs more than conventional concrete made with the same aggregates (see Chapter 7);

· Vertical water pressure on the upstream face, if that face is inclined. Vertical silt pressure (including the effect of water) may be assumed equivalent to the pressure of a soil with a wet density;

· Uplift pressures on any horizontal plane-an internal hydrostatic pressure;

· Inertial force of the mass of the dam during an earthquake.

The structure is also subjected to thermal stresses generated by hydration of the cementitious materials and subsequent cooling, as described ahead.

⇒ **Loading combinations:** An RCC dam should be designed for all reasonable combinations of the loads previously listed. As the probability of a certain combination of loads happening at the same time decreases, the required safety factor for design decreases. Loading combinations can be categorized as usual, unusual, or extreme, as described below.

· Usual loading combination: The usual loading combination consists of hydrostatic pressure of the reservoir water at the normal operating elevation, gravity dead loads, uplift, silt pressure, ice pressure, and tailwater pressure, if applicable, together with appropriate temperature effects occurring at the same time;

· Unusual loading combination (overtopping): The unusual loading combination consists of hydrostatic pressure of the reservoir water at the maximum design elevation, gravity dead loads, uplift, silt pressure, ice pressure, and tailwater pressure, if applicable, together with the appropriate temperature effects occurring at that time;

· Extreme loading combination (earthquake): The extreme loading combination consists of hydrostatic pressure of the reservoir water at the normal operating elevation, gravity dead loads, uplift, silt pressure, ice pressure, temperature effects, and tailwater pressure, if applicable, plus the effects of the maximum credible earthquake (MCE).

The dam should also be analyzed for any other loading combination the designer feels appropriate, including uplift with drains inoperative.

4.4.3 Factors of Safety

The safety factor recommended by most standard criteria for stability analyses of RCC dams is normally the same as for CVC dams.

The safety factors used in dam design are usually determined by standard practices or an agency responsible for regulating the safety of the dam. In the USBR [4.07;4.08] criteria, minimum factors of safety required are :

⇒ **Foundation Stresses**

- Usual loading (normal reservoir) combination = 4.0
- Unusual loading (maximum reservoir) combination = 2.7; and
- Extreme loading (earthquake) combination = 1.3

⇒ **Concrete Stresses within the dam**

- Usual loading (normal reservoir) combination = 3.0;
- Unusual loading (maximum reservoir) combination = 2.0; and
- Extreme loading (earthquake) combination = 1.0.

Limits are also applied to maximum admissible compressive stresses. In no case should the admissible compressive stress exceed 10.3MPa for the usual loading combination. The maximum admissible compressive stress is increased by 50 percent to 15.5MPa for the unusual loading combination. For the extreme loading condition, the maximum admissible compressive stress can be determined in the same way, using a safety factor greater than 1.0.

Concrete is assumed to crack, if its tensile strength is exceeded by an extreme combination of loads, including the loads induced by a maximum credible earthquake. The dam is then analyzed with cracking included, and if structural stability is assured, the dam can be considered safe against a sudden release of the reservoir despite the sustained damage.

4.4.4 Drainage

Prudent design should follow the principals developed over the years for CVC dams to relieve hydrostatic pressures in the foundation and within the dam through drainage. This is normally done by the construction of galleries within the dam and sometimes adits in the foundation connected to a network of drain holes. Proper drainage is especially important in the design of very high RCC dams given the fact that relatively high permeability zones often occur at horizontal construction joints between lifts (lift joints) in RCC dams. The potential for uplift along these planes has led most RCC dams to be designed assuming total uplift along horizontal lift joints. Proper drainage is, therefore a critical consideration when analyzing the stability of very high RCC dams.

Placement of drains and ensured lifetime effectiveness of those drains should be addressed. If lifetime effectiveness and continued efficiency cannot be ensured, then appropriate conservative uplift assumptions should be made.

The uplift pressure at the foundation drains can be considered one-third of the uplift pressure at the drains corresponding to a linear pressure transition from headwater to tailwater. A linear decrease in uplift is then assumed from the uplift pressure at the foundation drains to tailwater pressure at the downstream face.

Many experienced investigators have discussed the percent of base area subject to uplift. While varying percentages have been used, most designers today assume 100 percent of the base area will be affected in time. High RCC joint permeability can significantly affect uplift pressure intensity and distribution within the body of the dam to the extent that the above assumptions may be unconservative.

Various internal drainage systems can be used to reduce uplift and consequently improve stability. By monitoring the drainage system it is possible to assure that it remains effective during the life of the structure.

4.4.5 Stress and Stability Analysis

Stability analysis of an RCC dam is carried out using the same methods for CVC dams. This usually entails linear elastic two or three-dimensional finite element analyses to determine safety factors against sliding, and to determine the distribution of internal stresses within the dam.

As in a conventional concrete gravity dam, resistance to sliding within the concrete section depends on the cohesive shear strength (cohesion), the coefficient of internal friction in the concrete, and the average normal force on the potential failure plane. Over the years, accepted values of shear strengths of concrete in relation to the compressive strength used in the design of gravity dams have been established. Most conventional design criteria require that gravity dam sections be designed so that no tensile stresses will occur under usual loading combinations. Dam concrete design must, therefore only consider compressive and shear stresses resulting from these conditions. Figure 4.05 [4.01] shows the nearly linear relationship between dam height and compressive strength and lift-joint shear strength requirements under normal operating conditions assuming the usual 3.0 safety factor. It can be noticed, that even for a hypothetical 300-m high dam, the required compressive strength is less than 15MPa, which is easily achievable, even with a relatively lean RCC mix. Lift joint shear strength, however, is a more critical design issue.

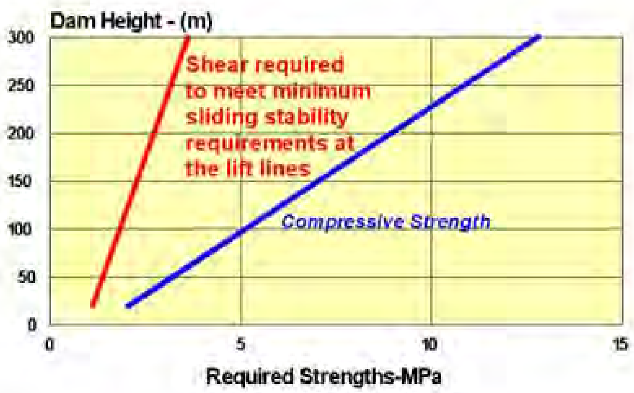


Figure 4.05 Shear stress distribution at a construction joint [4.01].

As shown in Figure 4.05, a 100-m high dam will need to be designed with a minimum lift joint shear of about 0.9MPa. Shears up to this level have been achieved on most RCC dams built to date. The hypothetical 300-m high dam, on the other hand requires a shear of nearly 3.0MPa, which represents a value that can only be achieved using high strength RCC and/or specific lift joint treatment measures.

In highly seismic areas, extreme loading combinations change the internal stress distribution, and analyses indicate significant tensile stresses alternately at the upstream and downstream faces of the dam as it rocks back and forth during the seismic event. As dam height increases these tensile stresses become more significant. The resulting tensile stresses under seismic loading will therefore be critical for determining the strength requirements of the RCC mixes within the dam. The orientation of tensile stresses will be nearly vertical and therefore will have to be transmitted across lift joints if structural continuity is to be maintained. In order to achieve this, it will probably be beneficial to provide higher strength RCC zones in the high tensile regions of the dam's cross-section. Such zoning will have the additional advantage of a more favorable thermal stress distribution since the interior zones will have relatively low cement content.

For very high RCC dams in highly seismic areas, the tensile stresses indicated by the usual linear elastic analysis may be higher than tensile strengths achievable in practice. In this case, a more realistic non-linear analysis could be performed, allowing for separation of the RCC at the horizontal lift joints during the earthquake event. With this approach the resulting tensile stresses would be significantly lower and probably would be within the range of achievable strengths. A post-earthquake analysis would have to be performed to assure that the dam would still be stable with the horizontal discontinuities at the lift joints produced by the design earthquake.

For relatively low RCC dams (less than 50m) analyses have shown that the distribution of stresses within the dam can most economically be accommodated by specifying a vertical upstream face and 0.75 to 0.8 horizontal to 1.0 vertical downstream face. For very high RCC dams, however, particularly those in highly seismic areas, it may be necessary to batter the upstream-face in the lower portion of the dam to relieve vertical tensile stresses and to improve stability or resistance against overturning.

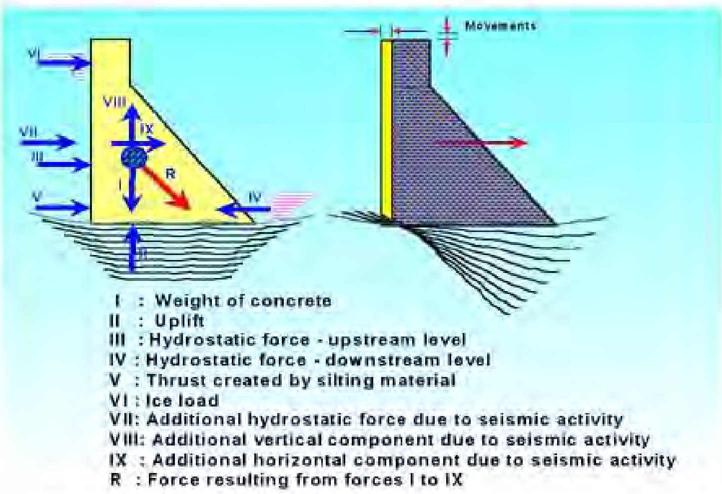


Figure 4.06 Stability against Shearing-Sliding.

The stability of a gravity dam against shearing-sliding at construction joints- through weaker or cracked portions of the concrete - and at, or near, the dam-foundation contact, is a chief consideration. However, it is not the only factor governing the safety and stability of the dam. Since typical shearing-sliding analyses are considered relatively simple; there is a noticeable trend in current design practice for RCC gravity dams to emphasize this aspect while not addressing other equally important factors, such as cracking, which can also affect dam stability. For example, the ACI Report, "Roller Compacted Concrete"[4.17] states that *gravity dams are designed essentially for stability against overturning and sliding.*

A typical shearing-sliding analysis involves the determination of the shear-friction factor (SFF) defined as follows:

$$SFF = \frac{CA\ (\Sigma N - \Sigma U) \tan\varnothing}{\Sigma H}$$

where:

C = unit shear resistance or bond or cohesion;
A = uncracked area of potential sliding surface;
ΣN = summation of normal forces;
ΣU = summation of hydraulic uplift forces;
$\tan\varnothing$ = coefficient of internal frictional resistance;
ΣH = summation of shear forces.

This apparently simple factor for assessing the stability of concrete gravity dams is based on monolithic behavior of the entire structure with elastic continuity at the construction joints. Monolithic behavior, provided by bonding or cohesion along the entire surface of the joints, is essential. Since sliding-shearing is essentially a progressive phenomenon, frictional resistance is fully mobilized only after the bond has been overcome by differential shear. Several questions need to be considered regarding sliding-shearing along construction joints:

- ✓ Where will it start?
- ✓ At what rate will it progress?
- ✓ How much differential shear movement would render the dam block unstable?
- ✓ Can "residual" cohesion at a joint, which has already undergone differential shear deformation, be relied upon to assure an adequate margin of stability?

A more realistic method of assessing stability against shearing-sliding is to determine values of "unit" Shear-Friction Factor, that is, per unit area of the potential sliding plane. The unit SFF will vary from the upstream to the downstream side of the dam, being low or even negative in the critical upstream part, where low normal compressive forces, or even tension, is likely to occur and the uplift forces or pore pressures should be higher. In some RCC dams only a small upstream part of the construction joints is covered with bedding mix, in order to provide sufficient bonding, which when combined with frictional resistance over the entire joint, helps obtain the desired shear-friction factor.

However, the distribution of the frictional resistance, [Â (N-U)tanÐ], may not be uniform along the joint due to the variation of the vertical normal stress and uplift. If bond is lacking over a large portion of the joint surface, frictional resistance over that part can not be relied on for additional resistance to shearing; the upstream bonded part would tend to shear first and the actual safety factor against shearing-sliding may be unacceptable. In order to assure adequate stability against shearing-sliding at the construction joints of high RCC gravity dams "**sufficient**" bond should be provided over the entire surface of each joint.

Effective bonding and shear resistance of a construction joint in an RCC dam are influenced mainly by the intervals between placement of RCC layers, and type and extent of treatment of the joint before placement of a new concrete layer, as discussed ahead. Actual values used in final designs should be based testing of the materials used or careful extrapolation from tests on RCC mixtures from other projects with similar aggregates and cementitious materials content.

Although these measures increase costs and slow down RCC placement, the improvements in quality and long-term performance are cost-effective in high dam, allowing reduced maintenance costs and stability factors equal to those of a comparable CVC dam.

The approach to stability analyses against overturning used for RCC dams is similar to that used for conventional concrete structures. Consideration must be given to the materials used and the subsequent unit weight of the in place concrete, along with the adopted cross-section. As in sliding stability analyses, the stability of all lifts must be reviewed, especially if no impervious upstream concrete is used, thereby allowing the potential for uplift along lift lines within the dam.

The shear friction factor is not really significant in the body of an arch dam, where it is presumed that sections do not act independently; this factor indicates only the integrity or competency of the particular section to which it is applied. Any local weakness would mean a redistribution of load to the arches. What is important for the overall stability of an arch dam, though, is the shearing resistance of the abutments, which is assessed by applying the shear friction factor to three-dimensional rigid block analyses of the sensitive sections of the abutments. The problem lies in defining these sections and giving realistic values to the cohesion and the angle of friction, especially along bedding planes and joints in the rock.

Arch dams are highly hyper-static structures; therein lies their strength and also the difficulty of analysis. Before the existence of the trial load and the finite element methods, the structure had to be reduced or simplified to something that could be analyzed. This led to comparing the structure to such things as a section of a thin cylinder or a variation of some kind; a series of independent arches, either horizontal or plunging; membranes and shells; and cantilevers and arches acting in unison. It also led to the use of the structural solid model.

The structural model developed from the necessity for a way to analyze arch dams, other than the cumbersome and time-consuming mathematical analysis methods, that were all there was before computers made sophisticated mathematical analyses practicable for the design engineer. At that time, it was a question of either oversimplifying the problem or engaging on a long and tedious analysis, which could still produce unsatisfactory results leaving no time for refinements. The result was that shapes prepared for such analyses tended to be overconservative.

4.4.6 Design Details

4.4.6.1 Upstream Face

The basic form used to improve durability in CVC dams, as adopted in large concrete dams in Brazil (Itaipu, Tucurui, Ilha Solteira, Itumbiara) and other regions, is a "boundary concrete". This "boundary concrete" relies on an impermeable or relatively impermeable upstream face or membrane as the primary water barrier. As secondary seepage control, the upstream facing designs may also include a drainage system behind the face.

The various methods chosen for improving the durability of RCC dams by reducing or controlling seepage have produced a great variation in design. Figure 4.07 shows the statistical data of the upstream face types used in RCC dams until 1997[4.18].

Willow Creek, which was the first lean RCC dam, and Upper Stillwater, the first high-paste-content RCC dam, are both cases where the entire dam section was considered in design as the water-retaining element. Precast concrete panels were used as forms for the vertical RCC upstream face at Willow Creek, while horizontal slip-formed elements of conventional concrete served both as forms and as the durable exterior skin for Upper Stillwater Dam.

Although initial seepage that occurred at Willow Creek Dam may be considered acceptable for a flood-control dam, most designers would not consider it acceptable for other reservoir purposes. Based on Willow Creek's performance, designers have developed a number of more impermeable solutions. Nearly all of these following seepage-reduction solutions are based on an upstream-face waterbarrier.

Selection of the upstream face depends essentially on watertightness requirements and cost considerations.

• **Unreinforced concrete face with waterstopped contraction joints:**

This basic design has varied considerably regarding face thickness, joint spacing, and depth of the contraction joint into the RCC mass. Dams built with Japanese RCD method, such as

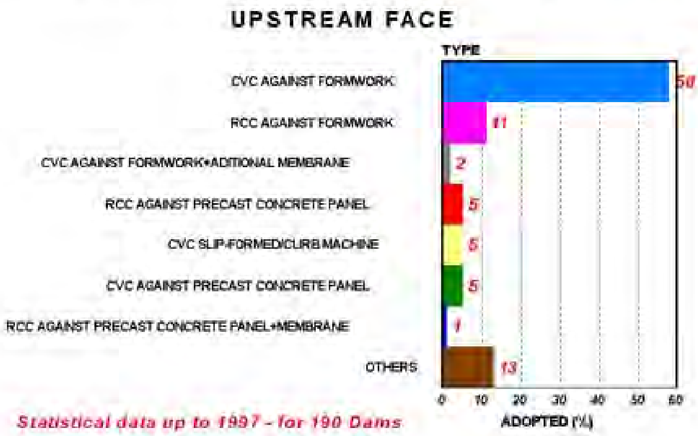


Figure 4.07 Statistical data of the upstream face types in RCC Dams [4.18].

Shimajigawa; Tamagawa, Myagase and Urayama, have 3m (the width of a concrete layer when a concrete bucket is opened) CVC upstream faces with vertical joints spaced at 15m centers. For the Japanese dams and at Elk Creek, crack inducers – in-line with the waterstopped joints - were produced by inserting galvanized steel sheeting into the RCC across the dam for its entire height, before compaction. The design of a dam built with the RCD method is identical to that of a gravity dam built entirely with conventional concrete. The RCC is used for the large volumes in the interior of the dam replacing more costly conventional concrete. Unique mix design and construction methods, including transverse joints spaced at 15 m, were developed in Japan.

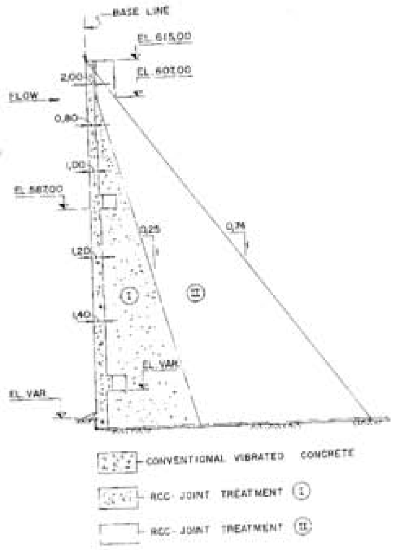


Figura 4.08 Transversal section from Jordão Dam, showing the "Concrete Face"

Figure 4.08 shows the face used at Jordão Dam (in Brazil). A bedding mortar was placed over the surface of each lift for the Japanese dams and at Jordão Dam. Japanese dams use an upstream membrane with a conventional concrete facing, rising together with the RCC placement. There are no signs of cracks or failures.

The face thickness can be calculated based on permeability and absorption of the material (CVC) used for the upstream membrane, considering the water pressure head from the reservoir and the time necessary for the water to be collected in the drainage system.

At this point it is worth considering the possibility of this concrete acting as a "Concrete Face" improving impermeability of the dam. The thickness of this " Concrete Face " may be calculated based on [4.19], where it is adopted that the distance (thickness) of percolation is stated by the expression $\mathbf{e = (2*P*K*t/a)^{1/2}}$ where:

e = Thickness of the concrete face with permeability "K";

P = Water column height acting on the dam;

K = Concrete coefficient of permeability;

t = Time considered for the percolation to happen and cross all the "Concrete Face";

a = Absorption of the concrete from the "Concrete Face".

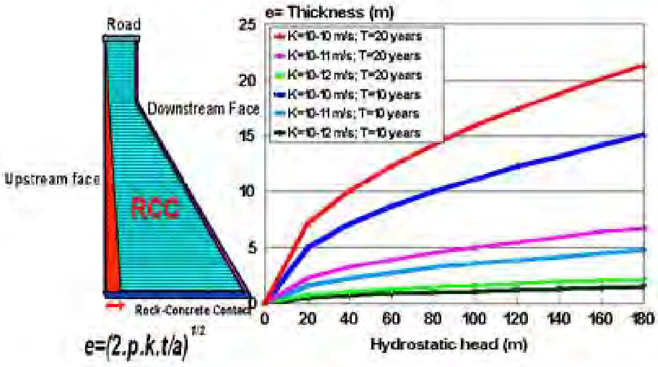


Figura 4.09 thickness of the "Concrete Face", for different values of "t" and "K" .

The thickness of this face concrete, calculated by the expression, with a 5% absorption, is shown in Figure 4.09 for several values of "**t**" and of "**K**".

The curves in Figure 4.09 clearly reveal that the use of concretes with permeability of 10^{-12} m/s is convenient only for dams with height under 40m, for filling the space from face to gallery, when the latter is placed less than 3m from the face of the dam. For dams under 40m high and a drainage gallery placed more than 3m away, the use of a face concrete with a coefficient of permeability higher than 10^{-12} m/s is possible.

A simplified expression, considered an example by Roy W. Carlson [4.20], can be used, with a coefficient of permeability of about $5.5*10^{-12}$ m/s, and a height of 122m (400 feet) as $\mathbf{d = (0.02574*T)^{1/2}}$, where:

d = Distance of water penetration (m);

T = Time (days) considered for the percolation to happen and cross all the distance "d"

From both equations, Figure 4.10 can be obtained, for different values.

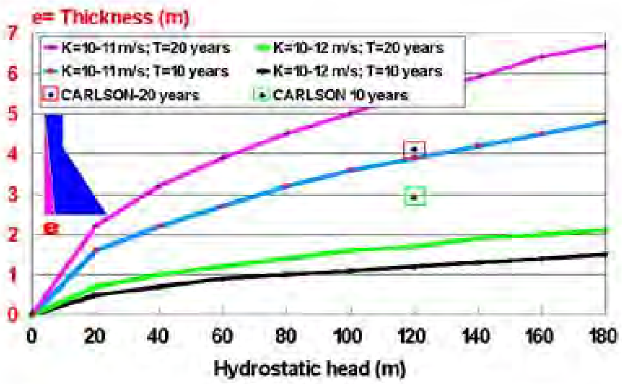


Figure 4.10 Unreinforced CVC face thickness.

Mix design and construction control for unreinforced concrete faces are important in order to produce a high degree of watertightness. The conventional concrete upstream-face mix should primarily be designed to meet permeability and durability requirements. A wide-range water-reducing admixture has been used to reduce mixing water requirements. This tends to minimize drying shrinkage of the face. More importantly, a retarding admixture should be considered in order to keep the facing concrete alive until the next lift is placed. In no case should the top surface of the facing concrete be allowed to dry out producing a "cold joint" and a potential seepage path. Applying a bonding mortar mix (bedding mix) to any surface that has the potential to become a "cold joint" is one solution.

⇒ **Unreinforced concrete face without waterstopped contraction joints:**

Unreinforced upstream faces built with conventional concrete without waterstopped joints have been used on quite a few low to moderate-height RCC dams. Examples of this type of design include Middle Fork, Galesville, and Grindstone Canyon. For these dams, the face thickness has averaged between 0.45m and 0.60m with a partial bedding mix extending up to 2.4 m downstream.

At Middle Fork and Grindstone Canyon Dams, blockouts in the upstream wood forms produced notches in the facing concrete that acted as crack inducers at 3.7m and 4.9m horizontal spacing, respectively. The unreinforced concrete face will crack at the location of the weakened planes formed by the crack inducers. The cracks in the notches can then be sealed prior to reservoir filling.

The upstream membrane can be built with RCC especially proportioned mix, as adopted for some Spanish [4.21] (Santa Eugenia; Los Canchales; Maroño; La Puebla de Cazalla) and Chinese [4.22] (Jiangya) dams. A high fine content RCC mix, with low heat hydration, can be used as an impermeable membrane.

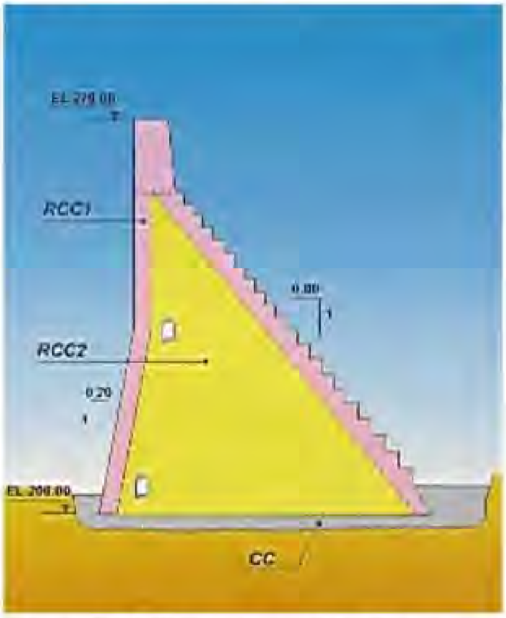


Figure 4.11 Concrete zoning diagram at Spanish RCC dams (from [4.21])

Figure 4.12 Concrete zoning diagram at Jiangya Dam (from [4.22]).

⇒ Membrane-faced concrete panels

Precast concrete upstream facing panels with a 1.65-mm thick polyvinyl chloride (PVC) liner bonded to the downstream side in the manufacturing process were used at Winchester Dam. The joints in both directions were heat welded in the field to form an impermeable upstream membrane and were backed by an average of 0.5m of conventional concrete. A "bedding mix" atop each 0.3-m thick RCC lift extended another 0.5m downstream. The PVC membrane was embedded horizontally in conventional concrete in the foundation keyway and wrapped into a trench cut into the abutments to complete the impermeable dam facing. In the entire construction process, care must be taken so as not to puncture the membrane. The liner was tied into the foundation by wrapping the liner under the dam along an RCC layer and tying it into an RCC cutoff trench in the foundation. Each joint in the liner was spliced in the field by heat welding.

Figure 4.13 PVC membrane inside the panel form at Capanda Dam.

Figure 4.14 Concrete placement in the panel mould at Capanda Dam.

Figure 4.15 Precast concrete panel curing at Capanda Dam.

Figure 4.16 Handling and tilting up the precast panel at Capanda Dam.

Figure 4.17 Anchoring the precast panel at site at Capanda Dam.

Figure 4.18 General view of the precast panel and membrane at Capanda Dam.

Figure 4.19 Precast concrete panel and the PVC membrane, bonded after the panel casting at Urugua-i Dam.

Figure 4.20 Precast concrete panel and the PVC membrane for Winchester Dam,

This method was also used for the 77-m high Urugua-i Dam in Argentina, and the 110-m high Capanda Dam in Angola.

For Urugua-i Dam, the thickness of the conventional concrete downstream panels averaged 0.7m. The width of the bedding mix atop each 0.4-m thick RCC layer varied from 5 m near the top to 12 m at lower elevations.

For Capanda Dam the thickness of the conventional concrete downstream panels was calculated as a second watertightness barrier. The width of the bedding mix atop each 0.4-m thick RCC layer was considered as 25% of the dam base. The membrane thickness used is 2.0mm.

Dam	Country	Height (m)	Casted	Dam	Country	Height (m)	Casted
Stacy Spillway	USA	31	After	Salto Caxias	Brazil	70	After
Allan Henry Spillway	USA	25	After	Petit Saut	French Guyana	48	Before
Pak Mun	Thailand	26	After	Villanur	France	16	Before
Longmentan	China	58	After	Sep	France	46	Before

Figure 4.21 Dams with reinforced and jointed concrete faces, until 1997 [4.18].

Figure 4.22 Reinforced and jointed concrete face at Salto Caxias Dam, during construction-1996.

⇒ **Reinforced and jointed concrete face:**

The membrane can be built with a constant-thickness concrete face reinforced in both directions. The reinforced upstream concrete face can be cast after or before the interior RCC. The reinforced and jointed concrete face is very similar to the upstream face design for a concrete-faced rockfill dam. Vertical water-stopped joints can be spaced horizontally and the construction joints can be spaced vertically.

⇒ **Slipformed Curbs:**

A way of forming upstream and downstream faces is by using powered curbing machines to slipform conventional concrete curbs or facing elements against which the RCC placement can be made within about 8 hours. This method is more used in wide valleys and large projects where the rise rate of RCC does not exceed the slipforming rate. At Upper Stillwater it was possible to maintain an average production rate of 0.6 m vertical rise (two RCC lifts) per day with the curbs having enough time to develop the necessary strength.

⇒ **Precast Concrete Panel as Form:**

Vertical and very steep faces can also be controlled with precast concrete panels (as used for Willow Creek, Siegrist, Spring Hollow Dams) or blocks. Precast concrete panels consist of relatively thin high-quality concrete slabs with integral and/or external supports for lifting. These panels act as insulation themselves or can incorporate added insulation to protect the interior concrete in extremely cold regions. They can also include a heavy-duty flexible impervious membrane attached to the rear of the panel (as previously mentioned for Winchester, Urugua-i and Capanda Dams) to provide watertightness. With dry consistency RCC, the rate of rise of the RCC is limited only by the rate at which the panels can be placed. When a wetter consistency mix is used, especially if it is cold and/or otherwise retarded, the rate of rise will be limited by the setting time of the RCC unless additional anchorage or panel support is provided.

Figure 4.23 Upstream face being casted at Upper Stillwater Dam.

Figure 4.24 Precast concrete panel as form at Spring Hollow Dam (Courtesy: Rotec Industries).

Figure 4.25 Uncompacted slopes at Guadalemar Dam in Spain.

⇒ **Uncompacted Slope:**

If no attempt is made to compact the edges of an RCC placement, the sides will take a natural angle of repose of about 50 degrees with crushed aggregate and 45 degrees with rounded aggregate (as Guadalemar Dam in Spain). This presumes tremendous care with spreading and compacting. Any way of containing loose concrete at the edge, results in steeper faces: for example by board-forming the height of the lift supported by pins driven temporarily into the RCC.

⇒ **Other upstream facing methods:**

Other methods of increasing the watertightness of the upstream face of an RCC dam have been used. In China, at Kengkou Dam, a 60-mm thick asphalt-mortar membrane was placed between the RCC surface and a 60-mm thick precast concrete panel upstream form. At Longmentang Dam, an expansive-cement-concrete mix was used for waterproofing. No transverse joints were placed in either dam.

Figure 4.26 Elastomeric upstream membrane at Gallesville Dam (Courtesy: Selmo C. Kuperman).

All three RCC arch dams have used 2 grade RCC on the upstream with a 40 mm aggregate; its thickness for Puding Dam varied from 2.0-6.5m. To improve impermeability, treatment of layers' surface used 1.5-2.0cm cement fly-ash slurry. The drilling of holes has proven the core to be in very good contact and the permeability coefficient has reached 10^{-10}cm/s. For Wenquanpu arch dam, the same construction method was used, and the same value of permeability was reached. For leakage safety, an additional 1.5-mm thick PVC membrane was used up to the dead water level; total water head is 17.5m

During the International Symposium on RCC Dams, held in Santander-Spain, in 1995, [4.23] it was reported that:

"*...2.3- Upstream Face*

For approving of impermeability on RCC dam, several kinds of anti-seepage structures were applied in practice. They are:

· Asphalt mortar, applied on Kengkou RCC dam;

· Expansive reinforced concrete, applied on Longmentan RCC dam;

· Precast concrete blocks, bedding mortar and deeply pointed joint, applied on Shuidong RCC dam;

· Conventional concrete with 2-4m thickness, applied on Shuikou, Yantan,etc...;

· Rich content cementitious material with maximum aggregate size of 40mm, within 6 to 2m on upstream face applied on Rongdi dam.

All types compared, the first two did not work very well. For the last type, it is more convenient to use 2 grade rich cementitious RCC. As RCC itself has high impermeability, at least 10^{-6} to 10^{-10} m/s, the problem is how to treat the surface of layer. If the RCC technology proved good contact, no doubt the impermeability will satisfiy the design specification".

Waterproof elastomeric membranes were applied to the upstream faces at Galesville Dam; the relatively thin elastomeric material was sprayed onto the exposed upstream face. It has been unable to bridge cracks and its overall effectiveness has been poor. Treatment consisted of cleaning the surface with water jetting and then, a primer coat and two membrane-coats were applied using standard spraying equipment. A two-layer elastomeric material sprayed on the face of Galesville Dam as a secondary seepage control measure was thought to have sufficient elongation to stretch over any cracks that may have formed. The material, however, failed to span the cracks and repair damage caused by the membrane-face separation - resulting from high internal pore pressure or freezing-, floating debris and vandalism.

At Concepción Dam (68m high)[4.06], a PVC membrane was applied to the upstream face after the RCC dam body had been built.

Figure 4.27 PVC membrane applied after the construction of Concepción RCC Dam (Courtesy: CARPI Systems).

4.4.6.2 Downstream Face and Slope

There are various methods for building downstream faces of RCC dams as shown in Figure 4.28; a few of these are listed below:

⇒ **Unreinforced stepped CVC concrete:**

Unreinforced downstream faces built of conventional concrete with or without waterstopped joints have been used at Capanda and Salto Caxias Dams.

⇒ **RCC and precast panel concrete face;**

RCC downstream faces built against precast concrete panels have been used at Urugua-i Dam. At Saco de Nova Olinda Dam, the RCC was cast against mould (cast-in-situ), as can be seen on Figure 4.30.

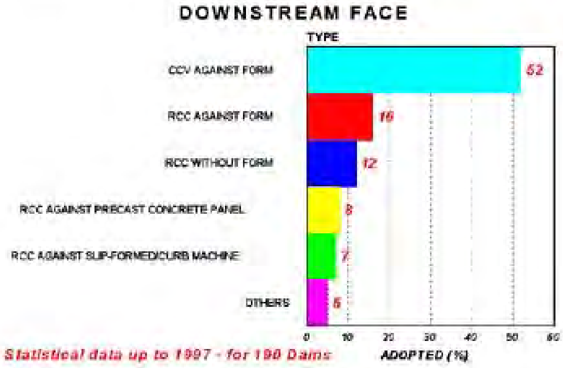


Figure 4.28 Statistical data of downstream face construction [4.18]

Figure 4.29 Unreinforced stepped CVC concrete at downstream face of Salto Caxias Dam.

Figure 4.30 RCC cast against mould (cast-in-situ), for downstream face at Saco de Nova Olinda Dam.

⇒ **Slipformed concrete face:**

Made with a slip-form machine, as mentioned above.

⇒ **Unreinforced concrete face;**

Built gradually as the compacted concrete structure rises with the same technique used for the upstream face, previously mentioned. The Japanese RCC Dams are the most important examples of this technique.

⇒ **RCC poured without form:**

Construction of a poured-in-place RCC downstream embankment. In this case, if the natural slope is 0.9 H/1V or less, a volume of material, more than required for the stability conditions (slope of 0.8H for 1V or even of 0.7H/1V), will be poured. This method often results in the building of an irregular downstream face, such as those of Willow Creek and Siegrist Dams.

A machine called slope compactor was used for compacting, as suggested by studies on compaction methods. Research on more economical procedures to minimize work volume while significantly contributing to the densification of the downstream face of the dam has lead to the development of the slope compaction method. The use of special-purpose equipment to compact slopes is a method in common use in France [4.24;4.25;4.26]. However, given the dimensions of this equipment, a minimum distance between faces is required. This procedure has been used for batters from 0.7H/1V to the natural slope and could be used on steeper slopes, provided preliminary tests are done. The machine includes two independent vibratory plates with adjustable angle. One plate rests on the upper fill surface while the other is set on the inclined surface of the dam. The vibration frequency of each plate is adjustable, therefore allowing the operator to adapt the compaction on the material. The complete machine can be attached to the end of a hydraulic shovel arm (as schematically showed in Figure 4.31) which positions it and creates a static densification load, vertically and horizontally. The downstream face of Olivettes Dam (Figure 4.32), sloped at 0.75 H:1 V, was obtained by compacting the RCC according to the procedure described here.

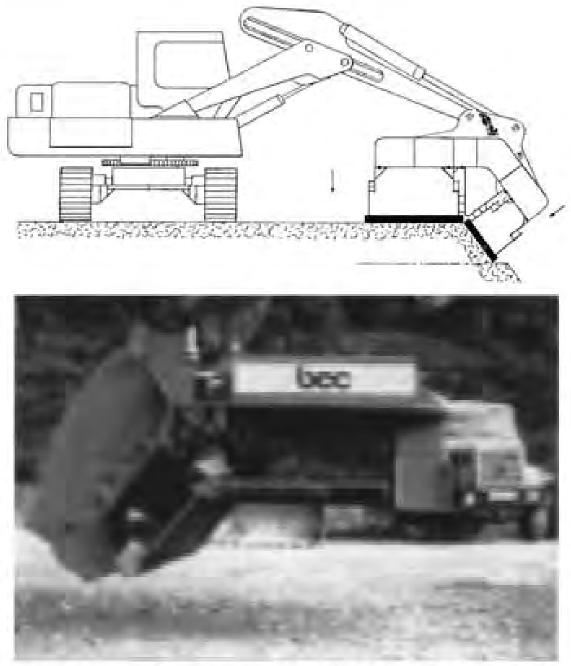


Figure 4.31 Slope compactor developed by BEC FRERES SA [4.24].

Figure 4.32 Downstream face of Les Olivettes and Petit Saut Dams.

4.4.6.3 Spillway

An earlier practice in RCC dams was to design an ogee spillway aligned with the streambed and uncontrolled, i.e., no gates were added to the crest for control so when the reservoir elevation exceeded that of the spillway crest, the discharge flew free down the face of the dam. The downstream face was either formed or unformed, depending on volume and usage. Faces may consist of conventional concrete formed as steps, which are designed to dissipate the flows progressively and provide erosion resistance, or smoothed CVC surfaces.

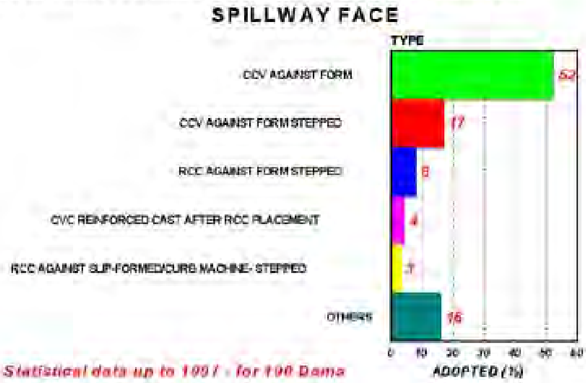


Figure 4.33 Statistical data of the downstream face for RCC dam spillway.

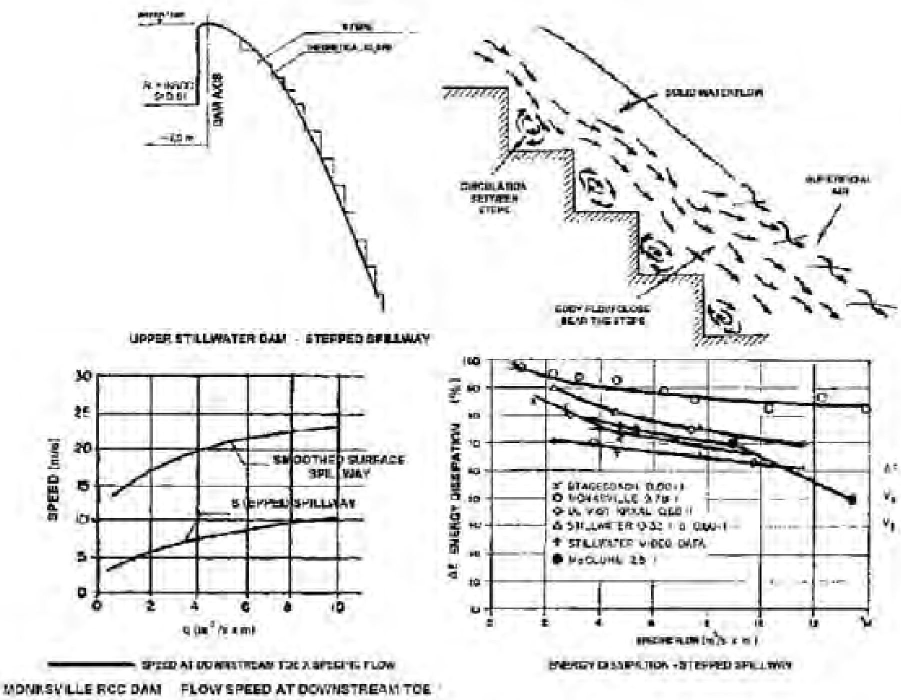


Figure 4.34 Stepped spillway section.

Unformed faces have the rough, textured appearance of RCC placement. Forming after RCC placement with conventional concrete or shotcrete can effectively shape the ogee crest. Loose or uncompacted RCC is removed to provide a sound surface for the shaping concrete.

In most dams, the ideal location for a spillway is over the dam itself. As larger and higher RCC dams are built, the spillways for some of them will have large discharge capacities and large crest control gates. In these cases, the current practice is to use a smoothed CVC surface over the RCC body.

Figure 4.35 Capanda Dam Spillway, during construction. A smoothed CVC concrete face over the RCC mass body provides the surface for the water flow.

The specific discharge, **q = m³/s/m** length of crest, is often the governing criterion in sizing the spillway and its gates. Economy, energy dissipation and frequency and duration of spillway operation determine the design **"q"** and the height of the crest gates. Economics generally dictates height and number of crest gates. In current practice, the largest radial gates for spillways over CVC dams range 15-20m in height and 10-20m in width. As the use of RCC for dams increased, new dams and reservoirs with large flow capacity were designed with large gates, such as Salto Caxias Dam.

Dams' large spillway gates are mobile dams, which transfer very large forces to the piers supporting their trunnions. In turn, the loads on the piers, which are reinforced concrete structures, are transmitted into the body of the dam. The piers and the dam blocks under them need to be designed as a structural unit, without overstress in the unreinforced concrete and particularly, on its construction joints.

Could a spillway structure consisting of a cap of CVC in Brazil, (14 radial gates 16.5m-width*20,0m-high) over an RCC dam have adequate safety margins and warrant safety and operability of the gates under all emergency conditions? For high gravity dams, like any other dam type involving a large investment and a high downstream hazard potential, the overall safety and operability of the spillway should be a primary consideration. Therefore, for high RCC dams with large gated spillways, it may be necessary to increase the CVC component of the spillway blocks.

Stepped spillways have been used on RCC dams and are a very efficient method of dissipating energy [4.27 to 4.31]. Stepped spillways are particularly common for dams with a relatively low flow per unit length (less than 15 $m^3/s/m$), although a number have been designed for unit discharges of up to 30 $m^3/s/m$ (De Mist Kraal Weir [4.31]).

Figure 4.36 Jordão Dam in Brazil – Uncontrolled Spillway. Smoothed CVC concrete surface- Q_{max}= 7,300m^3/s.

Figure 4.37 Caraibas Dam in Brazil- uncontrolled stepped spillway.

The use of stepped RCC spillways has three major limitations:

I. The frequency of spill;

II. Head over the spillway crest;

III. Height of the Dam.

Reference [4.31] mentions:

"....Stepped spillway offer various cost saving for RCC dams but the benefits are not fully exploited due to the lack of proper understanding of the hydraulics involved. So far most research has been project orientated and thus the full potential of these spillway has not yet been determined...."

Similar consideration can be seen in the reference [4.32].

Conduits are usually built with traditional concrete before initiating RCC placement. Locating the intake structure upstream the RCC dam and control house and the energy.

Figure 4.38 Rio do Peixe Dam in Brazil- uncontrolled stepped spillway.

Figure 4.39 Urugua-i Dam in Argentina- uncontrolled spillway. Smoothed CVC concrete surface.

Figure 4.40 Salto Caxias Dam in Brazil- controlled spillway. Smoothed CVC concrete surface- Q_{max}= 49,600m³/s.

4.4.6.4 Outlet Works and Diversion Structures

Current practice in placement of outlet elements in RCC design is to set the conduits into or along the rock foundation to minimize delays in RCC placement dissipator downstream its toe also minimizes interference with RCC placement. Avoiding large inserts in the dam simplifies construction, minimizes program disruptions and can maximize savings.

Figure 4.41 Diversion gallery and intake tower at Saco de Nova Olinda Dam.

Figure 4.42 Diversion tunnel at Capanda Dam.

Figure 4.43 Diversion sluiceway at Salto Caxias Dam.

4.5 Thermal and Volume Changes

4.5.1 General

The main volume changes associated to massive placements of concrete result from the temperature changes that occur during the life of the structure. Drying shrinkage is limited to the exposed surfaces of the mass. Autogenous volume changes are normally irrelevant, if not caused by alkali-aggregate reaction. They depend mostly on the quality and quantity of the cementitious materials used but may also be influenced by aggregates or by environmental agents.

Volume changes of massive placements are mainly restrained by the bonding of the concrete to the foundation base rock and by the interior of the same concrete mass, which does not change in volume at the same rate. Cracking of the mass will occur when restraint of the change in volume exceeds the strain capacity of the concrete.

Main factors affecting cracking are the peak internal temperature reached soon after placement, the average annual environment temperature, which will eventually cause the mass to cool; creep, the modulus of elasticity, and the degree of restraint acting at the crack location. These cracks appear during the first or second winter season and generally initiate at exposed surfaces adjacent to the foundation where restraint is the greatest. From there, they will propagate inward and upward with continued cooling of the mass. If the volume change is large enough, the cracking will penetrate the full thickness of the dam and become a path for leakage.

Propagation of the crack in the vertical direction depends on the distribution of restraint within the mass and is primarily a function of the base length at a 90-degree angle to the plane of the crack. For this reason, cracking in the longitudinal direction is generally limited to a height of approximately one-quarter of the base length of the dam. For instance, if an RCC dam is built without contraction joints, cracks can propagate to the full height of the dam in the upstream to downstream direction depending on the thermal change in volume.

The designer should also be concerned with cracking that may initiate as a result of quick surface cooling (temperature differential between day and night) while a warm interior mass provides restraint to surface contraction. Although internal restraint is limited and surface cracks may penetrate no more than 0.5 –1.0m as a result of that restraint, they can be responsible for initiating full section cracking that might not have occurred otherwise.

The most effective way of preventing massive concrete from cracking is to reduce the difference in temperature between the peak temperature reached after concrete placement, and the final stabilized temperature, thus limiting the temperature drop of the structure. The allowable temperature drop is a function of the block size and geometry, relative location to the foundation, relative stiffness of the concrete and the foundation rock, tensile strength and creep behavior of the concrete, rate of temperature drop, etc.

The designer has a variety of options that may be used to minimize thermal stresses. These include substitution of pozzolanic material for some of the cement, limiting placement of RCC to the time of year when cool weather is expected, form insulation, lowering the placing temperature, jointing, and increasing the dam section so that a lower strength with a lower cement factor can be used.

When the option is available, selecting an aggregate of low elastic modulus and lower coefficient of expansion will help. Pre-cooling can be used in RCC construction, but this is not practical because of the large area (RCC layer surface) available to heat exchange and the small thickness of the RCC layer. Stockpiling aggregates in large piles during cold weather and reclaiming them in their naturally pre-cooled condition during warm weather has been effective. Post-cooling is not commonly considered practical in RCC construction, but the increase in RCC arch dam construction has led designers to develop new ideas regarding the post-cooling use.

Exposure of relatively thin lifts of RCC during initial hydration may contribute to modify peak temperatures depending on environmental conditions and length of exposure.

Some conditions may contribute to reduce uncontrolled cracking potential of the mass. They are: a high tensile strength and low thermal stress coefficient of the RCC (the stress related to structural restraint and temperature changes, which is a function of its modulus, creep and coefficient of expansion); or strategically located transverse contraction joints that will not directly affect the structural stability.

During operation, the structure will continually undergo cyclical thermal and volumetric changes. The reservoir acts as insulation for the upstream face from the great amplitude of ambient air temperatures. Reservoirs over 30m deep may vary annually in the lower half by only 2.5 °C. Consequently, a more moderate thermal gradient with its resulting stress will exist in that portion of the structure after the reservoir is filled.

While it is important to minimize internal tensile stresses within the dam due to thermal contraction by controlling placement temperatures, minimizing cement content and maximizing the use of pozzolanic material to reduce heat build up, it is also important to predict where cracks will occur. Early RCC work, even for relatively small dams, involved elaborate thermal studies, the objective of which was to design RCC dams that could be built continuously without the formation of transverse thermal cracks. This approach had limited success for small dams with nearly ideal thermal conditions. However, to date most RCC dams built without special provisions for crack control have suffered some form of thermal cracking, which has often required repair. Most designers focused on designing vertical contraction joints supplied with waterstops and drains- as in conventional concrete dams- to control transverse thermal cracking. The number of these joints can be reduced – ***theoretically***- compared to CVC dams, because of the relatively low heat build up associated with low cementitious content and adequate pozzolanic-material/cement ratios used in RCC. The degree of concern over cracking in an RCC structure should be based on the facility role and the public impact should cracking result in significant leakage of a water controlling structure.

As dams become higher, thermal tensile stresses in the transverse direction become more significant because of additional constraint within the larger mass. Such stresses create a potential for near vertical cracking parallel to the longitudinal axis of the dam. This type of cracking has much more serious structural implications than transverse cracking because it would create discontinuities in the basic gravity cross section leading to structural instability.

Therefore, the design of very high RCC dams requires complete thermal analyses to determine the potential for longitudinal cracking and the most economical transverse joint spacing. RCC placement temperature, ambient temperature, placement rates and schedule, curing conditions, adiabatic temperature rise, thermal diffusivity, specific heat of the RCC and rate of subsequent cooling must all be considered in the analyses. The results of these analyses will be used to determine the location of transverse contraction joints and if control of longitudinal cracking, such as pre-forming groutable joints, is necessary.

Thermal analysis should also consider asymmetrical thermal gradients resulting from overtopping of the dam during construction and/or planned construction joints required by local weather conditions. Once the contractor has submitted his construction plan and placement schedule or whenever there are significant changes to that schedule, the thermal analyses should be rerun and placement restrictions revised if necessary.

Experience has shown that specifying transverse contraction joints for crack control does not significantly increase the cost of RCC construction. However, providing longitudinal contraction joints may become a much more difficult and costly enterprise because it would be necessary to provide for grouting of the joints after the concrete has cooled to restore structural continuity to the dam.

4.5.2 Thermal Cracking Analysis

Volume changes caused by temperature and moisture variations have long been a concern during the design of mass structures of CVC. The same concern applies to RCC dams. However, dams built of RCC have two advantages with respect to thermal control over dams built using conventional concrete. The advantages are:

I the lower cementitious contents of RCC mixtures, and

II the fast placement of RCC, in layers of small thickness that minimize surface exposure to radiant heat and that are usually higher air temperatures.

Both of these conditions create a reduced temperature rise within the RCC dam, therefore making it less susceptible to cracking when compared to a similar dam built of CVC. Concrete expands with an increase in temperature and contracts with a temperature drop. Similarly, concrete expands with an increase in moisture and-contracts with a moisture loss. Because concrete is strong in compression and weak in tension, the decrease in volume caused by decreases in temperature or moisture are of greatest concern. Thermal tensile strains that can cause cracking deep into or through the dam are of much greater importance to designers than drying shrinkage, which is usually limited to the exposed surface of the mass structure.

Structural cracks are defined [4.02] as those that occur within the body of the dam and alter its monolithic, isotropic and elastic behavior. Drying shrinkage cracks, which mostly occur in the exposed surfaces of concrete, have a random pattern and do not penetrate more than a few centimeters from the surface; they are not considered structural cracks.

The most common cause of structural cracking is the high tensile stresses that occur during the relatively rapid cooling rate and consequent contraction of concrete. The higher the constraint against contraction, the higher the tension; cracking begins where tensile stress exceeds the tensile strain capacity of the concrete. Structural cracks can also be caused by excessive, differential and rapid foundation deformations, tensile overstressing of concrete, such as around large openings or due to an earthquake, or can be due to alkali-aggregate reaction. In the worst scenario, structural cracking may be caused by a combination of several factors.

The undesirable consequences of structural cracking in a dam can be diverse:

✓ leakage into the galleries, or through the dam, to downstream;

✓ leakage into the dam from the foundations;

✓ leaching and weakening of concrete;

✓ restart or spreading of dormant alkali-aggregate reaction, acceleration of weathering and deterioration of concrete, particularly due to freezing-thawing, impairment of the structural integrity and stability of the dam;

✓ high internal uplift pressures if the cracks link with saturated or leaky construction joints, and;

✓ difficult and expensive repairs, particularly if the reservoir cannot be emptied.

Transverse cracks in a gravity dam generally start at the concrete-foundation rock contact and progress upward and inward into the dam. The cracks may start during the first colder season, some few months after concrete was placed on the foundations, and may not be visible for several months thereafter. The cracks travel faster when the weekly drop in temperature exceeds 20°C-25°C. If concrete placement (CVC or RCC) is interrupted for periods exceeding 30 days during the cold season, even with surface insulation, cracks may extend to the surface, yet not be easily discernible. Cracks can also start at a surface exposed to swift and large drops in daily ambient temperatures and progress into the concrete.

Sometimes cracks may stay dormant in the body of the concrete for a long period and reach the surface only when external loads such as reservoir pressure, foundation deformations, prolonged freezing weather and quick drop temperature of the outer zones, or earthquake increase the tensile stress concentrations at the ends of the cracks.

The orientation, configuration and extension of transverse cracks may be neither a vertical plane normal to the axis or the upstream face of the dam, nor extend across the full cross section of it. The configuration and extent of a crack may radically change as the reservoir is filled, and continue to change over a period of several years. In colder climates, seasonal changes can be marked in the opening and extension of a crack.

Cracks along a sloping abutment are likely to start normal to the abutment slope and curve into a near vertical direction, which may not be normal to the axis. Transverse cracks can also occur in the upper part of the dam placed against a near vertical abutment, because of the high restraint against deflection of the structure. Transverse cracks in concrete upstream of a longitudinal gallery can be caused by steep temperature gradients between the gallery and the upstream face of the dam exposed to cold air or water.

Typical ranges of principal stresses that may be expected in the upstream face of a 200m high, fully-monolithic gravity dam, that is with contraction joints keyed and grouted, are shown in Figure 4.44. Semi-horizontal tensile stresses are indicated in the upper half near the abutments; if the dam is located in a wide valley, these tensile stresses are more pronounced. In long RCC gravity dams, such as Upper Stillwater [4.03] and Urugua-i [4.33], the cracking due to thermal effects may have been enlarged by structural tensions caused by the transfer of loads to the abutments by beam action and torsion. The longer the monolithic dam, the larger the contribution of such tensions to cracks in the dam.

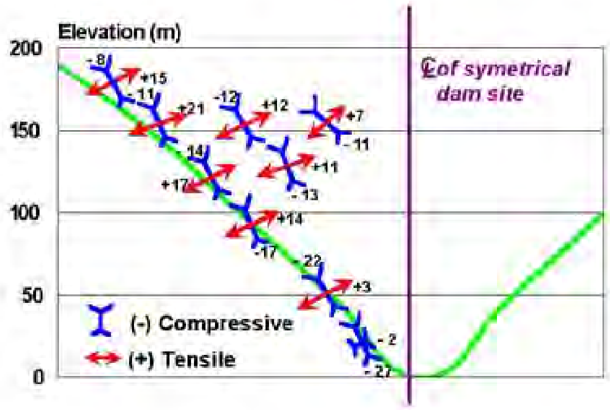


Figure 4.44 Typical stresses at upstream face of a 200-m high monolithic gravity dam (reservoir full+ earthquake)[4.02].

Because of the consequences stated above, structural cracks are considered unacceptable in high CVC dams. For high RCC dams, such an explanation regarding the importance of crack control can result in dams of inferior quality and durability, with shorter operational life and higher maintenance costs.

To reduce the risk of cracking, several provisions are adopted in the design of both RCC and CVC dams. These are: low cement and adequate pozzolanic material content, use of low-heat cement, controlling of the peak temperature, restricting concrete placement to cooler periods and provision of contraction joints. Full-section transverse contraction joints at a 15-20m spacing have been universally provided in all CVC dams of various heights and sizes, and should be well analyzed and considered for high RCC dams. It is widely known that zero-slump RCC has much lower shrinkage than conventional concrete; its very low cement content and hydration heat allows continuously placed RCC to have adequate tensile strain capacity and not develop structural cracks, if placement temperatures are controlled.

However, experience at several completed RCC dams has shown that without properly spaced full transverse contraction joints, cracking could not be prevented. Figure 4.45 lists completed RCC dams, where transverse cracking has been reported.

Dam	Country	Crest Legth (m)	Max Height (m)	RCC Volume (1000m3)	Cementitious Content (kg/m3)	Contraction Joints Number or Spacing (m)	Remarks
Aoulouz	Morocco	480	70	610	100 C	[@] 45m	Stone leakage
Asahiogawa	Japan	260	84	361	96 C + 24 FA	[@] 15m	No cracking
Capanda	Angola	1203	110	757	70 C	[@] 20m	No cracking
Copperfield	Australia	340	40	140	95 C + 15 FA	Three contraction joints	One through transverse crack with seepage
Elk Creek (a)	USA	365	25	260	118 C + 56 FA	[@] 90m	Cracks between contraction joints
Galesville	USA	290	51	170	52 C + 54 FA	No	Seven cracks. Some started from top of dam. Leakage
Knellport	South Africa	200	50	59	61 C + 142 FA	Yes	Through induced cracks-joints. Some leakage
Mano	Japan	239	69	219	96 C + 24 FA	[@] 15m	No cracking
Miyagase	Japan	400	155	2000	91 C + 39 FA	[@] 15m	No cracking
Pirika	Japan	910	40	365	84 C + 36 FA	[@] 15m	No cracking
Quail Creek	USA	609	42	131	135 C + 152 FA	[@] 40m-100m	No cracking where joint spacing < 60m, except along abutments
Riou	France	308	26	45	40 C + 120 FA	No	Several cracks.
Shimajigawa	Japan	240	89	317	91 C + 36 FA	[@] 15m	No cracking
Shuikou	China	646	50	300	50 C + 100 FA	[@] 30m	No cracking between block joints
Upper Stillwater	USA	815	90		80 C + 175 FA	No	Several through transverse cracks at 5m to 15m spacing
Urugua-i	Argentine	690	76	600	60 C	[@] 20m at Upstream Concrete Face &4 joints in RCC dam body	Four through transverse cracks
Wolwedans	South Africa	268	70	210	58 C + 136 FA	Yes	Through induced cracks-joints. Some leakage
Zaaihoek	South Africa	527	47	134	36 C + 84 BFS	Yes	Through induced cracks-joints. Some leakage

(a)- First Stage; C- Cement ; FA- Fly Ash; BFS- Blast Furnace Slag

Figure 4.45 Crack in some RCC dams

If the RCC in the dam were free of any restraints, the decrease in volume caused by a uniform temperature drop across the section would present no problem. RCC dams are bonded to rock foundations, however, and are thus subjected to an external restraint. Restraint can also be initiated when the cool exterior surface restrains a hot interior. The two types of restraint lead to two different temperature analyses, which may be called external restraint in the first case and internal restraint in the second.

External restraint is greatest (fully restrained) at the dam foundation contact and nearly zero (unrestrained) at the crest near the centre of the dam. Internal restraint is greatest in the zones where the temperature change is occurring at the slowest rate. For the external restraint condition, the temperature of the mass peaks and then cools for some time until it reaches the average ambient air or reservoir water temperature at the site. When the volume reduction, caused by this relatively long-term temperature-drop combined with foundation restraint, exceeds the tensile strain capacity of the RCC, transverse cracking occurs at the section of least resistance. Cracks produced by the external restraint condition are usually vertical or near vertical and can extend through the entire dam section.

In the interior restraint condition, the temperature at the center of the concrete mass is higher than at the exposed dam faces. As the surface cools and wants to contract, compressive stresses remain in the warm interior while tensile stresses develop at the outer surface.

Surface cracking occurs when the tensile stress, due to non-uniform temperature change, together with internal restraint, causes a strain that exceeds the capacity of the concrete. The resulting surface cracks are generally vertical, transverse to the dam's axis, and rarely extend through the entire dam. Once cracks are initiated, the energy required to propagate these cracks is less, so both restraint conditions can combine to produce a deeper crack.

As discussed under design considerations, pre-forming or inducing contraction joints at a spacing determined by thermal analyses and cracking studies will be necessary for the next generation of very high RCC dams. Experience to date has shown that the installation of crack inducers, water stops and drain holes at contraction joints can be done without interfering significantly with production. Because of the slower rate of rise and increased working area available, this can be expected to have even less of an impact for larger RCC dams. The cost associated with these features has been shown to be a small percentage of total dam cost and will decrease with increased dam height.

Appropriate solutions to predict thermal cracking are:

I. eliminate crack occurrences by using thermal controls during construction;

II. control the effect of the cracks by building joints with waterstops;

III. eliminate the problem that the cracks create by providing upstream impermeable membranes for leakage prevention; and

IV. modify the geometry of the structure to maintain stability after cracking

4.5.3 Thermal Studies

Thermal computational methods can range from a sophisticated computer-aided finite element analysis to hard computation methods. Most major RCC dams have employed some form of a finite element analysis to determine temperature distributions within the concrete structure from which strains and stresses are determined. Finite element models can be detailed three-dimensional grids of the entire structures.

The heat-flow program simulates temperature distribution with time within the RCC dam as the dam is built in thin horizontal lifts. The temperature within the structure depends on the placing temperature, the heat-generating characteristics of the RCC mixture and the boundary conditions at the various exterior surfaces. The boundary temperatures include that of the air or water and absorbed radiant heat on the exposed upper RCC surface, upstream and downstream faces, and the temperature of the foundation rock.

In conducting a thermal analysis, it is necessary to determine certain properties of the RCC mixture and to develop a detailed construction schedule. The properties can include specific heat, diffusivity, conductivity, coefficient of thermal expansion, adiabatic temperature rise at various ages, tensile strength at various ages, as well as modulus of elasticity, strain capacity and creep coefficients at various ages.

The planned construction schedule is required because expected air temperatures are an input variable to the computer program. If there is a delay in the start of construction, or construction is not progressing as fast as anticipated, or both, it may be necessary to recalculate the temperatures within the mass.

A delay in the construction start usually means the ambient temperatures are warmer and that higher peak temperatures than predicted will occur. In addition, a slower placement rate indicates material properties that are time-dependent, such as tensile strength and modulus of elasticity, may differ from predicted values. Also, the placing temperature of the RCC is a required input for the analysis and this value is directly affected by ambient temperature.

The revised analysis may predict higher tensile stresses in the structure, which may then dictate that more joints be placed in the upper portion of the dam.

The rate of rise of the dam body under construction is important for thermal control under the RCC method. Since it is designed for construction-time reduction, the RCC method makes fast and orderly placement possible, thereby shortening the time required for the placement of dam concrete. The faster concrete is placed, the greater the internal temperature increases. However, considering thermal stress control, the RCC method is more advantageous than the columnar block method because thin lifts cause quick heat radiation and a constant placing speed and continuity between placements make it possible to maintain a gentle temperature gradient within the dam body.

Studies of the heat generation and temperature rise of massive RCC placements indicate that the sequential and rapid placement of layers can reduce cracking because of its more consistent temperature distribution throughout the mass when compared to more traditional ways of placing large volumes of concrete.

Several methods have been proposed for analyzing thermal stress in concrete. In a study [4.34], a temperature history calculation is performed using the finite element method for one-dimensional heat conduction. Next, restraint thermal strains are calculated by a Restraint Matrix Method, which is in general use in the field of dam engineering.

As a result of the parameter analyses described, it was found that the maximum restraint thermal strain on the tension side, which is an important factor to be considered for thermal control, occurs in the maximum temperature fall zone and in the rock contact zone. It was also found that the dam height and the speed of concrete placement are parameters that greatly affect the "maximum restraint thermal strain". These results show that in the maximum temperature fall zone restraint thermal strain tends to be greater at lower placing speeds, and restrain thermal strain in the rock contact zone tends to be greater in higher dams. In the rock contact zone, restraint thermal strain is smaller at lower placing speeds because temperature rises are reduced by heat radiation from the lifts. When the placing speed is high, gentle temperature gradients in the dam body result in small restraint thermal strains. Hence, there are placing speeds at which the restraint thermal strain is maximized. This peak value varies with the dam height, but in the rock contact zone there is no clear relationship between the placing speed and the restraint thermal strain as in the maximum temperature fall zone.

As mentioned in the study [4.34], the major factors affecting restraint thermal strain include the placing speed (v) and the dam height (h). Since dynamic similarity as well as geometrical similarity holds true under the Restraint Matrix Method, it is possible to eliminate the effect of the size of dam by establishing the placing speed in relation to the dam height and introducing a new concept of relative placing speed (v/h).

As mentioned, the maximum restraint thermal strain occurs at and near the elevations of the lifts placed in the summer months (maximum temperature fall zone) or in the rock contact zone. Therefore, in formulating a thermal control plan for a dam to be built by the RCC method, it is possible to optimize the concrete placement plan by comparing restraint thermal strains at these locations.

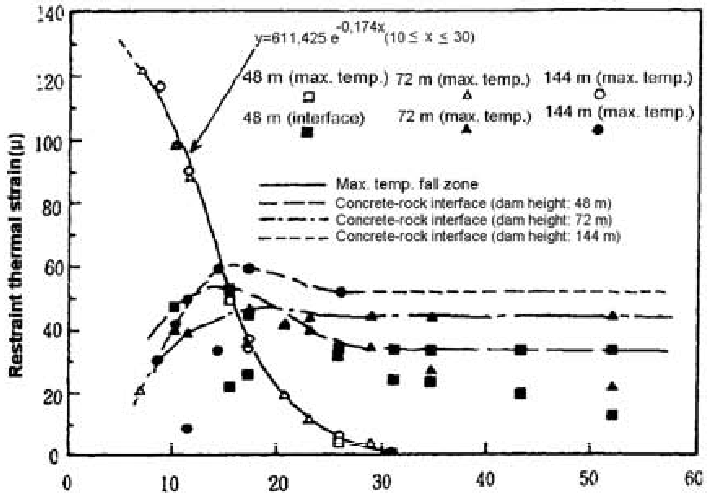


Figure 4.46 Relation between relative placing speed and restraint thermal strain (in the maximum temperature fall zone and at the concrete rock interface) (from [4.34]).

Figure 4.46 [4.34] shows the relationship between the relative placing rate (horizontal axis) and restraint thermal strain (vertical axis) in the maximum temperature fall zone. As shown in Figure 4.46, the relationship between the restraint thermal strain in the maximum temperature fall zone and the relative placing speed is independent of the dam height and is represented by a single curve. The influence of the dam height can therefore be eliminated. The reason for this is as follows:

- ✓ When the relative placing speed is constant, the maximum temperature fall zone (H) and the layer length (L), which greatly affect the degree of restraint if the dam is low, become relatively small.
- ✓ On the other hand, they become relatively large if the dam is high. Thus, the ratio (H/L) remains unchanged.

Figure 4.46 indicates that lowering the relative placing speed reduces the restraint thermal strain in the maximum temperature fall zone dramatically, thereby facilitating thermal control. The restraint thermal strain in the maximum temperature fall zone can be kept within $100*10^{-6}$ by maintaining a relative placing speed of v_h=10, that is, by maintaining placing rate of at least 5 cm/day, 10 cm/day, and 15 cm/day for dam heights of 50 m, 100 m and 150 m, respectively.

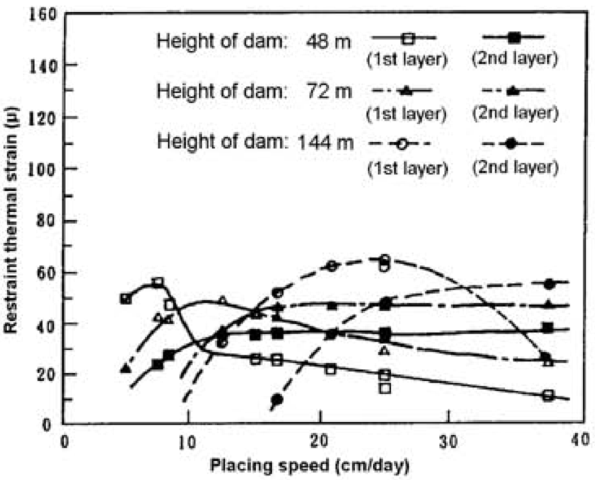


Figure 4.47 Relationship between placing speed and restraint thermal strain (at the concrete-rock interface) (from [4.34]).

Figure 4.47 shows the relationship between the restraint thermal strain in the rock contact zone (first and second layers of the restrain matrix) and the relative placing speed. The restraint thermal strain in the first layer is greater at low relative placing speeds, and in the second layer is greater at high relative placing speeds. At relative placing speeds of 20-25 cm/day, the relationship between strains in the first and second layers is reversed. The peak value of restraint thermal strain occurs in the first layer at relative placing speeds of around 15 cm/day. At relative placing speeds of 25 cm/day and above, the restraint thermal strain is roughly constant. Thus, the relationship between the relative placing speed and the restraint thermal strain in the rock contact zone is not so clear as that in the maximum temperature fall zone. This is because strains in the rock contact zone are caused partly by external strains, and restraint thermal strain is affected considerably by not only the temperature gradient but also temperature drops. Consequently, raising the placing speed in the rock contact zone is not so effective in thermal control as in the maximum temperature fall zone. It is therefore thought that in the rock contact zone, conventional methods for increasing heat radiation, such as the use of half lifts, are more effective in controlling temperature fails than the RCC method. Restraint thermal strain in the second layer increases with the dam size, but it does not exceed 60×10^{-6} even at a dam height of 144 m, thus posing no serious problem regarding long-term thermal stress.

Figure 4.46 compares restraint thermal strains in the maximum temperature fall zone with those in the rock contact zone. The plots include strains in both first and second layers. The restraint thermal strain in the maximum temperature fall zone is dominant at relative placing speeds of about 15 cm/day or below, and that in the rock contact zone is dominant at relative placing speeds of about 15 cm/day or above. At relative placing speeds of about 25 cm/day, the restraint thermal strain in the rock contact zone levels off. These results indicate that in order to control long-term thermal stress when the placement of concrete is started in the begining of the winter season, it is desirable to adopt relative placing speeds of about 15 cm/day or above, regardless of the dam size. Restraint thermal strain is minimized when relative placing speeds of about 25 cm/ day or above are used, but there is little point in using higher relative placing speeds as far as thermal control is concerned.

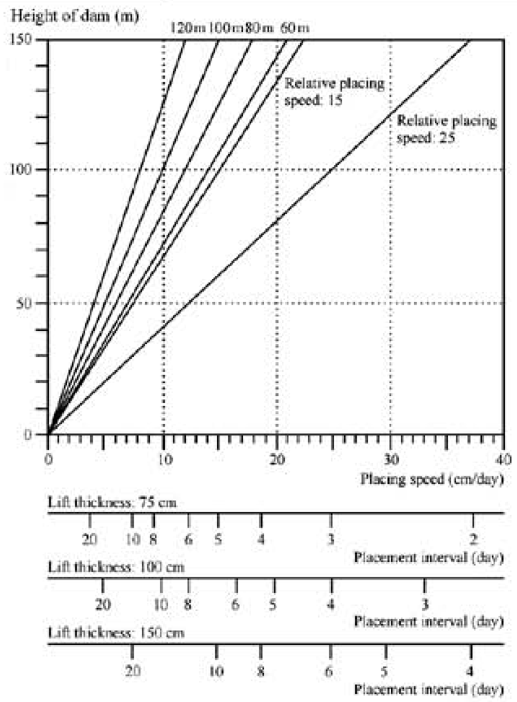


Figure 4.48 Dam height and placing rate (from [4.34]).

Figure 4.48 summarizes the relationship between the dam height and the placing rate for convenience in actual construction: "*The restraint thermal strains resulting from the relative placing speeds of 15 and 25 cm/day are represented by thick lines, and restraint thermal strains in the maximum temperature fall zone of 120*10^{-6}, 100*10^{-6}, 80*10^{-6}, and 60*10^{-6} are represented by thin lines. The lower half of Figure 4.48 shows placement intervals for lift thicknesses of 75 cm, 100 cm, and 150 cm which correspond to the placing speeds shown above*". According to the Figure 4.48, in order to maintain relative placing speeds of 15 or above, it is necessary to place concrete at a rate of at least 15 cm/day. This indicates that lift thicknesses of 75 cm, 100 cm, and 150 cm require placement intervals of not more than 5 days, 6 days, and 10 days, respectively. The figure clearly expresses that, as the dam size increases, it is necessary to increase the placing rate by increasing the lift thickness or shortening the placement interval, in order to achieve the relative placing speed of 15 or the restraint thermal strain of 100*10^{-6}. At a placing speed of 10 cm/day, for example, the relative placing speed for a 100-m high dam and a 50-m high dam should be 10 and 20, respectively. The maximum temperature fall zone is critical for the former, and the rock contact zone is critical for the latter. Thus, the greater the height of dam, the more effective it becomes in thermal control to increase the placing rate.

Based on studies it was concluded that [4.34]:

I. "Under the RCD method for long-term thermal control, the rate of placement of dam concrete greatly affects restraint thermal strains in the dam body;

II. Restraint thermal strain in the maximum temperature fall zone can be roughly expressed by a single curve by introducing the relative placing speed obtained from the standardization of the placing speed with respect to the height of dam. Restraint thermal strain can be reduced more effectively at higher relative placing speeds;

III. The relationship of the relative placing speed with the restraint thermal strain in the rock contact zone is not so clear as that with the restraint thermal strain in the maximum temperature fail zone. In the rock contact zone, increasing the relative placing speed is not very effective in reducing restraint thermal strain;

IV. At relative placing speeds of 15 cm/day or below, restraint thermal strains in the maximum temperature fall zone are dominant. At higher relative placing speeds, restraint thermal strains in the rock contact zone are dominant. Therefore, if the restraint thermal strain in the maximum temperature fall zone is to be reduced, it is desirable to adopt as high relative placing speeds as possible. At relative placing speeds of 15 or above, however, the restraint thermal strain in the rock contact zone is dominant, and higher relative placing speeds do not contribute significantly to thermal control;

V. From the above results, it can be concluded that when a large dam with a height of around 150 m is built by the RCD method using a concrete mix having a unit cement content of $C+F=130kgf/m^3$ $(F/(C+F)=30)$ or so at typical ambient temperatures in Japan, concrete temperature can be effectively controlled by shortening the placement interval or increasing the lift thickness to maintain a high relative placing speed."

As previously mentioned, a planned construction schedule is required because expected air temperatures are a variable input to the computer program. But another point need to be added: this can take in account the upstream membrane face in CVC or an especially RCC proportioned mix concrete, as watertightness barrier.

A published paper [4.35] describes the dam design with an impervious screen and a specified water permeability, which is achieved by an increase of cementitious materials in the composition of RCC. The downstream shell adjacent to the impervious screen without any joints, butts, i.e., as a single block, is also built of rolled compacted concrete with minimum content of cementitious materials. For optimization of the dam design, calculations of temperature conditions and a stress state of the dam body were carried out taking into account lift-by-lift placement of concrete, exothermic heating, gradual cooling down and static loads on the structure. Investigations showed that from the standpoint of crack resistance of placed concrete for the dam with height of 100m; the best alternative is a screen of not more than 12m in thickness.

In most cases, RCC dams are provided with CVC lining of the faces (see Figure 4.07). On the upstream face, such lining plays the role of a membrane.

In an effort to simplify concrete placement operations and to provide thermal crack resistance, an alternative gravity and arch-gravity dam can be investigated. In this case, both the main portion of the section and the impervious screen are built of roller compacted concrete of two different compositions.

An RCC screen built with a higher content of cementitious materials (cement plus pozzolanic material) is quite possible, on condition that concrete crack resistance is provided. Based on experience, dams built entirely with RCC are regarded as the most economical and simple dam construction. These dams need, however, special impermeability requirements at the upstream face. In the case of a gravity dam with the zoned placement of the RCC, different concrete compositions are characterized by the required grade of impermeability. The grade is specified as usual according to the head gradient, i.e., defined by the acting head and thickness of the screen. Vertical drainage is provided behind the screen in the RCC with lower cementitious materials content by, for instance, drilling a row of bore holes.

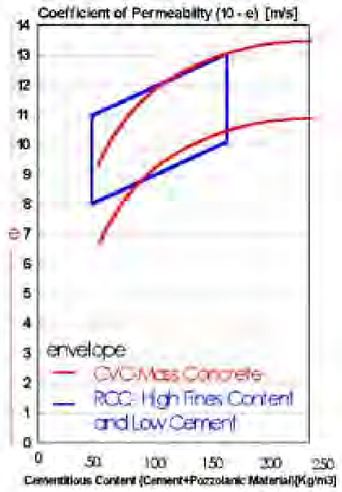


Figure 4.49 Permeability ranges for CVC and RCC.

To determine the necessary content of cementitious materials in the RCC a curve of permeability coefficient versus the content of cementitious materials may be used. According to Figure 4.49 (simplified from Chapter 7) the relationship between the coefficient of permeability of the RCC and the content of cementitious materials is fairly stable.

Horizontal construction joints play an important role in providing the required permeability of the impervious screen. An adequate content of cementitious materials is achieved when the contact between RCC layers is tight and the placement of the bedding mix in each joint is not necessary unless required for some other reason.

Experience shows that a concrete mix with a higher content of cementitious materials and a consistency of 15-20 sec may be compacted by both vibro-rollers and internal vibrators. This makes it possible to compact the concrete mix near the formwork and embedded parts with the use of vibrators and eliminates the use of conventional concrete as a facing material and around galleries, shafts, etc.

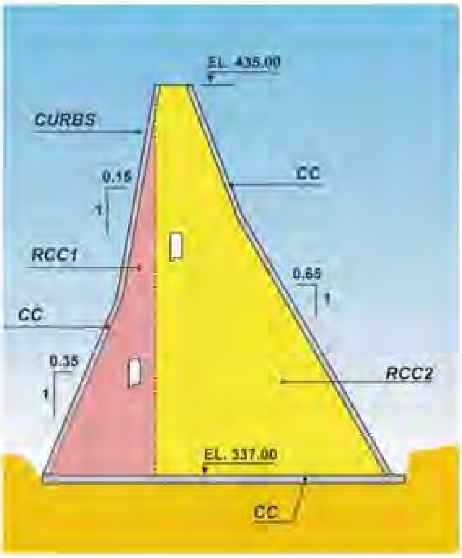
Finally, the main advantages of zoned placement of RCC within the limits of the impervious screen are as follows:

- the required impermeability of the upstream face of the dam is achieved in a simple and economical way;
- tight contact between the RCC layers, with adequate content of cementitious materials, is probably achieved without the use of the bedding mix of the plastic concrete;
- complete compaction of the concrete mix near the formwork, waterstops, drainage pipes, joint-cuts, etc. performed by conventional vibrators;
- monolithic interface of the impervious screen with the rest of the dam is achieved naturally by simultaneous placement of the RCC in horizontal layers along the whole dam profile.

Higher cement consumption within the boundaries of the impervious screen, however, results in temperature rise caused by exothermal heating and additional temperature stresses. To reach a solution, design investigations and a technical and economical comparison of screen alternatives were required.

A possible solution is the alternative used for Rialb dam (in Spain) as shown in Figure 4.50. Transition zones, joints and butts are not used between the impervious screen (1) and the downstream shell (2). Construction of vertical drains (3) is a conventional solution to exclude seepage water on the downstream face. Grouting (4) and drainage (5) in the dam foundation are also done by traditional methods.

The width of the concrete membrane can be calculated as previously mentioned. Besides it is recommended that the width of the screen should warrant the inner zone of the dam protection against seasonal temperature variation, durability and ease of concrete placement.



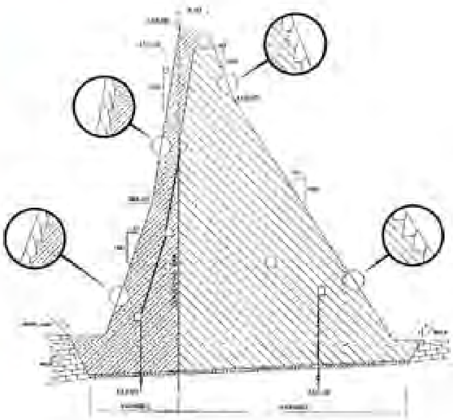


Figure 4.50 Rialb Dam in Spain.

An optimum thickness of the impervious screen is determined by a technical and economical comparison of different screen alternatives. A thinner screen is less costly but its higher content of cement will result in extensive exothermal heating of concrete within the limits of the screen, i.e., appearance of tensile thermal stresses, which may cause insufficient crack resistance of the screen. Consequently, studies in search of the optimum solution led to the Capanda dam example: 110m in height, built under warm tropical climate conditions with placement temperature of 26°C and a final temperature in the mass concrete, after cooling, of 22°C. Three screen alternatives and their respective RCC parameters were analyzed, as can be seen in Figure 4.51. The slope of the downstream face of the dam was 1(V):0.7(H). The width corresponds to the admissible head gradient. In all alternatives, the RCC behind the screen was considered for a similar compressive strength, with a cement consumption of $75 kg/m^3$ plus similar amount of stone powder used as pozzolan and microfiller.

To determine the stress patterns inside the dam, two-dimensional analyses regarding thermal conductivity and thermal elasticity were accomplished using the finite element method. The analysis considered dead weight, hydrostatic load from the side of water, dam profile with different modulus of elasticity, water uplift in horizontal sections of the screen and temperature changes during construction and operation periods. To determine the maximum temperature of exothermal heating, thermal analysis considering lift-by-lift of the concrete mass placement, with zonal distribution of two different RCC compositions was carried out. Exothermal heating during the initial period after concrete placement was determined using a value of complete adiabatic heating of 0.13 ($^oC/kg/m^3$), considering certain intervals of placement of concrete layers (thickness of 0.4m) and the schedule of dam construction (average placement interval of concrete layers - 2 days).

Prolonged cooling-down of concrete was provided on the upstream and downstream faces and on the constantly rising surface.

In the case of a dam with an impervious membrane, thermal analyses revealed the need to consider different cooling-down periods for the concrete: at the center of the screen, at the interface with the downstream shoulder, the central zone and the external faces of the dam. Temperature stresses caused by such peculiarities appeared larger on horizontal planes. Final values for elastic-instantaneous stresses decreased by one half by concrete creep and were combined with stresses resulting from static loads.

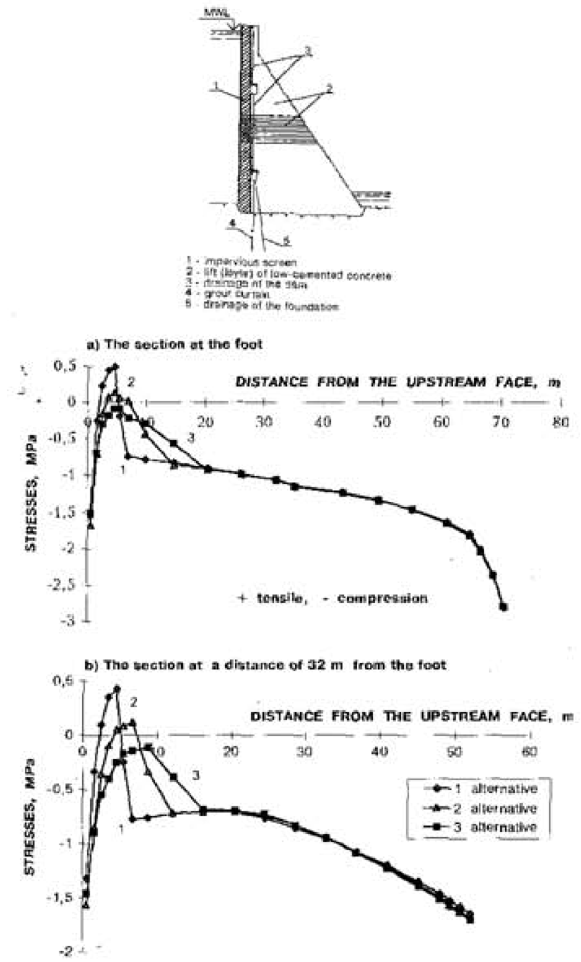


Figure 4.51 Total stresses for horizontal sections (from [4.35]).

Thermal analyses of different screen alternatives made it possible to define the difference in maximum temperature during construction inside the downstream shell and in the center of the impervious screen. As height of the placed concrete rises and not regarding the near-rock zone, changes of the maximum temperature did not exceed 2-3°C. In the downstream shell, the maximum temperature was, as a rule, 33-35° C, in the center of the screen, it was 40-42 °C at 12 m thickness, 43-45 °C at 8 m thickness and 46-48 °C at 5 m thickness.

Maximum vertical tensile stresses resulting from temperature actions can be observed in the upper section of the dam (around 1/3 of the height) at a distance of 4-6 m from the upstream face.

Bearing in mind the lower strengths in horizontal joints it may be concluded that in the first alternative the risk of crack formation is likely. In the third alternative, the risk is unlikely. The second alternative though, may be considered controversial. But in all alternatives, analyses showed compressive stresses on the upstream face resulting from temperature actions. In this case, appearance of cracks may be expected in the first alternative only, i.e., for screens with 5m of thickness. Along the entire height of the dam, the pattern is much the same: on the upstream face total compressive stresses are 1.5-1.7 MPa, then they rapidly reduce to zero or change to tensile stresses at a distance of 4-6 m from the upstream face and finally they become compressive stresses again. It should be emphasized that the zone of detectable temperature stresses does not exceed 10-12m from the upstream face. In the rest of the dam, mass vertical static stresses appear and their maximum values on the downstream face do not exceed 3.0 MPa.

For a technical and economical comparison of screen alternatives, additional expenses for construction of the impervious screen of the RCC dam were calculated. These expenses originate differences in the consumption of cement in the RCC of the screen and the downstream shell. Comparison of additional expenses showed an increase of 20-25% in the first alternative (screen thickness of 5m) which, are lower many times those of the second alternative.

The results obtained in this technical and economical comparison of different screen alternatives considered certain singularities of the case studied, in particular, climatic conditions and rate of dam construction. The considerable importance of thermal analyses compared to technical parameters in the given case does not allow us to consider the selection as multi-purpose. A technical and economical comparison may though, be recommended as a necessary step at the stage of dam designing.

4.5.4 Controlling Temperature Rise

The maximum internal temperature rise in a massive structure can be limited either by reducing the temperature rise of the concrete mixture or by reducing the placing temperature. Consistent with strength and permeability requirements, the use of low-heat cement, a reduction in total cementitious material and an increase in pozzolanic material percentage will reduce the temperature rise of the mixture. Pre-cooling aggregates by winter production or cooled water spray or cooled air, introducing ice to satisfy mixing water requirements, placing the concrete at night, or at winter time season are methods that have been used to reduce the placing temperature of the concrete mixture. Night placement also helps by minimizing radiant heat effects on the exposed upper surface. These procedures are valid for both concrete types: CVC and RCC.

Dam sites that have low annual average temperatures, such as, those far from tropics or on high mountains provide a greater potential temperature drop. Designers of RCC dams at such locations may desire to limit concrete placing temperatures to as low as 10°C. This was the case at Upper Stillwater Dam, Miyagase Dam in northern Japan, and other specific cases.

A different situation was considered for the design of the Xibin dam, in China [4.36]. The RCC thin arch dam was designed for a high construction rate, which can greatly reduce the construction period of an arch dam with smaller concrete volume and simplify the flood-release structures during construction. Since the arch-plan is the principal form of transmitting forces, the weaker RCC layers play a less important role in the stability of dam. The low cementitious content of the RCC is important to lower temperature rise during construction. But strong restraint on the abutments on both sides causes intensive tensile stresses, for any temperature change, to an arch dam without transverse joints. Having been eliminated the cooling pipe system, the concrete temperature should decrease very slowly, in a later period, delaying the date of pounding, should grouting of transverse joints or cracks be necessary. Rapid concrete placing technology causes a large temperature difference between the interior and the exterior of a concrete structure, which will produce cracks on the upper and downstream faces of the dam. These cracks always propagate through inner tensile regions in the summer time and radial cracks will eventually occur. In order to maintain the integrity of the arch dam, transverse joints or cracks must be grouted.

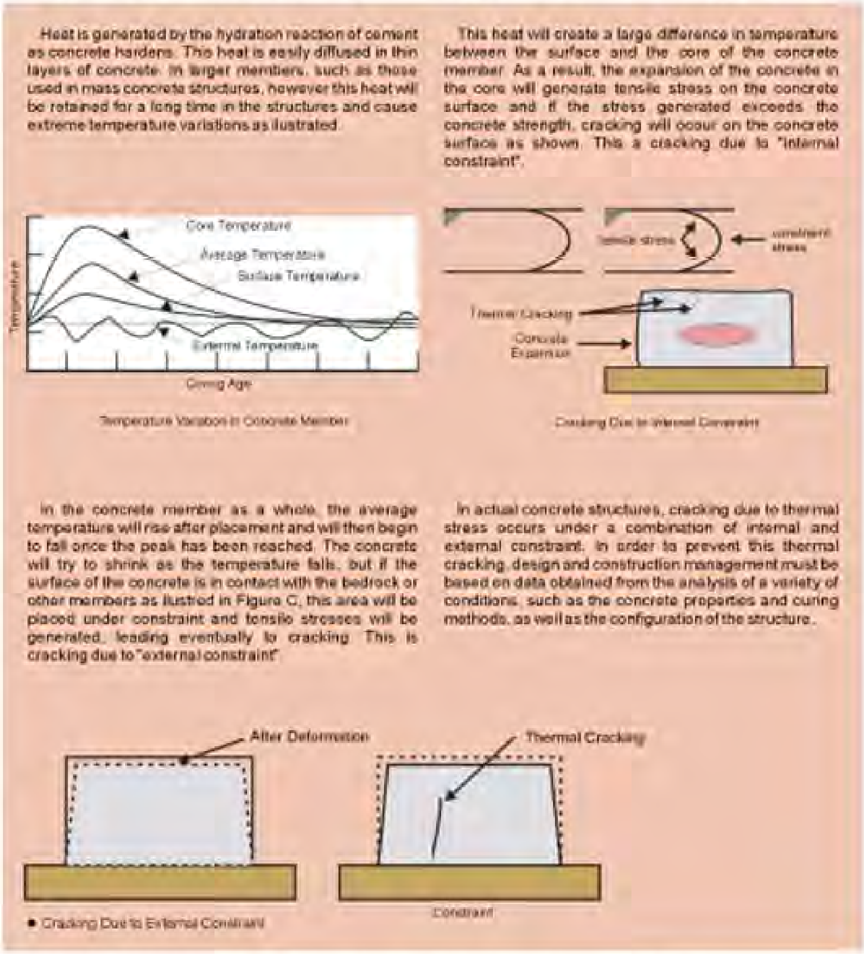


Figure 4.52 Temperature variation and cracking occurrences.

4.6 Contraction Joints

4.6.1 Transversal Contraction Joints

The efficacy of transverse contraction joints in preventing structural cracks in CVC gravity dams of various sizes has long been proven. However, for RCC dams, some designers have been reluctant to accept the necessity of full transverse contraction joints at 15-20m spacing, mainly because joint construction could slow down RCC placement and increase cost. Instead, partial measures, such as crack inducers or joints in the upstream CVC were adopted. The main functions of contraction joint spacing are to control the effects of foundation and abutment restraint, to prevent relative displacements due to some relevant topography and to allow contraction of the concrete to occur without cracking in the dam. In some RCC dams, a few full transverse contraction joints were provided only at locations where differential foundation settlement was expected or where there were pronounced irregularities in the foundation profile. Another line of reasoning would accept cracking in a dam storing water occasionally or for short duration.

The main problems caused by cracking in RCC and other gravity dams are appearance, durability and leakage control. The spacing of cracks extending the full height and thickness of a dam, caused by foundation restraint, is directly related to temperature change, the tensile strength and stress coefficient of the concrete during the period it occurred and for how long it lasted.

Thermal changes throughout a dam are influenced by many factors but are mainly affected by environmental conditions, construction sequence and size and shape of the dam. The rate of thermal change is significantly greater at the surfaces. Surface cracking is generally caused by internal restraint rather than foundation restraint and is therefore limited in depth. Foundation restraint can contribute to surface cracking in a dam built without contraction joints; however, the propagation of surface cracks relieves the internal restraint condition, thus requiring a continuing decrease in volume for further propagation.

Engineers in several countries have conducted studies to determine the optimum spacing of transverse contraction joints to prevent cracking in RCC dams and in theoretical conclusions verified against the experience of completed dams.

Figure 4.45 lists a summary of the current practice and experience regarding crack prevention and contraction joints in various RCC dams, and countries, with transverse contraction joints which have been completed. It is not proposed to provide full contraction joints in future dams. In five relatively high RCC gravity dams, scheduled for construction in the near future, Miel-I (185m), Miel-II (141m) and Porce II (118m) in Colombia, Platanovryssi (95m) in Greece and Pangue (115m) in Chile, contraction joints are to be provided selectively to respond to changes in foundation conditions and to form the spillway blocks.

Up to the end of 1987, nearly 70% of the completed RCC dams did not contain contraction joints. During the period between 1988 and 1989 the percentage had dropped to 35%, and in the 1990's only 10% of RCC dams did not have joints in one form or another.

Spacing of joints is 60m in Miel I and II, 40m in Porce II and about 50m in Pangue and Platanovryssi dams. It is also pertinent to note that thermal stress analyses for Upper Stillwater[4.41] dam had concluded that a joint spacing of 60m would be adequate to prevent cracking. Actually, cracking occurred at closer spacing than that anticipated.

The provision of full transverse contraction joints at closer spacing of 15-20m, can be considered prudent for high, long and large RCC gravity dams. The Japanese experience in building the highest RCC dams and that at other dams such as Quail Creek[4.42], USA, has shown that the joints can be cut without slowing down construction and at a nominal additional cost. Large Brazilian RCC dams were designed with contraction joints spaced at 15-25m. Such contraction joints also provide safety against cracking when ambient temperatures may not be ideal at the time of RCC placement, or when cement content may have to be increased to compensate for poorer than specified quality of pozzolanic materials. This in turn can avoid delays on the completion of the dam, while ensuring a better quality crack-free RCC structure.

Parallel to the construction of jointless RCC dams during the past 12 years, several RCD gravity dams were built in Japan with transverse contraction joints. The RCD-Japanese-RCC type is considered a conservative version of the standard RCC dam. Since no completed RCD dam has suffered cracking, the additional cost of providing contraction joints, if any is considered justified, particularly for high RCC gravity dams.

The three RCC arch dams have different crest lengths. The crest length of Xibin dam is only 93m and no joints were used. The Puding arch dam has a crest length of 195.7m and the topographic condition required several joints; there are three joints dividing the dam into 4 blocks, of 30, 55, 80 and 31m. The joints are introduced and measured by joint gages. In the case of the 75-m high Puding dam (in China), the thick-arch RCC dam was also designed to be built during a cooler season and so only three groutable contraction joints, about 90m apart, were provided. It is reported that none of the joints has opened.

Three general forms of contraction joint, as shown in Chapter 8, have been used in RCC dams:

- Post-formed contraction joints through the whole dam created by vibrating crack inducers into the RCC, either after spreading or after compaction - this is the most common approach.
- Formed contraction joints against formwork, in a similar way to traditional concrete dams.
- Induced joints, in which only part of the joint is formed, usually near the faces, allowing thermal movement to create the rest of the joint, if so required.

4.6.2 Longitudinal Contraction Joints

Before 1965, most CVC gravity dams ◄150m in height were built with longitudinal contraction joints. The world's highest CVC gravity dams, Grande Dixence, Switzerland (285m) and Bhakra, India (226m) have two or more longitudinal contraction joints. The main purpose of the longitudinal joints was to prevent longitudinal cracks. These joints had to be grouted before filling the reservoir and after the concrete had been slowly cooled down to the average ambient temperature, by circulating cold water through embedded pipes placed on top of each lift. Longitudinal contraction joints were also provided in several high thick arch dams. Performance of these high dams over 40-50 years has proven the efficacy of longitudinal contraction joints in preventing longitudinal cracks and facilitating essentially monolithic behaviour of the structures as anticipated in design.

Since forming of longitudinal joints and their treatment increase construction costs, during the last 25 years several high CVC gravity dams were built without longitudinal contraction joints. Noteworthy examples are: Dworshak, USA (219m), Revelstoke, Canada (175m) and Piedra del Aguila, Argentina (172m). The designs of these dams incorporated several features to eliminate the risk of longitudinal cracking, such as the use of relatively lean concrete mixes with low cement and adequate pozzolanic material content, low concrete placement temperatures and post-cooling in the lower part of the dam. The criteria for Revelstoke dam are typical: it is assumed that if the temperature gradient of the concrete near the foundation rock did not exceed 21°C, then tensile strains that would develop as the concrete cooled would not be high enough to cause cracking. Concrete mix was designed following the concept of crack-free mass concrete for Dworshak and Libby dams [4.43]. However, Revelstoke, Dworshak and Libby dams suffered some unanticipated structural cracking before, as well as after the filling of the reservoir [4.44]. In Revelstoke and Libby dams, some of the cracks were longitudinal.

Longitudinal cracks generally begin at the foundation at the central part of the block and progress upward, and can also occur in a new lift placed over older concrete. The upper part of the old concrete may have cooled considerably and with the temperature of the new concrete peaking about a week after its placement, a large temperature gradient at the joint would induce longitudinal cracks in the new layer.

Since longitudinal cracks progress upward slowly, if subsequent lifts of concrete are placed rapidly at short intervals, they may not be noticed during construction. Such cracks are generally detected in transverse galleries or unlined outlet conduits in the lower portions of the dam; sometimes several years after completion of the dam and filling of the reservoir. Longitudinal cracks may also reach the top of a block where concreting had been interrupted for a whole cold season, or appear on the exposed transverse face of a block.

Longitudinal cracks can endanger the stability of a dam, particularly if they show a tendency to progress as the reservoir pressure is applied, or if they connect with transverse cracks or joints, or are penetrated by water under high pressure. Another consideration is the risk of extension of such cracks during an earthquake. Therefore, prevention of longitudinal cracking in high gravity dams, whether RCC or CVC, is as imperative as the control of transverse cracks.

The experience of high CVC gravity dams discussed before, where transverse or longitudinal cracks occurred despite all the preventive design provisions, indicates that the risk of longitudinal cracks occurring in high RCC dams cannot be ignored. Such advantages of RCC as no-slump concrete and lower hydration heat because of lower cement content, are offset by the lack of post-cooling, which was provided in lower parts of Dworshak and Revelstoke dams. Although no longitudinal cracking of RCC dams has been reported so far, it should not be a reason for complacency; because of the lack of transverse galleries and rapid placement of RCC, such cracks cannot be visually detected during construction, may not surface for several years, may remain hidden and may connect with transverse cracks.

The risk of longitudinal cracking in RCC gravity dams increases with height. For a 200-m high dam with vertical upstream slope and 0.8(H):1.0(V) downstream slope, the lower layers would be 160m wide. Considering that in RCC dams contraction joints at 15-20m intervals in the axial direction are considered necessary to reduce the tensile strains near the foundations, why would that not be not be valid in the transverse direction? Another risk factor is the concrete mix, if it is necessary to increase the cement content near the foundations to obtain higher strength; the need for a richer mix increases with the dam height.

Since post-cooling for grouting vertical longitudinal contraction joints in RCC dams would be impractical and costly, an alternative would be to provide an inclined longitudinal construction joint. Essentially, the RCC dam would be built in two stages. The concept of the two-stage construction of a 200-m high RCC gravity dam is shown in Figure 4.55. The lower 100m of the dam would be built in two monoliths, A and B; A being built first, with B following it a few weeks later, as may be convenient for construction, and to ensure that the temperature differential between concrete in the two monoliths is not excessive when second stage concrete is placed.

Two practical alternatives are suggested:

I. Monolith A is on the upstream side, with the construction joint parallel to the downstream slope of the dam. Its main advantage is that **Monolith A** can be completed rapidly to a height above the upstream cofferdam, providing additional safety against flooding if the cofferdam is overtopped. It may also be used for earlier start of storage in the reservoir. Another positive feature is that the weight of **Monolith B** would exert compressive pressure on the joint, closing it and improving its shear strength and would offset the flexural tensile stress component when the reservoir pressure is applied. A possible disadvantage of this arrangement is that tensile concentrations may occur at the interface with **Monolith B** at the top of **Monolith A**, which may require steel reinforcement in that zone to prevent cracking.

II. Monolith A forms the downstream part of the dam and has an upstream slope of 0.40(H):1.0(V). Upstream inclination of the construction joint is necessary to take advantage of the weight of **Monolith B** and the component of the principal stress normal to the joint. The main disadvantages of this alternative are:

a) the volume of concrete in **Monolith A** is 55% more than **Monolith A** of Alternative I;

b) cofferdam protection will be required for building the second stage and

c) early storage of water in the reservoir would not be possible.

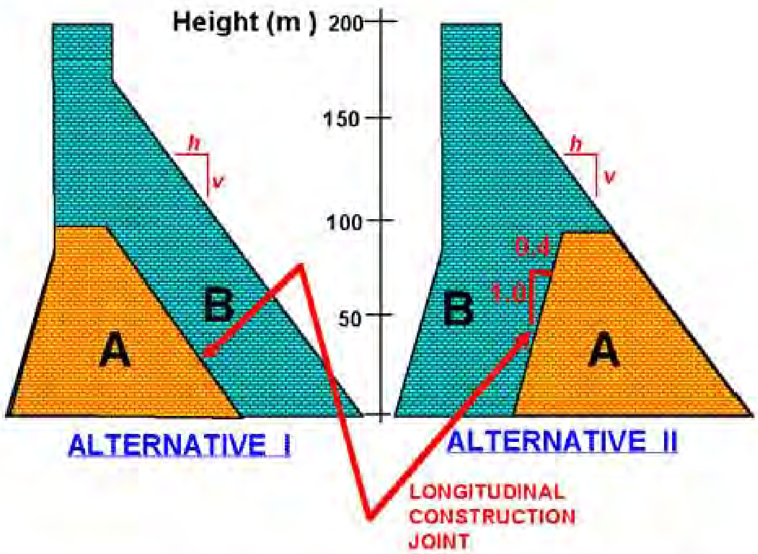


Figure 4.53 Two-stage construction of a 200-m high RCC gravity dam [4.02].

Alternative I is preferable and more suitable than Alternative II from the viewpoints of construction convenience, early storage of water and overall economy. Alternative I is similar in concept to the two-stage construction of the Guri dam, Venezuela, where the 110-m high first stage was built in 1968 and the second stage raised to a maximum height of 162m fourteen years later. The reservoir was full when the second stage was added. Both stages of the dam were built of conventional mass concrete.

The sloping construction joint could be stepped or formed with a plain surface. Before placing the second stage (**Monolith B**) RCC, the joint surface would be thoroughly cleaned by high-pressure hydroblasting. A layer of CVC concrete, about 0.3m wide, would be placed against the joint, as each layer of RCC is placed and compacted. Tests at Ross [4.16] dam, USA, Guri and other dams have shown that adequate bonding can be obtained between conventional old and new concrete by hydroblasting or equivalent treatment and that key or steel dowels are not required. Two-stage construction with inclined construction joints was also adopted for some blocks of Capanda [4.45] dam in Angola.

4.7 Construction Joints Between Layers

4.7.1 General

Current experience indicates that the bond, shear and tensile strengths of typical untreated construction joints between layers are considerably less than that of the RCC itself. This is particularly true when no treatment - bedding mix - concrete or mortar layer is used on the joint surface and the time elapsed between placement of layers exceeds 8 hours [4.16]. On the other hand, in a CVC gravity dam, where construction joints receive such treatment as hydroblasting, sand blasting or green cutting, and without a new mortar layer, the shear, bond and tensile strengths of the joint are almost the same as that of the mass concrete. Special treatment of construction joint surface in CVC is required to remove laitance, contaminants and inferior material not compatible with cement, and to clean the surface of exposed aggregates and the already set mortar. Laitance and excess water may not seem a problem with the no-slump, low cement content RCC. But the paucity of mortar on the compacted construction joint surface would result in low and unevenly distributed bond, which is accomplished by cement grain and is not due to either the roughness of the surface or intimacy of surface contact between aggregates or hardened concrete [4.16], and the construction joints would become planes of relative weakness in the dam.

Low shear and bond strengths at a construction joint also mean lower effective modulus in shear along the joint. The relatively weaker joints make the concrete mass laminated or anisotropic and elastically heterogeneous; it would have a different type of response to sustained, as well as dynamic, loads than a truly monolithic structure. Ideally, to ensure elastic and monolithic response of the dam to all types of loads in all directions, including shearing forces, the bond, shear and tensile strengths of the construction joint should be equivalent to that of the concrete. A joint substantially weaker in shear than the concrete, would alter the deformations and magnitude and distribution of normal and shear stresses in the concrete and, particularly, at the joint. In high RCC gravity dams, the resulting shear and tensile stresses may exceed the permissible limits. Thus, sufficient bond and shear strength at the horizontal construction joints is necessary not only for adequate safety against shearing-sliding, but also against overstressing, cracking and subsequent deterioration of concrete, for both RCC and CVC gravity dams.

Typical distribution of horizontal shear stress along a construction joint or at a horizontal plane in mass concrete of a CVC dam can be seen in Figure 4.54. In an RCC gravity dam, shear stress distribution at a construction joint could be entirely different. If a bedding mix is used only near the upstream face, bond strength in that part of the joint would be nearly equal to that of the concrete. If the rest of the joint surface is untreated and it has very low or no bonding, the distribution of shear stress would be altered with "concentrations" occurring in the upstream part of the joint, as shown in Figure 4.55. On the other hand, if the bond in the upstream portion is much lower than along the rest of the joint and tension in the upstream portion opens it, critical shear stresses would build up in the downstream portion with a risk of ultimate shear failure commencing there.

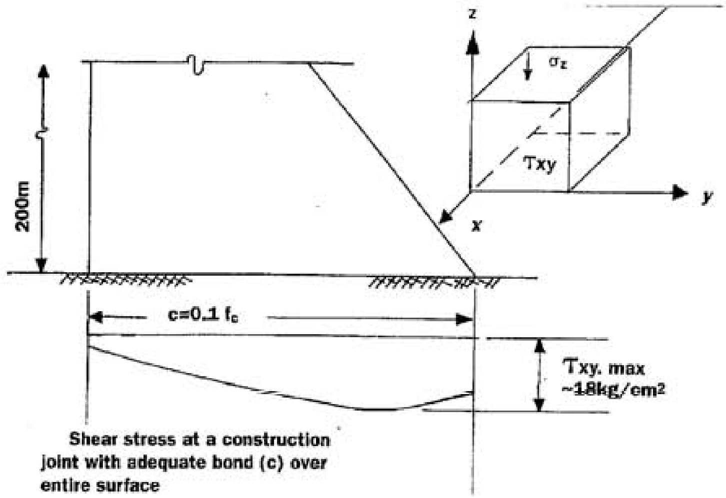


Figure 4.54 Shear stress at a construction joint with adequate bond (C=0.1fc) over entire surface [4.02].

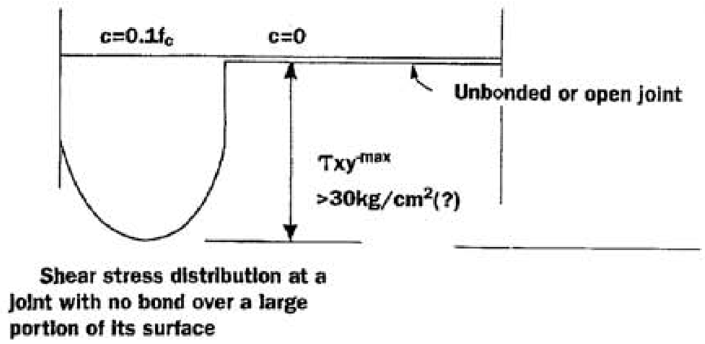


Figure 4.55 Shear stress at a construction joint with no bond (C=0) over a large portion of its surface [4.02].

The effective modulus of elasticity in shear would vary similar to the variation of bond along a construction joint. For a 200-m high CVC gravity dam, the maximum horizontal shear stresses would be about 1.8 MPa. If the average bond strength of a joint is 60% of that of the RCC, or that of a joint with a bedding mix over its entire surface, then the maximum shear stresses might be 50% higher than in a comparable CVC gravity dam. If the maximum shear stress exceeds the effective bond strength of a construction joint, then that joint could be the weakest feature in the structure where shear failure might start. For high RCC gravity dams such a situation would pose a high risk.

To better appreciate the impact of the above discussed, i.e., the "lamination effect" on the structural behavior of the dam, data on two 200m high RCC and CVC gravity dams with identical cross-sections are compared. Assuming that RCC is placed in 0.30m layers and conventional concrete in 2.5m lifts, the total area of construction joints in the RCC dam would be more than eight times that in the CVC dam. Because of the fast rate of RCC placement, it is likely that bond and shear strength will vary considerably over the joint surface, and with values higher than 50% of that of concrete over perhaps 30% of the area. For a 100-m length of the dam, it represents a joint surface area of about $1.5 \times 10^6 m^2$ which may have deficient shear strength, and consequently lower safety margins against shear failure, than considered acceptable for a high gravity dam. This deficiency and the corresponding risk increases with the height and size of the RCC gravity dam.

Horizontal construction joints may be either planned or unplanned. When a placement layer has not been covered by the time it reaches initial set, a cold joint is formed between the two layers. The time required for a cold joint to form depends on climatic conditions (temperature, sunlight, wind, moisture), the amount of cementitious material in the mixture, the type and set time characteristics of the cement, and the use of admixtures.

Treatment of horizontal lift or construction joints differs from that of conventionally placed CVC mass concrete in that there is no surface water gain during set of the concrete. Thus, there is no weak laitance film at the surface. Surface water gain (bleeding) is the result of subsidence during set when the excess water separates from the mixture and is displaced to the surface by the heavier materials. Bleeding does not occur in properly proportioned RCC. However, in full consolidation of RCC, paste may be brought to the surface. If dirt, mud or other foreign elements have contaminated the surface, the prescribed treatment should require removal of the foreign matter. If the surface has been allowed to dry completely and/or a cold joint has developed, it should be thoroughly cleaned and may require a special bedding mixture if bonding to the subsequent layer is desired.

The extent of bedding depends on the degree of watertightness required and the shear resistance needed for stability at that location.

It should also be noted, however, that RCC or CVC dams construction need be based on sliding analysis.

Various bedding mixtures have been used, studied, and evaluated. There is no agreement on what is best, probably because different bedding mixtures are suited to different construction techniques, RCC mixture proportions, and environments. Bedding is necessary to provide bond (tensile and shear) and improved watertightness after a cold joint develops. Marginal safety factors against sliding that sometimes exist in the upper reaches of a dam may be improved when properly designed and applied bedding mixtures are used.

Since the working dam surface is wide and flat, it is a standard practice in Japan, to green-cut the joints with motor sweepers, etc., and then apply a layer of mortar.

The bedding thickness has the same dimension as the maximum size aggregate particle in the mixture. Cores have consistently shown that this procedure thoroughly bonds the RCC layers. The bedding mixture blends into the RCC and does not leave a layer of mortar or bedding that is clearly defined.

The RCC layer is spread over the bedding while the bedding retains its slump or workability, and the RCC is then compacted into the bedding. The results from this procedure can be checked by test.

For final design, values for tensile and shear strength parameters at lift joints can be determined in several ways (as shown in Chapter 7):

(a) In-situ direct shear tests can be performed at various confining loads on blocks cut into full-scale trials made with full production equipment and site personnel.

(b) Drilled cores can be removed from RCC full-scale trials and tested in shear and direct tension.

(c) Joint shear tests can be performed on a series of large blocks of the total RCC mixture cut from test placements compacted with pedestrian rollers under laboratory conditions. Various joint and surface conditions of the actual mixture for the project can be evaluated and used to confirm or modify the design and construction criteria.

(d) Individual specimens can be compacted and tested in the laboratory. Nevertheless for these tests to be valid the mixture should be of a consistency, and the aggregate of a size, that permits representative individual samples to be made. It is very difficult to simulate joint conditions in the laboratory.

4.7.2 Lift Thickness

The layer thickness design depends primarily on the construction equipment available and the consistency of the RCC mixture. The lift thickness is defined as the thickness of RCC that is compacted at one time, although it may have been spread in a number of layers and pre-consolidated by the treads of the spreading dozer. In determining a lift thickness, the goal is to provide a thickness that can be compacted to the required density uniformly throughout the layer with readily available equipment considering the consistency of the RCC mixture.

The thickness of RCC lifts has ranged as shown in Figure 4.55, from 0.23 m, for overtopping protection for the Brownwood Country Club Dam in Texas, to 0.75 m at Tamagawa Dam in Japan. The thin lift was chosen for the Brownwood Dam rehabilitation project because only 1070m^3 of RCC was required and the designer figured this thickness could be easily placed by a small contractor using available spreading and compaction equipment. The thicker lifts at Tamagawa are typical of the Japanese RCD method wherein a wetter consistency mix is spread in three or more layers and then compacted. The 0.75m lifts at Tamagawa were used for the upper portion of the dam while 0.50m lifts were used for the lower portion adjacent to the foundation rock. The most typical RCC layer thickness to date has been 0.30m.

Thicker lifts are desirable because there are fewer lift lines forming potential seepage paths and planes of shear weakness. Caution should be applied in selecting lifts greater than 0.30 m, however, particularly for dams built of lean, drier-consistency mixes. Thicker lifts put on in a single layer are more difficult to spread and compact and take longer to place than thin lifts. Construction complexity creates potential for voids at the bottom of the lift and reduced bonding. If thicker lifts are considered, they should be well investigated in a test section prior to the start of construction.

Design details for many RCC dams are independent of the lift thickness. However, if facing elements or precast concrete panels are used to form the exterior faces or a stepped spillway is incorporated into the design, the height of the elements, panels, or steps should be an even multiple of the lift thickness, mainly to simplify construction. In areas where handheld compactors or small rollers are necessary due to space limitations, the lift thickness should be reduced to ensure adequate compaction.

RCC is generally placed in horizontal lifts that are sloped slightly to allow for drainage of rainwater. Middle Fork Dam had a 2% downward slope toward the upstream face. An upstream to downstream slope of 2%, as used in Capanda Dam, may work better in removing rainwater and keeping it from collecting behind the critical upstream facing system. An upstream dip, however, improves the shear friction factor between successive lifts.

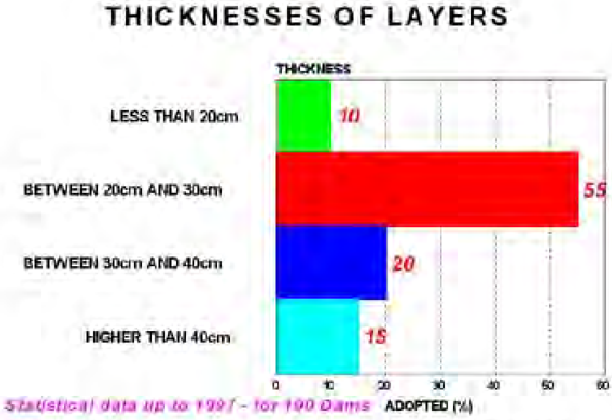


Figure 4.56 Statistical data on RCC lift thickness.

4.7.3 Bonding Successive layers

Because RCC dams are built in a series of compacted lifts, bonding of the successive lifts is important both from a stability and performance standpoint. Poorly bonded lifts have lower shear resistance due to low or no cohesion at the interface, have less tensile resistance for seismic loading, and offer a path for horizontal seepage. Therefore, the designer should consider methods for improving or assuring adequate bond between successive lifts where needed. Bonding methods fall into - two basic categories:

I. RCC to RCC bonding, and;
II. Bonding RCC with bedding mixes.

4.7.3.1 RCC to RCC

Research on the factors affecting the bond between successive lifts of RCC has been going on in the field and in the laboratory since 1970. Cores drilled from RCC dams correlated with construction records have provided additional valuable information.

The basic factors affecting bonding have been identified, but have not been completely quantified. Whether there is some bond or no bond between lifts is probably more important than the degree of bond or shear strength. The principal factors that affect bonding are

1. Condition of the lower RCC lift surface;
2. Time delay between placement of RCC lifts;
3. Consistency of the covering RCC;
4. Compaction or consolidation of the covering RCC.

The lower RCC surface must be kept continuously moist but without ponding water to assure bond. Excessive surface moisture is detrimental to bond development, but drying of the surface may lead to no bond. All loose and dry material should be removed from the RCC prior to placement of the next lift.

If a compacted RCC lift is covered with the next lift before the lower lift reaches initial set, satisfactory bond will usually develop. With increased time delay, a cold joint begins to develop with a resulting loss in bond strength. Many factors, such as RCC mixture proportions, ambient temperature and sunlight and surface moisture conditions, affect the time at which the cold joint begins to develop. Set delayers, high pozzolanic material content mixes, low temperatures and moist curing extend the life of the lower RCC lift.

Bond between lifts improves as the volume of paste increases for the covering RCC as long as the lower compacted lift is still alive and moist. This applies to all RCC mixes. Since the water content is basically constant for a certain mix design approach, bond improves with mixes containing more cement and pozzolanic material. Once the lower lift has hardened, bond depends on the adhesion of the covering-mix paste to the pore-structure of the lower lift. Compaction of the covering RCC is a factor in achieving bond, at least to the extent that high compaction indicates a reduction of voids at the lift interface. Poorly compacted or segregated RCC mixtures produce greater voids at the lift line and, therefore, less potential area for achieving bond.

4.7.3.2 RCC and Bedding Mix

Satisfactory bond at horizontal lifts can be assured with the use of a bedding mix of either mortar or concrete. A mortar bedding mix is designed to fill the surface voids in both the compacted lift below and the covering layer above as well as to "glue" the two RCC layers together. A mortar bedding mix over the entire surface of each lift is typical of the Japanese RCC method (RCD) and was also used for some other dams.

Biaxial shear tests of cores drilled from the Elk Creek test section showed that the mortar bedding significantly increased the average shear strength as compared to areas where no mortar was applied. The test program also indicated higher shear strength when there was no cleaning of the lift as compared to lifts that were washed prior to the application of the mortar. Wash water remaining on the lift surface may have increased the water/cement ratio, thereby weakening the bedding mortar mix. If correctly applied, concrete bedding mixes assure positive bond and seepage control for the area over which they are applied.

4.7.3.3 RCC and Rock

RCC and rock bonding can be analyzed as a construction joint surface, adding that the irregularities on the rock foundation can require a CVC application.

4.7.4 Lift Joints

Large-scale field and laboratory tests have been made for several RCC dams to assess the effectiveness of various types of treatment of construction joints [4.16; 4.46]. The results for Capanda [4.45; 4.47] and Jordão dam [4.48], in Figure 4.57 (summarized from Chapter 7), show great improvement in shear strength when a bedding mix is placed on the joint.

Significant conclusions drawn from tests results at several relevant dams are:

· Without a layer of bedding mix, the effective tensile and shear strengths at the joint would be 50% - 60% of that of RCC, depending on the time interval between layers.

· Use of a layer of bedding mix immediately before placing the new RCC layer improved the bond of the joint in about 40%, to almost that of RCC itself, regardless of the time interval between layers.

· Cleanup of joint surface with low-pressure (about 7 kgf/cm^2) air-water jet before placement of the new RCC layer, increased the bond strength in 5 - 10%.

An additional benefit of using a bedding mix over the full area of the joint is the improvement in its impermeability, offsetting the need for a thicker upstream zone of CVC, provided in some completed RCC dams [4.49].

The Capanda [4.45; 4.47] tests showed also that with bedding mix, the shear strength of the joints was considerably higher than that of the dam-foundation contact. The foundations at Capanda dam are predominantly meta-sandstone. The shear strength of the construction joints without bedding mix was about the same as that of the dam-foundation contact.

Considering the above, to obtain adequate monolithicalty and shearing resistance along construction joints, for high RCC gravity dams, the following criteria can be suggested:

· Adequate bond and shear strength over the surface of each construction joint is essential for monolithic action of the dam block. In areas of high seismicity, the construction joints should also have adequate tensile strength, particularly those upstream.

· Before placing a new layer of RCC, the entire surface of the old compacted layer should be cleaned with low pressure air-water jet.

· Regardless of the interval between placement of RCC layers, place a thin layer of bedding mix over the surface of the joint, immediately before placing the new layer of concrete.

As discussed above, the key element of concern in the stability analysis of RCC dams is the tensile and shear strength at the horizontal lift joints. Because lift thickness is generally 30-40cm there are four to eight times as many joints in an RCC dam as there would be in a CVC concrete dam with 2.5 to 3.0 m lifts of CVC concrete. It is extremely important therefore, that each of these lift joints have sufficient bond or tensile strength to support tensile stresses generated by the design. Over the years, laboratory and field experience have focused growing attention on achieving cohesion at these lift joints. Methods used alone or in combination have included:

⇒ Clean-up and preparation of the lift surface to be covered;
⇒ Controlling joint maturity (degree-hours) between placement of successive lifts of RCC;
⇒ Prolonging initial set by use of a retarding admixture or pozzolanic material;
⇒ Using high cementitious RCC mixes;
⇒ Controlling segregation of coarse aggregate at the base of the covering RCC lift;
⇒ Applying bedding concrete or mortar between lifts.

The single most effective method to guarantee good bond between lifts is the application of bedding concrete or mortar between lifts. For very high RCC dams consideration should be given to using a combination of all of the above techniques to provide lift joint strength reducing its permeability.

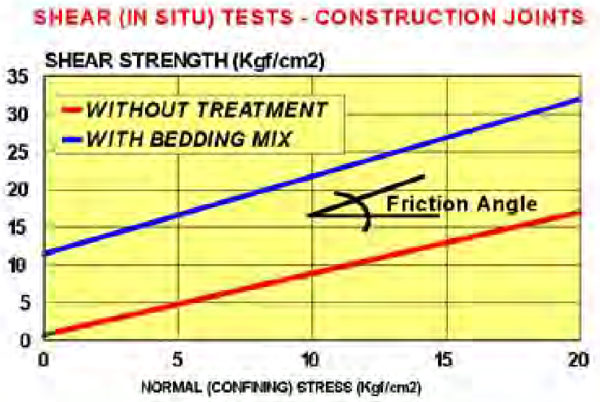


Figure 4.57 Capanda RCC shear "in situ" test results.

4.8 Galleries and Adits

4.8.1 General

Galleries and adits have traditionally been incorporated in conventional concrete dams to provide space for:

I. collection of drainage;
II. drilling both drain and grout holes into the foundation;
III. inspecting and monitoring behavior of the dam;
IV. carrying out remedial work;
V. access and space for mechanical and electrical equipment for operation of spillway gates and outlet works;
VI. access for electrical power or control cables, and;
VII. access and routes.

Design requirements for RCC galleries and adits are commensurate with those of CVC dams. The paradox is that the inclusion of galleries in RCC dams interferes with clean, efficient placement and compaction of RCC. For that reason, designers of RCC dams would like to omit galleries and adits, especially in low dams where the need for them may be questionable.

Galleries provide the only immediate interior access during operation for inspection, for safety, and to clean or redrill drains to maintain stability or injection holes, as designed. Designers of RCC dams should evaluate the advantages and disadvantages of galleries and consider other options. Some of the more innovative gallery construction methods developed for RCC dams are described in Chapter 8.

Whether a gallery is required or not depends primarily on the design requirements for the dam. While most gallery functions can be accommodated elsewhere, a gallery may be important in providing a space to drill and reestablish drain holes or injection holes into the foundation and to receive and collect drainage from holes drilled from above.

The purpose of drain holes in the foundation is to reduce uplift pressures, which in turn affect the shear resistance on any horizontal plane due to a change in the normal stress. The need for a gallery can be greatly reduced if foundation drains are eliminated and the dam is designed for full uplift pressure.

The location of a gallery is usually a trade-off between functional requirements and construction ease. Where possible, the gallery should be at a single level and as low in the dam as possible. The gallery may end where uplift pressure reduction is no longer required, such as close to the abutments.

The equipment widths should be considered in deciding on a minimum width: the gallery should be as small as possible, but its dimensions must permit access of the equipment that will work inside. Structural considerations will determine if and how much reinforcing is needed in the RCC above the gallery. A gutter is generally provided along the upstream gallery face to drain seepage flow and to support flow-measuring weirs.

4.8.2 Criteria and Comparison

The need for inspection galleries and drainage in large RCC dams cannot be denied. However, in small dams- less than 40m high- their need is most controversial, especially regarding construction.

From project conception and construction all the way to dam operation, the inclusion of a gallery in higher zones is advantageous and the few problems related to its execution are insignificant if compared to the potential benefits that it produces.

Figure 4.58 illustrates the basic sections for comparing advantages and disadvantages of the drainage system in dams of small height (less than 40m).

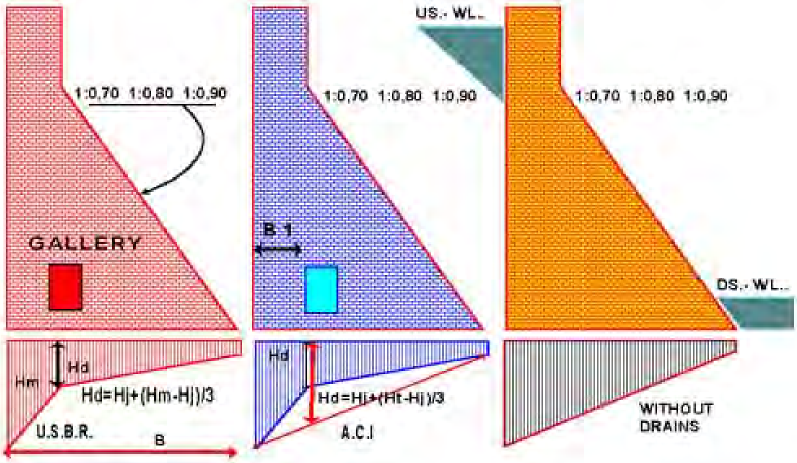


Figure 4.58 Typical sections of dams with and without drainage gallery [4.50].

For the evaluation the following conditions are assumed:

- Transversal section with vertical upstream face and downstream slope (0.7H:1.0V); (0.8:1.0); (0.9:1.0);
- Gallery with dimensions of 2.3m (base) and 2.6m (height), with a drainage curtain locatedat 0.5m to 9.0m from the upstream face;
- Width of the dam crest: 4m;
- Variable heights of 4m, 6m, 8m and from 10m to 40m, every 5m;
- Specific gravity of RCC equivalent to 2.45 t/m^3.

In the absence of drains, the consideration of the uplift pressure effect is analyzed by means of a linear diagram between the values of hydrostatic pressure upstream and downstream, according to the scheme in Figure 4.58.

When the action of the drains is considered, the uplift pressures diagram on the dam surface in contact with the foundation material is plotted according to different criteria, the USBR (United States Bureau of Reclamation) [4.07;4.08] being one of the most used, as also shown in Figure 4.58.

Another criterion used is the one suggested by the ACI (American Concrete Institute), in Committee 207 - "Roller Compacted Mass Concrete" [4.17], also mentioned in Figure 4.58. This criterion takes into account the position of the drainage line when determining the uplift pressures diagram, unlike the USBR criterion.

It should be stressed that the USBR criterion additionally states that the distance between the dam face and the gallery wall- displayed as B1 in Figure 4.58- is 7.5% of the height of the hydrostatic column or, at least 3m. This positioning, however, is not taken into account in the uplift pressure analysis.

On the other hand, the ACI criterion includes the positioning of the gallery in the calculation of the uplift pressure.

The construction of galleries in RCC gravity dams with height under 40m apparently generates difficulties during construction. However, these small height dams normally do not have an instrumentation system for monitoring during construction and operation. In this case, the galleries could be a direct access for visual evaluation of the structure. Besides, they allow remedial actions to be taken in a clear and objective way.

By calculating the uplift pressures acting in the three cases mentioned in Figure (4.58), the following comparisons can be done.

As observed in Figure 4.59, including the gallery provides weight reduction for small height dam. On the other hand, the use of the drainage system, admitted by USBR, allows a substantial reduction in uplift pressure, as can be seen in Figure 4.60.

Figure 4.61 shows that applying the ACI criterion and admitting a drainage location determined by the USBR criterion- about 3m from the face- there is a 20% reduction of uplift pressure in dams 8m high and a 8% to 6% in dams 40m high. This comparison does not apply to dams smaller in height, because of the position of the gallery and its dimensions.

Figure 4.62 and 4.63 emphasize the significance of the drainage system in reducing the uplift pressure and weight due to the inclusion of the gallery. By adopting a safety factor of 2.0 applied to the action of uplift pressure, the gallery location provides positive effects (translated as enhanced safety – above 2.0; and decreasing uplift pressure) for dams over 12m high.

It is also observed that, as the drainage system shifts downstream, its advantages decrease: from 30%-25% for a drainage system placed 0.5m from the upstream face and from

25%-15% for a drainage system placed 9.0m from the upstream face. Finally, a drainage system placed 0.5m from the upstream face of a dam with height above 12m shows the same advantages as one placed 9.0m from the upstream face and 18m high.

The positioning of the gallery, in relation to the upstream face, requires this region to be filled with a certain type of concrete.

The incorporation of a gallery together with a drainage system, even in small RCC dams (with height of 10 to 40m) reduces the possibility of building pore-pressure in the dam body.

Not using a gallery may result in the need to build a "step" or "plinth" near the upstream slope toe to be able to drill a grouting-curtain. Costs must be compared keeping in mind that a gallery provides the additional advantage of allowing the grouting curtain and drainage to be executed at any time, even before the filling of the reservoir

The gallery allows a complementary action at any time, even during dam operation. It also allows the evaluation and monitoring of percolation, separating percolation originated from the foundations, contraction joints or from the concrete surface may be clearly depicted.

It allows the water collected in the drainage curtain executed in the dam body to be properly quantified and drived to outside of the dam.

The evaluations conducted lead to the following statements:

- It is advantageous to incorporate the inspection and drainage gallery in dams with height over 10m;
- It is convenient to evaluate the properties (permeability and thermo-volumetric stability) required for the "Concrete Face " when considering the placement of the gallery (see Figure 4.09) ;
- The methods of construction of the gallery simplify the RCC methodology;
- Few occasional execution difficulties that may result from adopting the gallery for small height dams do not offset the potential benefits that it yields, as for instance, being able to run inspections inside the body of the dam for remedial and monitoring actions.

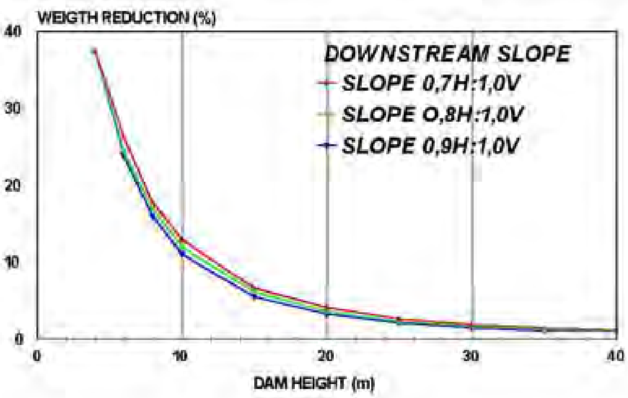


Figure 4.59 Weight reduction due to the inclusion of the gallery (USBR Criterion) [4.50] .

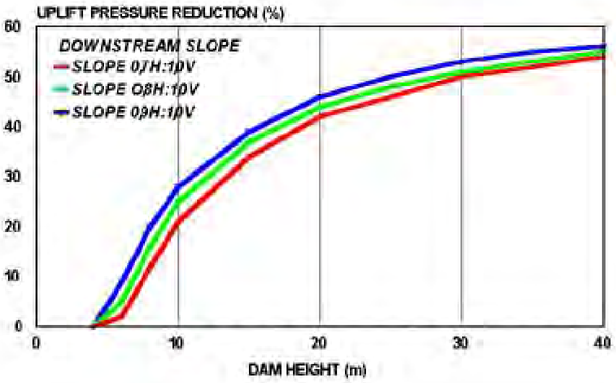


Figure 4.60 Uplift pressure reduction due to the gallery relief action (USBR Criterion) [4.50].

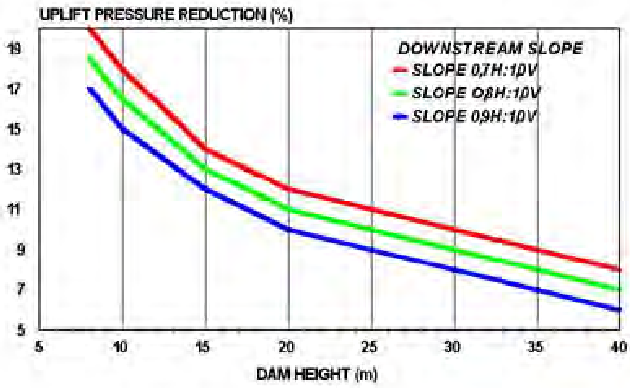


Figure 4.61 Uplift pressure reduction when comparing the ACI Criterion with the USBR Criterion [4.50] .

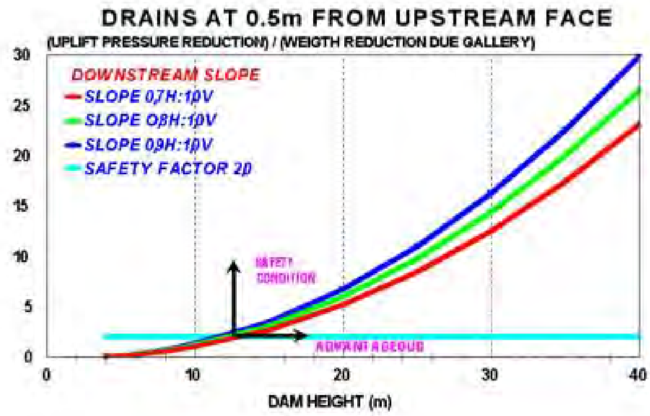


Figure 4.62a Effect of drains position, ACI criterion - 0.5m [4.50].

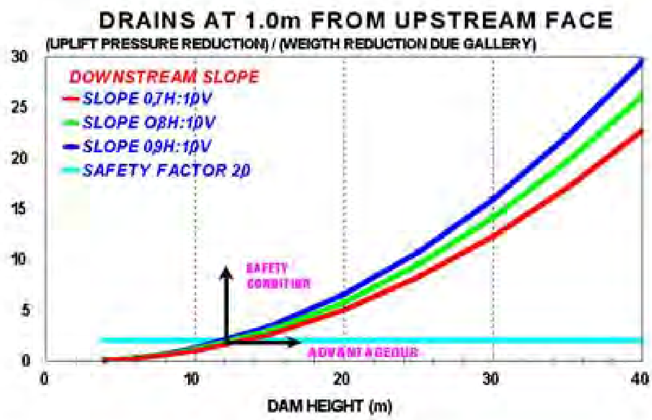


Figure 4.62b Effect of drains position, ACI criterion - 1,0m)[4.50].

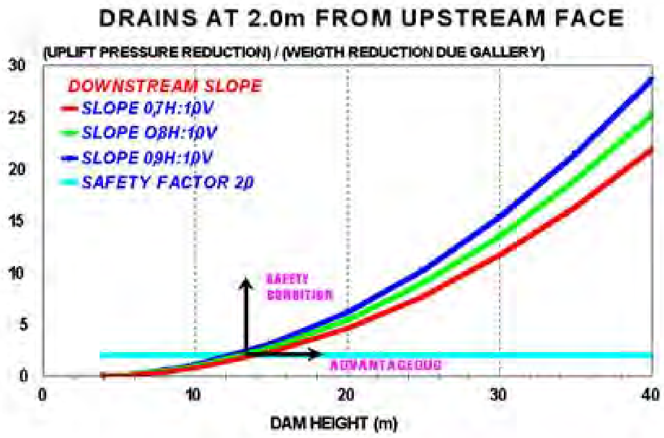


Figure 4.62c Effect of drains position, ACI criterion - 2.0m)[4.50].

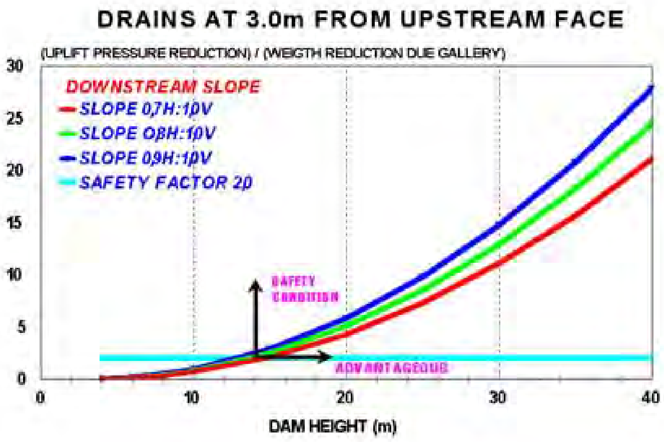


Figure 4.62d Effect of drains position, ACI criterion - 3.0m)[4.50].

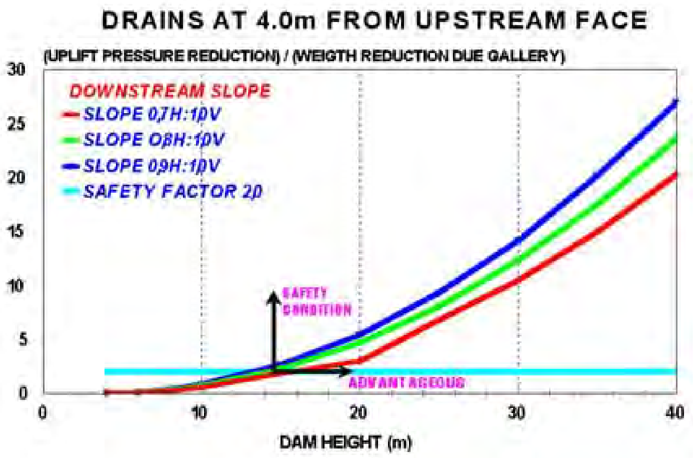


Figure 4.63a Effect of drains position, ACI criterion -4.0m [4.50].

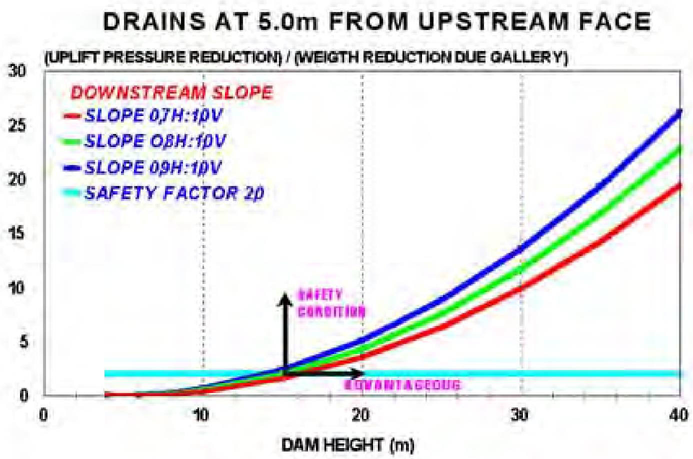


Figure 4.63b Effect of drains position, ACI criterion -5.0m [4.50].

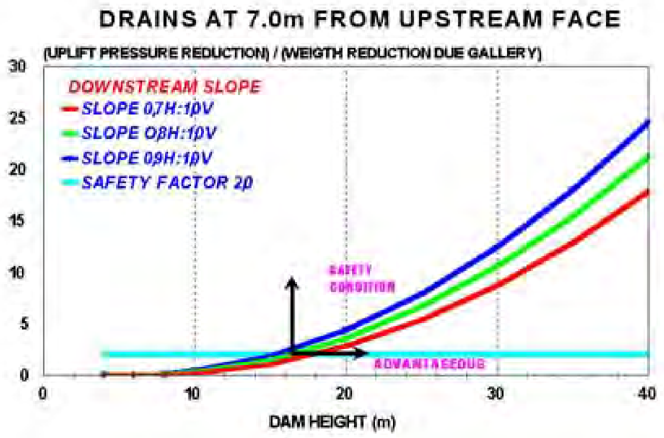


Figure 4.63 Effect of drains position, ACI criterion -7.0m [4.50].

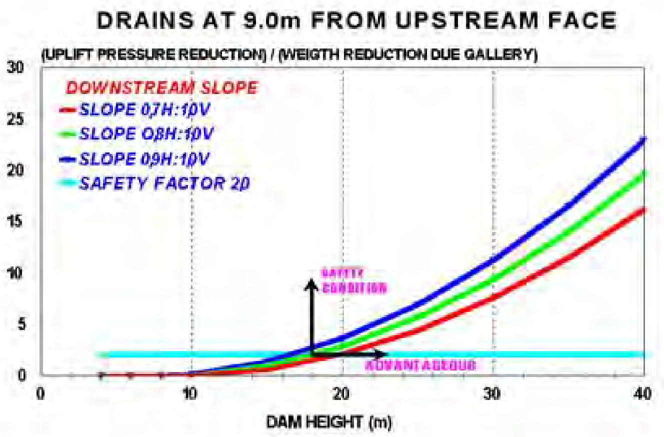


Figure 4.63d Effect of drains position, ACI criterion -9.0m [4.50].

4.9 Seepage control

4.9.1 General

A design according to the concrete dam concept assumes that an RCC dam should have the same appearance, watertightness, and performance of an CVC dam, but cost less. In general, the entire dam is considered as the water barrier.

The various methods chosen for reducing or controlling seepage have produced the greatest variation in design for RCC dams. The basic form of seepage reduction can be divided into two categories:

⇒ those that rely on the entire interior RCC mass for the dam's impermeability, and

⇒ those that rely on an impermeable or relatively impermeable upstream face or membrane as the primary water barrier.

For secondary seepage control, the upstream facing designs may also include partial or full bedding mixes between lifts, and some form of drainage collection system downstream from the face.

4.9.2 Drainage and Seepage control

The durability of a wet concrete dam can be impaired by leaching of minerals, excessive weathering of exposed surfaces and damage by freezing and thawing. Damp concrete is more susceptible to alkali-aggregate reactions than dry concrete. Also, pore pressures in the dam body of both CVC and RCC type dams, can be a destabilizing force similar to hydraulic uplift at construction joints or at the dam-foundation contact.

The coefficient of permeability of RCC dams varies depending on the construction method. This coefficient determines seepage through the dam. Some amount of seepage may be acceptable for flood control dams, which store flood-water temporarily. However, large amounts of seepage could be a major problem for dams used for permanent water storage. Therefore, seepage control is also an important consideration in the design of RCC dams.

Internal drainage systems, namely a curtain of formed or drilled drains near and parallel to the upstream face, discharging into galleries in the dam from which the drainage water can flow out, either by gravity or by pumping, have proven most effective in keeping many large CVC dams dry. The same type of drainage system could be effective in keeping high RCC dams dry and seepage under control, provided that the coefficient of permeability of the RCC used is as low as that of the CVC and a bedding mix is used on construction joints.

In some RCC dams [4.49], the drainage curtain and the galleries are located at a considerable distance downstream of the upstream face. In such dams, a large upstream portion of the dam could become saturated and develop high pore pressures. This is undesirable in high dams because this part of the dam will have either low compression or tension, and would be susceptible to cracking, which combined with hydro pressure in the cracked portion, may affect the stability of the dam.

Before proceeding with the final design of an RCC dam, the designer should have project goals clearly in mind and should be familiar with all aspects of the site. Factors that can affect the general concept used in the design of the dam include the owner's requirements for cost, construction period, appearance, watertightness, operation and maintenance.

Upstream-membrane concept dams tend to be more economical, especially for low to moderate-height dams, than those that follow CVC concrete gravity dam concepts. Depending on design details, however, the cost advantage may be counteracted by disadvantages in appearance, watertightness, and maintenance. In addition, the increased shear or tensile properties of a more a conventional concrete RCC mix may be used to produce a steeper downstream slope and, therefore, less volume in the dam.

The purpose of the dam may also encourage a certain design approach. A conventional concrete concept would be preferable for a complex hydroelectric dam, for example, while the upstream-membrane concept seems more logical for a flood-control dam where watertightness may not be a prime consideration. Dams for water storage or multipurpose reservoirs can be designed in accordance with either concept.

The main concern of the engineering community regarding RCC dams is the perception that "they leak". This is not necessarily true if appropriate measures are provided in the design. Minimizing seepage should be the goal for any well designed dam; for high dams, this becomes even more important because of the high hydrostatic head involved, the potential for internal erosion and the economic value of water lost through seepage. Designers have usually taken one or both of the following approaches to watertightness:

⇒ Design the RCC dam itself to be the primary seepage barrier, or

⇒ Design an upstream facing element that will provide the required permeability without depending on the RCC dam for anything except stability

Designing the RCC in the dam to be the primary seepage barrier starts by designing a low permeability mix. The problem of segregation of coarse aggregate along lift joints not only results in horizons of low shear strength but also high permeability. Permeability of this zone can be reduced by minimizing segregation by limiting MSA of aggregate, and over-sanding the mix and/or placing a layer of bedding mortar ahead of the RCC.

The other source of seepage in RCC dams has been the vertical transverse thermal cracks or induced contraction joints. This seepage is usually controlled by embedding a PVC waterstop in conventional facing concrete at the upstream face. Other methods have included caulking with elastomeric filler or epoxy, covering with a neoprene lined steel plate at the upstream face and chemical grouting of the joint/crack with polyurethane.

Another approach to watertightness is to provide an impervious facing element on the upstream slope. With this design permeability of the RCC and the lift joints is not so critical. Upstream impervious barriers have included conventional concrete facing placed simultaneously with the RCC and after RCC placement, precast concrete panels lined with PVC, and elastomeric liners applied to the upstream face of the dam after completion.

Regarding the need for high shear strength between lifts, the solution involving low permeability RCC with bedding mortar between lifts, seems to be the most conservative approach. This method should probably be applied along with a conventional concrete upstream facing which will serve as a first line of defense to seepage and to accommodate waterstops and possibly embedded drains. Inducing vertical contraction joints in a controlled location with one or more waterstops across the joint and a vertical formed drain in conventional facing concrete will probably be essential for very high dams.

Internal seepage is generally drained by vertical holes located near the upstream face, either formed during construction or drilled during or after construction. At Galesville Dam, 76mm diameter holes were drilled with 3m spacing through the galleries into the foundation to different depths. These drains allow seepage into foundation galleries where the flow continues by gravity to some discharge point on the downstream slope. Without internal seepage control, uplift pressures may build with time, reducing the effective vertical pressure necessary for stability, as it has already been discussed. Internal control is the second line of defense against seepage.

4.10 Instrumentation

Instruments should be installed at selected locations throughout the dam and its foundation so that measurements can be taken to monitor the structure's behavior during construction and subsequent operation. It can be considered that there are two main purposes to use the instruments:

Control- Of primary importance is the gathering of information by which the structural safety can be assessed.

Research- Of secondary importance is the use of the information obtained, learn about the RCC behavior, and to provide better criteria for designing future RCC dams. This use becomes more important as RCC dams become higher and larger.

The number, type, and location of instruments installed during construction of RCC dams become extremely important in that they may hamper rapid placement, thereby increasing construction costs. The designer, with a clear understanding of the project's purpose, can design an unexpensive but functional instrument package and layout to provide immediate and long-range dam and foundation behavioral data.

Instrumentation used in RCC dams is similar to that used in conventional concrete dams. Embedded instruments can be used to determine temperature, strain, stress, and hydrostatic pore pressure, and to measure cracks. These may be the Carlson elastic wire type or the vibrating wire type, both of which require electrical circuitry. Thermocouples installed in the concrete structure during construction in a predetermined grid will provide continuous temperature data during and after construction. Wherever there is a substantial change in mass cross sections, crack detection meters should be installed as well.

External methods of determining information involve precise surveying methods such as can be achieved with electronic distance measurement. By performing collimation readings along the crest immediately after construction and frequently for the first 5 years of reservoir operation, a behavioral history is recorded of the interaction among the dam, foundation and reservoir. Triangulation networks can be established to develop the overall three-dimensional deformation of the dam from the major influences of reservoir, temperature and foundation. This instrumentation is suitable mainly for arch dams and typical gravity dam.

To establish data base for the unloading and loading of the foundation, instruments that measure foundation deformation should be installed shortly before construction begins.

Judiciously placed weirs in the foundation gallery gutter will supply information on the volume of seepage and changes in flow rates. Abnormal flows may indicate serious conditions in the dam or foundation. Sediment in the gutter may indicate material erosion in the dam or foundation. Periodic chemical analyses of seepage will indicate dissolution of materials. Uplift in the foundation, essential to stability of the RCC dam, should be measured at a frequency set by the designers. Electric cable embedments can be accomplished during construction by excavating small trenches while the concrete is green or by drilling holes after the concrete has hardened.

As is regularly done for conventional concrete dams, instruments associated with RCC dams should be maintained and read at prescribed intervals for an extended period of time after construction to create a structural behavior historical record. Data reduction in the form of measurement versus time plots will quickly show continued acceptable performance or trends suggesting careful monitoring. Sudden or accelerated departure from the annual cyclic plots will require immediate attention to determine if the readings were made correctly, the instruments needed maintenance, or a structural anomaly has occurred about which the owner should be alerted.

4.11 References

4.01 MOLER, W. A; JACKSON, H. E. "How High RCC?", in: Proceedings of the International Symposium of Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.02 SARKARIA, G. S.; ANDRIOLO, F. R. "Special Factors in Design of High RCC Gravity Dams", in: International Water Power & Dam Construction Magazine. April/August, 1995.

4.03 RICHARDSON, A. R. *Performance of Upper Stillwater Dam;* in: Roller Compacted Concrete III, Conf. Proc. American Society of Civil Engineers, February 1992,

4.04 PALTA, B. R and AGGARAWALIA, S. K. *Foundation Problems at Bhakra Dam and Their Treatment*, in: R 66, Q 32, IX ICOLD Congress. Istanbul, Turkey, 1967.

4.05 BARBI, A. L.; PLASENTIN, C. et al. *Subsurface Treatment of Seams and Fractures in Foundations of Itaipu Dam.* Q 55, XIV ICOLD Congress. Rio de Janeiro, Brazil, 1982.

4.06 GIOVAGNOLI, M.; ERCOLI, F.; SCHRADER, E. *Concepcion Dam, Design and Construction Problems and Their Solutions, Roller Compacted Concrete III*, ASCE, February, 1992.

4.07 BUREAU OF RECLAMATION, Department of the Interior. "Gravity Dams - Part I - General Design Considerations". United States, 1976.

4.08 DEPARTMENT OF THE INTERIOR. "Design criteria for concrete arch and gravity dams". Bureau of Reclamation Monograph nº 19. United States, Denver, 1977.

4.09 URLICH, D. M., et al. "Design and Construction of Lower Chase Creek Dam", in: *Roller Compacted Concrete II.* Proceedings of the RCC Specialty Conference. San Diego, California, ASCE. New York, March 1988.

4.10 VERIGIN, W. M. and BENSON, S. A. "Cedar Falls Project - Rehabilitation with RCC", in: *Waterpower '87,* Proceedings of the International Conference on Hydropower. Portland, Oregon, August 1987.

4.11 BENSON, S. A.; VERIGIN, W. M. and CARNEY, M. J. "Cedar Falls Roller Compacted Concrete Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, March 1988.

4.12 "General Report"- Question 62, in: New Developments in the Construction of Concrete Dams- XVI ICOLD Congress on Large Dams. San Francisco, California, June/1988.

4.13 HOLLINGWORTH, F.; GERINGER, J. J. "Concrete Dams", in: *Large Dams and Water Systems in South Africa.* Durban: South African National Committee on Large Dams, 1994.

4.14 LONDE, P.; LINO, M. "The Faced Symmetrical Hardfill Dam : A New Concept for RCC", in: *Water Power & Dam Construction*. February/1992.

4.15 OLIVEIRA, P. J. R.; SALLES, F. M.; ANDRIOLO, F. R. "Soils & Cementitious Materials. A Technical Option for Use as a Structural Element for Dams", in: *Proceedings of the International Symposium of Roller Compacted Concrete Dams*. Santander, Spain, October/1995.

4.16 PACELLI, W. A.; ANDRIOLO, F. R. and SARKARIA, G. S. "Treatment and Performance of Construction joints in Concrete Dams", in: International Water Power & Dam Construction. UK, November 1993.

4.17 ACI- 207- "Roller Compacted Mass Concrete", 1989.

4.18 RCC Dams (>15m) - 1997 Yearbook - International Water Power & Dam Construction, 1997.

4.19 BAZANT, Z. P. "Pore Pressure, Uplift and failure Analysis of Concrete Dams - Criteria and Assumptions for Numerical Analysis of Dams", in: D. J. NAYLOR; K. G. STAGG; O. C. ZIENKIEWIEZ. Swansea, September/1975.

4.20 CARLSON, R. W. "Permeability, Pore Presure and Uplift in Gravity Dams". Berkeley, ASTM, USA, 1955.

4.21 "Spanish RCC Dams - 1996"- Instituto Español del Cemento y sus Aplicaciones - Comité Nacional Español de Grandes Presas.

4.22 Jiangya Project- Bid Documents.

4.23 SHEN CHONGGANG. "New Technical Progress of RCC Dam Construction in China", in: General Report on International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.24 BOUYGE, B.; LANGOIS, A. P. and MARTIN, J. P. «Quality of Works in RCC in France: A Contractor's Solution», in: Roller Compacted Concrete II, Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, March 1988.

4.25 BOUYGE, B. et al. "Roller Compacted Concrete Dam Construction and Work Supervision: a Team Job", in: Transactions, Sixteenth International Congress on Large Dams. San Francisco, vol. III, Q62, June 1988.

4.26 "Roller Compacted Concrete- RCC Dams", in: Projet National BaCaRá 1986-1996. Paris: Presses de L'École Nationale des Ponts et Chaussées, 1997.

4.27 SORENSEM, R. M." Stepped Spillway Hydraulic Model Investigation", in: Journal of Hydraulic Engineering, ASCE. New York, 1985.

4.28 FRIZELL, K. H. "Hydraulics of Stepped Spillways for RCC Dams and Dam Rehabilitation", in: Roller Compacted Concrete III, ASCE. New York, 1992.

4.29 PARKER, J. W. «Economic Factors in Roller Compacted Concrete Dam Construction», in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

4.30 BIRINDELLI, Lucy Inês Olivan; FERREIRA, Omar Vilela; INOUE, George; MIYAJI, Yssamu; SCANDIUZZI, Lutércio. "Estudo Térmico das Condições de Lançamento e de Definição do Espaçamento de Juntas de Contração em Barragens de C.C.R.", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April/1989.

4.31 GERINGER, J. "SPECIAL CONFERENCE - The design and construction of RCC dams in Southern Africa", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.32 TOZZI, Marcos; TANIGUCHI, Edie; OTA, José. "Concentração de Ar em Escoamentos Sobre Vertedouros com Degraus", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March/1996.

4.33 LORENZO, A. C.; CALIVARI, S. S. "Behaviour of Uruguai Dam", in: Roller Compacted Concrete III, Conf. Proc. ASCE, February, 1992.

4.34 HIROSE, T. et al. «A Study of Control of Temperature Cracks in Large Roller Compacted Concrete Dams», in: Transaction, Sixteenth International Congress on Large Dams. San Francisco, vol. III, Q62, June 1988.

4.35 FEDOSSOV, V. E. and KOGAN, E. A. "RCC dam with the zone placement of different concrete mixes", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.36 LIU, G. T.; MAI, J. X. and ZHANG, G. X. " Research and practice on Xi Bin roller-compacted concrete thin arch dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.37 DELORME, F.; BOURDAROT, E. and LALLEMENT, M. "Petit Saut RCC Dam: First example of a reinforced concrete face built before RCC. Lessons learnt during construction and after first impounding", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.38 GOMEZ LAA, G. «Roller compacted concrete dams in Spain», in: International Water Power & Dam Construction. United Kingdom, vol. 44, nº 9, September 1992.

4.39 HANG, Ma Zhong; HEMING, Cai and KOLLGAARD, E. B. «The Design and Construction of Shuikou Project RCC Diversion Wall», in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

4.40 HOLLINGWORTH, F., and GERINGER, J. J. «Roller Compacted Concrete Arch/Gravity Dams - South African Experience", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

4.41 DUNSTAN, M. R. H. «A Review of Design Criteria for High RCC Dams», in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

4.42 KOLLGAARD, E. B., and JACKSON, H. E. «Design and Construction of Quail Creek South Dam», in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

4.43 HOUK, Ivan E. Jr.; BORGE, Orville E., HOUGHTON, Donald L. «Studies of Autogenous Volume Change in Concrete for Dworshak Dam», in: ACI Journal Proceedings, vol. 66, nº 7, July 1969.

4.44 BRUNNER, W. J.; WU, K. H.- "Cracking of the Revelstoke concrete Gravity Dam Mass Concrete", in: Q 57- XV ICOLD. Lausanne, Swisterland, 1985.

4.45 ANDRIOLO, F. R., and SCHMIDT, M. T. «The Capanda RCC dam in Angola», in: International Water Power & Dam Construction. United Kingdom, vol. 44, nº 2, February 1992.

4.46 MCLEAN, F. G.; PIERRE, J. S. "Comparison of Joint Shear Strengths for Conventional and Roller Compacted Concrete", in: Proceedings of Roller Compacted II Conference – ASCE. February/1992.

4.47 ANDRIOLO, F. R. "RCC Propenties", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.48 KREMPEL, A. F.; HOLANDA, F. G. and ANDRIOLO, F. R. "Jordão River derivation dam. Data obtained from the test fill", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

4.49 CHAIRABI, A. F. "Lessons Derived from the Constructionof Aoulouz RCC Dam", in: - International Water Power & Dam Construction. September/October 1993.

4.50 GOLIK, M. A; JULIANI, M. A. C. and ANDRIOLO, F. R. "Inspection gallery and drainage in small dams: problem or solution?", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

5

Materials

5.1 General

RCC is a type of concrete that differs from conventional concrete mainly because of its consistency, which will support a vibratory roller. It has an aggregate grading and fines content suitable for compaction by the roller or other external methods.

The objective of RCC proportioning is to provide a dense and stable mass that meets the strength, durability, and permeability requirements for its application. Materials used for RCC include cementitious materials, aggregates, water, and admixtures. A wide range of materials has been used successfully to produce RCC mixtures.

All materials used in a high RCC dam, including cement, pozzolanic material, fine and coarse aggregates, should be similar in quality to those considered suitable for a comparable CVC dam. Particularly important are physical properties related to specific gravity, susceptibility to AAR, or excessive thermal expansion.

Materials for RCC have ranged from pit-run minimally processed aggregates with low cementitious material (cement plus pozzolanic material) contents to fully processed concrete aggregates with moderate to high content of cementitious material. The mixture designed for Saco de Nova Olinda Dam in Brazil used a combination of crushed quarry rock and natural silt graded in a curve with 76mm maximum size aggregate (MSA) with 75kg/m^3 cementitious materials (Portland Pozzolanic Cement). Urugua-i (Argentina), Capanda (Angola), Jordão Dam and Salto Caxias Dams (Brazil) used a combination of crushed quarry rock and crushed powder filler (with moderate pozzolanic activity) with no washing and low (Ordinary at Urugua-i and Capanda; Pozzolanic at Jordão and Salto Caxias) Portland Cement content. In these dams a graded continuous curve with MSA between 76mm and 50mm was used. Tamagawa Dam in Japan used conventionally graded 152mm MSA with 130kg/m^3 cementitious materials. Upper Stillwater Dam used 50mm MSA and 250kg/m^3 cementitious materials. Mixtures at Willow Creek Dam used a combination of crushed quarry rock and natural silt overburden with minimal processing and no washing. The MSA was 76 mm, and three size group stockpiles (without a separate sandpile) were used. Middle Fork Dam had two primary stockpiles with no separate sand material, and Copperfield in Australia used a single all-inclusive aggregate pile.

The larger the RCC dam, the more sensitive will the unit cost be based on the source and quality of aggregate and cementitious materials. A few key factors related to the production of RCC and, consequently, to its cost, are:

5.2 Cementitious Materials

5.2.1 General

RCC can be made with any of the basic types of cement or a combination of cement and pozzolanic material. Selection of cementitious materials to resist to chemical attack of sulfate and potential alkali reactivity with certain aggregates should follow the same standard procedures adopted for CVC.

The strength of RCC is primarily dependent upon:

- quality of the aggregate;
- degree of compaction;
- proportions of cement, pozzolanic material, water and admixtures, if used.

The type and quantity of Portland cement or cement plus pozzolanic material required in RCC mixes depend on the volume of the structure, its required properties, and the exposure conditions. In addition, most RCC dams are large enough to consider the heat of hydration of the cementitious materials. Cementitious contents used in RCC dams have ranged from 60kg/m^3 of cement used for Urugua-i Dam in Argentina to 248kg/m^3 for the predominant mix at Upper Stillwater Dam. In Japan, the cementitious content is usually about 120 kg/m^3 and pozzolanic material (Fly Ash) in amounts from 20% to 30% of the weight of the cementitious material to reduce the heat of hydration. Portland-blast furnace slag cement produced the desired strengths and heat-generation conditions for Les Olivettes Dam in France.

The type of cementitious material has a significant effect on the rate of hydration and the rate of strength development and, therefore, significantly affects strengths at early ages. At ages beyond 28 days, the difference in strength contributions for the various cementitious materials depends on the use, proportion, type and characteristics of the pozzolanic material.

If RCC is used in a massive structure, consideration must be given to the generation of heat by its cementitious materials. It is desirable to use low or moderate heat-generating cements and the maximum amounts of pozzolanic materials commensurate with strength requirements. The effectiveness of pozzolanic materials in reducing heat generation depends on strength requirements and on its ability to reduce water requirement, as well as cement content. The economic benefit of heat reduction through the use of pozzolanic materials depends on the relative cost of materials, including handling.

Figures 5.01 to 5.03 show a comprehensive study undertaken to define the most adequate cementitious material for a dam. Several Portland cement types and pozzolanic materials and basaltic rock powder filler were tested.

Large quantities of cementitious materials required for very high RCC dams might exceed the supplier's delivery capacity, for that market. Non availability of cementitious materials to meet production needs might force a reduction in the rate of placement and/or higher prices if transport of materials from a longer distance is necessary. Likewise, very high RCC dams with large volumes will require a great number of bulk transport vehicles travelling on public roads, which, in addition to environmental impact, might disrupt local traffic and increase road maintenance.

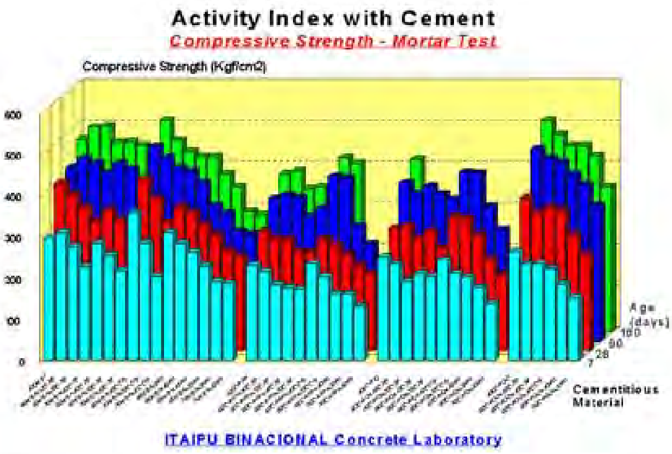


Figure 5.01 Mortar cement test to check the Pozzolanic Activity with different pozzolanic materials.

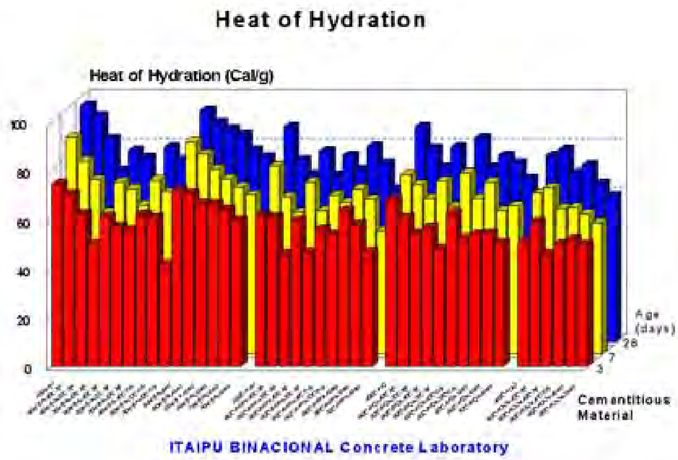


Figure 5.02 Heat of Hydration test to check the pozzolanic beneficial action with different pozzolanic materials.

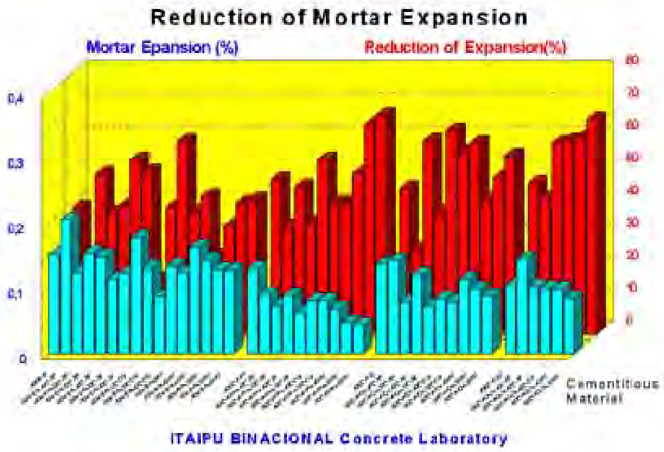


Figure 5.03 Mortar bar test –ASTM-C- 414 test to check the Pozzolanic Activity to Reduce Expansion, with different pozzolanic materials.

5.2.2 Cement

RCC can be made from any of the basic types of Portland cement. For mass applications, cements with lower heat generation are beneficial. They include Type II (low heat), Type IP (Portland Pozzolanic cement), and Type IS (Portland Blast Furnace Slag cement). The blended cement as shown in Figure 5.01, can be beneficial also. Strength development for these low heat cements is usually slower than for Type I at early ages, but at ages beyond 28 days, the slower early strength development cements ultimately produce higher strengths than Type I.

The choice of cement types for exposure to aggressive chemicals or aggregate reactivity should follow standard practice for CVC.

It is very important to mention from [5.01]:

"...from the first stage of construction, Grand Coulee Dam at the age of 2 years exhibited strengths in excess of 56MPa (8000psi)..... ...Considering the magnitude of the calculated stresses within the structure, it was evident that such high compressive strengths were quite unnecessary and that a reduction in cement content in similar future constructions might be expected to substantially reduce the tendency toward cracking. ...."

And from [5.02]:

"Minimum Cement Limit...

Economy

The lower permissible limit on the quantity of cementing material per cubic meter (yard) of mass concrete has not yet been reached....

Safety Factor

The safety of a concrete gravity dam should not be measured by the cement content (high cement content, high factor of safety; low cement content, low factor of safety).... "

It is very usual to consider that a ***Safe and Impermeable Structure*** is the one that is built with a "rich" (or unnecessarily high cement content) concrete. But, normally, this rich concrete will increase the crack potentiality and become permeable (through cracks). The optimum cement or cementitious content for CVC and RCC need be based on laboratory proportioning mix tests carefully carried out.

5.2.3 Pozzolanic Materials

The selection of a pozzolanic material suitable for RCC should be based on its conformance with the adopted standard (ASTM C- 618 [5.03] or other applicable standard) and its cost and availability, as shown in Figures 5.01 to 5.03.

ASTM C-618 defines pozzolan as *" siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties".*

The types of pozzolanic material can include natural pozzolans; diatomaceous earth; pozzolan from calcined clay ; Industrial waste material as fly ash or silica fume.

Use of a pozzolanic material in RCC serves some purposes:

1. as a partial replacement for cement to reduce heat generation;
2. to increase the compressive strength at great ages, if the material has high pozzolanic activity with cement;
3. to increase durability;
4. to reduce cost; and:
5. as a mineral addition to the mixture to provide fines to improve workability.

The partial replacement for cement (for the same strength level) and the cost benefit depends on the pozzolanic activity of the material with the cement, which is related with the hydroxides released during hydration, for the reaction with main elements (Silica; Aluminum; Iron Oxides) from the pozzolanic material. The use of a high content of pozzolanic material replacing the cement can "overdose" the available hydroxides and part of the pozzolan acts only as a filler (the 5^{th} purpose), with no Pozzolanic Activity. In this way, performance of pozzolanic materials in RCC has differed from the results expected in conventional concrete only in those instances involving aggregates containing large quantities of natural fines.

In proportioning mixtures for minimum paste volumes, one principal function of a pozzolanic material or other suitable fine material is to occupy space that would otherwise be filled by cement or water. To fill this space with water would obviously result in a reduction in concrete density and strength.

Liberal use of pozzolanic material as cementitious material is possible in many massive RCC applications with low early strength requirements.

5.3 Fillers

5.3.1 General

The use of continuous grading for RCC based on a cubic-type (or similar) curve takes into consideration a substantial quantity of fines, finer than 0.075 mm, for the adequate cohesiveness of the mixing.

In stiff RCC mixtures, increased quantities of these materials may actually be used to reduce water requirements so that higher limit may be used without adverse effects. Figure 5.04 from [5.03] provides guidelines for the amount of permissible fines in aggregate for lean RCC based on plasticity.

LIQUID LIMIT	PLASTIC INDEX	MAXIMUM PERCENT PASSING (No.200) 0.075mm
0 - 5	0 - 5	10
0 - 25	5 - 10	9
0 - 25	10 - 15	4
0 - 25	15 - 20	3
0 - 25	20 - 25	1.5
23 - 25	0 - 5	9
25 - 35	5 - 10	8
25 - 35	10 - 15	6.5
25 - 35	15 - 20	5
25 - 35	20 - 25	1.5
35 - 45	0 - 5	8.5
35 - 45	5 - 10	5.5
35 - 45	10 - 15	4
35 - 45	15 - 20	2
35 - 45	20 - 25	1.5
45 - 55	0 - 5	5.5
45 - 55	5 - 10	5
45 - 55	10 - 15	3.5
45 - 55	15 - 20	3
45 - 55	20 - 25	1.5

Figure 5.04 Maximum permissible fines content [5.04]

Note: The maximum permissible amount passing No. 200 sieve depends upon the plasticity (ASTM D 4318) of all of the fines (washed sample) passing No. 40 or No. 50 sieve. Experience has shown that results are similar for either sieve. The size can be based on testing convenience.

These fines may be of various kinds as previously mentioned: fly ash, blast furnace slag, natural or calcinated pozzolans, diatomaceous earth, silt and also the "crushed powder" (called ***pó de pedra*** in Brazil), a byproduct of rock crushing obtained during the aggregate production and manufacture processes.

The use of this "stone crushed powder" (fines smaller than 0.075mm) in the composition of RCC can show considerable advantages not only improving the cohesiveness of the mix while fresh, but also reducing the expansion resulting from the reactions with the cement alkali, as function of the Silica mineralogical form and its content (see Figures 5.03 and 5.18 ahead).

5.3.2 Development

Natural sand resources of Brazil's Southeastern & Southern regions (next to the Paraná River basin) are scarce. This situation commonly forces the production of crushed sand by crushing rocks, which normally are of the basaltic type in those regions. This is why dams like Itaipu (13.000.000 m_ of CVC), Salto Santiago (CVC, 480.000m_), Salto Osório (CVC, 472.000 m_), Foz do Areia (CVC, 600.000 m_), Segredo (CVC, 300.000 m_) and São Simão (CVC, 1.600.000 m_), among others, have used a great quantity of crushed sand in concrete production.

Figure 5.05 Available sources of pozzolanic materials, which are normally used in Brazil [5.05; 5.06].

During the construction of Itaipu Dam, it was observed that within each one of the crushing lines (1,800 t/h each) there were rejects of about 10t/h to 15t/h, next to the crushed sand washer (produced by VFC & Hydrofine-type Re-crushers). At first, the visual observation of these rejects did not indicate the presence of cohesive materials that could be considered prejudicial because the rejects resulted from the action in the classifying tanks and de-hydrator screws. In the circuit previous to that of the crushed sand production, there was no clay, or other materials.

This situation gave rise to the evaluation of that reject with a view to incorporating it to CVC and RCC conventional types of concrete [5.07]. Recently, during the construction of the RCC Urugua-i Dam (Argentina), the use of a grading curve type (see Chapter 6) for the aggregates' (from Basaltic rock) composition, required incorporating a certain amount of fines. As a part of the mixing studies for Urugua-i Dam, carried out at the Itaipu laboratory, the incorporation of the basalt "stone crushed powder" to the mixing was suggested and adopted [5.08].

At that opportunity, the physical improvement of the properties was noticed but the physic-chemical action of the "stone crushed powder" fines was not identified.

During the studies made for the Capanda Dam construction, the civil construction contractor and his consultant, together with Itaipu Laboratory and Eng. Albert Ossipov (*from the Moscow Scientific Research Center Hydroproject Institute*) performed extensive studies [5.09; 5.10] aiming at the characterization of the "stone crushed powder" activity as regards the Calcium Hydroxide that is released during the cement hydration. This action is similar to that of an activity with cement and with lime, normally observed in the characterization of pozzolanic materials.

The introduction of the method for "fixing lime on sands" in some Brazilian laboratories [5.05 to 5.12] came after such studies as well as the use of "stone powder" in the RCC during Capanda dam construction [5.09; 5.10].

5.3.3 Equipment to Produce Crushed Powder

The production of crushed sand may be done by means of crushing rocks using special crushers for fines, "Impactor", "Hydrofine" or "VFC-Very Fine Crusher" type.

Figure 5.06 48VFC Recrusher at Jordão Dam site.

Figure 5.07 BARMAC Recrusher at Jordão Dam site.

Figure 5.08 Hydrofine Recrushers at Capanda Dam site.

Figure 5.09 Aspect of the crushed sand produced by the 48VFC (left) and Barmac (right) Crushers.

5.3.4 Tests

The advantages of the use of fines (material smaller than 0.075 mm) in the RCC mixes (and also in the CVC) as regards the grading aspect, have already been mentioned and it has been recommended, e.g.:

...*"The fine material in crushed stone sand differs from that in natural sand in that it consists largely of stone dust and not clay. A higher content of it can therefore be tolerated and may be advantageous by improving the plasticity of concrete mixes containing angular crushed rock aggregate"*...[5.13]

The filler (finer than 0.075 mm) contained in the fine aggregates obtained by the Barmac and 48VFC Crushers, used in Jordão Dam RCC had their grading determined by the Laser Diffraction Granulometer as shown in Figure 5.11.

The average diameter of the "crushed powder" particles when compared to other materials is shown in Figure 5.10.

The evaluation of the sand filler shape was carried out petrographically, through optical microscopy, with emphasis on the morphology. Figures 5.13 and 5.14 show fragments of the fines produced by the two types of crushers: 48VFC and Barmac. From the photo-micrographics, magnified 200 times, it can be observed that the Barmac Crusher produces fragments both homogeneous and with an equidimensional form while the 48 VFC Crusher produces more elongated fragments with a serialized grading.

The reduction of the RCC permeability dosed with the addition of "stone powder" obtained from crushing was already mentioned in references [5.07; 5.14; 5.15], and can be seen in Chapter 7.

REQUIREMENT	UNITY	CP IS-32	CP-V-32	CP IS-32	CP-V-32	CP-V-32	FLY ASH	CRUSHED SAND AND FILLER			CEMENT	DIATOM.	POZZOLAN
		ITAMBÉ	ITAMBÉ	VOTORAN	VOTORAN	ELDORADO	GENERAL	FILLER 1	FILLER 2	FILLER 3	GENERAL	GENERAL	CALC.CLAY
% RETAINED ON # 200	%	2,36	0,87	2,5	0,1	0,7					2,3 - 8,8		
% RETAINED ON # 325	%	10,6	4,8	16,9	1,3	3,1	27 - 41	16,6			10,4 - 29,6	11,6	20 a 60
SPECIFIC SURFACE BLAINE	cm^2/g	3670	4600	3670	4800	5220	2900 - 3200	2520	3650	4320	2900 - 4000	13700	3000 - 8000
DIÂMETRO MÉDIO	microns						9.- 15				9 -. 20	2 -. 5	3 -. 10
APPARENTE SPECIFIC GRAVITY	g/cm^3										1,3 a 1,5		0,75 - 0,81
ABSOLUT SPECIFIC GRAVITY	g/cm^3	3,1	3,26	3,1	3,15	3,22	2- 2,3	2,96	2,79	2,76	3,0 - 3,15	2,3	2,63 - 2,65
TIME OF SETTING - INITIAL	h : min	03:36	02:22	03:16	02:40	02:30					01:30		
- FINAL	h : min	06:10	05:00	05:30	05:15	04:47							
LE CHATELIER - EXPANSION	mm	0,03	0,02	0,01	0,02	0,01							
AUTOCLAVE - EXPANSION	%												
IAP-WATER	%						110 - 115					105	103 - 111
IAP-LIME	kgf/cm^2						39 - 78					64	24 - 82
IAP-CEMENT	%						74 - 78					89	73 - 95
MORTAR EXPANSION							0,02						0,002 - 0,009
REDUCTION OF EXPANSION	%						57 - 75					101	71 - 84
COMPRESSIVE 3 DAYS	kgf/cm^2	250	266	232	361	240					143- 233		
STRENGTH 7 DAYS	kgf/cm^2	331	315	274	403	361					215 - 315		
(AGE) 28 DAYS	kgf/cm^2	365	380	378							315 - 476		
HEAT OF 7 DAYS	cal / g										57 - 84		
HYDRATION (AGE) 28 DAYS	cal / g										67 - 95		
LOSS ON IGNITION	%	3,7	4	2,66	2,5	3,21	5	2,28	2,13	2,68	1,0 - 3,67		0,6- 1,6
INSOLUBLE RESIDUE	%	0,56	0,73	0,72	0,66	0,54		91,26	89,61	89,41	0,05-17,89		
SiO2	%	19,65	19,28	18,89	18,64	19,49	52	49,31	49,54	50,17	15 - 23		74-75
Fe2O3	%	3,23	3,62	3,03	3,23	3,33	7,1	17,71	16,93	16,05	2,5 -3,8		4,8- 5,8
Al2O3	%	4,56	4,69	4,37	4,69	4,75	30	11,56	13,12	10,93	5.- 10		15,1- 16,5
CaO	%	62,2	60,82	61,85	61,17	62,37		9,45	10,31	9,45	50 - 65		0,6- 1,0
MgO	%	2,59	3,09	5,56	4,94	1,98	0,9	5,8	4,94	5,19	1,0- 6,0		2,01- 2,41
SO3	%	2,89	3,12	2,75	3,27	3,23	0,4	0,04	0,1	0,03	1,15- 2,82		
Na2O	%	0,03	0,05	0,05	0,05	0,03		0,93	1,1	0,9	0,04- 0,91		
K20	%	0,76	0,76	0,71	0,71	0,82		1,03	1,11	1,13	0,03- 0,86		
AVAILABLE ALKALIES	%	0,053	0,55	0,52	0,52	0,57		1,61	1,83	1,64			
FREE LIME	%	1,45	1,53	2	1,58	1,03		0,07	0,17	0,11			
C3S	%	60,46	55,42	66,63	61,84	59,83					35- 59		
C2S	%	10,81	13,55	3,98	6,87	10,82					14- 35		
C3A	%	6,63	6,31	6,46	6,97	6,96					6.-12		
C4AF	%	9,82	11	9,21	9,82	10,12					7.- 12		
SiO2+ Al2O3+ Fe2O3	%						90	78,58	79,59	77,15		95	94- 97

Figure 5.10 Data on the materials used for the Jordão Dam study [5.06].

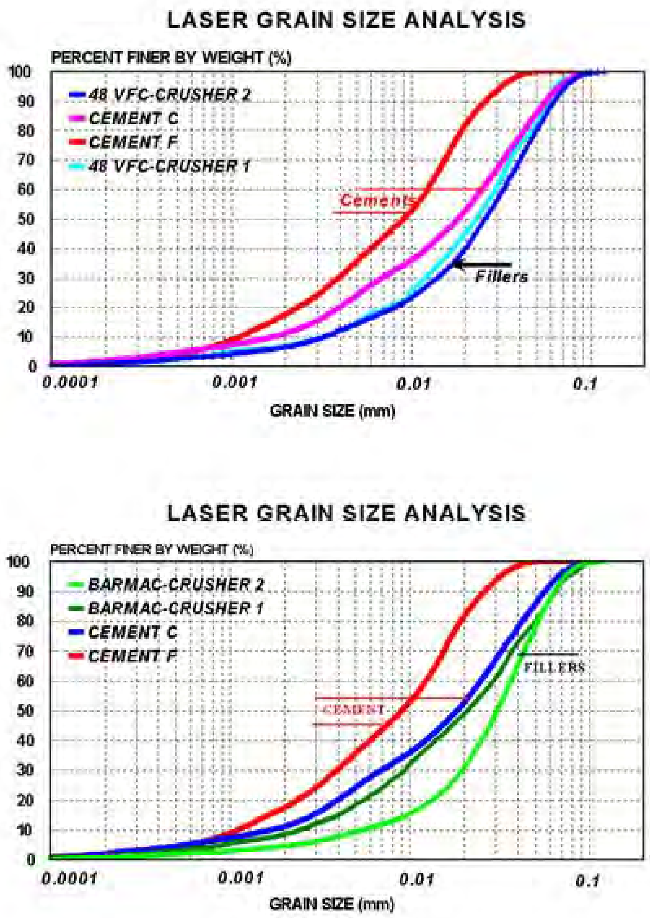


Figure 5.11 Filler Grading (Material Finer than 0.075 mm)

Recrusher	Blaine Specific Surface (cm^2/g)
Barmac	1909
48 VFC	2351

Figure 5.12 Blaine Fineness of the Filler samples (material finer than 0.075 mm)[5.06].

The compressive strength and the watertightness of the RCC and CVC are improved with the inclusion of the "stone powder" [5.05 to 5.08; 5.11; 5.12; 5.14 to 5.16]. The improvement in strength results from the pozzolanic action demonstrated by the "stone powder" to fix the Calcium Hydroxide released during the cement hydration and it must be mentioned that:

"*... The reaction of active forms of silica with lime improves strength...*" [5.13]

It is known that:

"*... Diffusion of ions or molecules through a gel containing solution may take place in two ways: (1) through the liquid phase in the ordinary way and (2) by surface diffusion if the soluble material is subject to adsorption by the solid phase. Surface diffusion is what then implies: a migration of adsorbed ions from one part of the internal surface to another part. The movement takes place in response to a gradient in surface concentration (a gradient in the degree of saturation of surface) just as ordinary diffusion depends on the gradient in solution concentration. Therefore, the relative amounts of adsorbed lime and adsorbed alkali that reach the reaction site should depend on the relative amounts adsorbed in the outer part of the gel layer...*" [5.17].

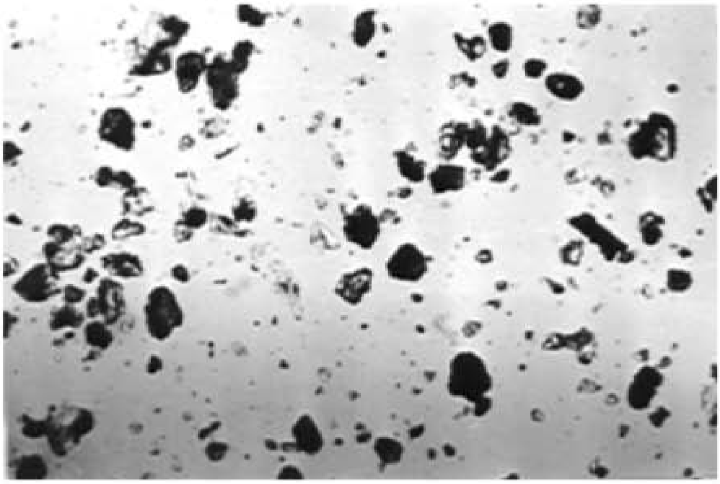


Figure 5.13 Photo-micrographic of the Filler produced by the Barmac - magnification 200x.

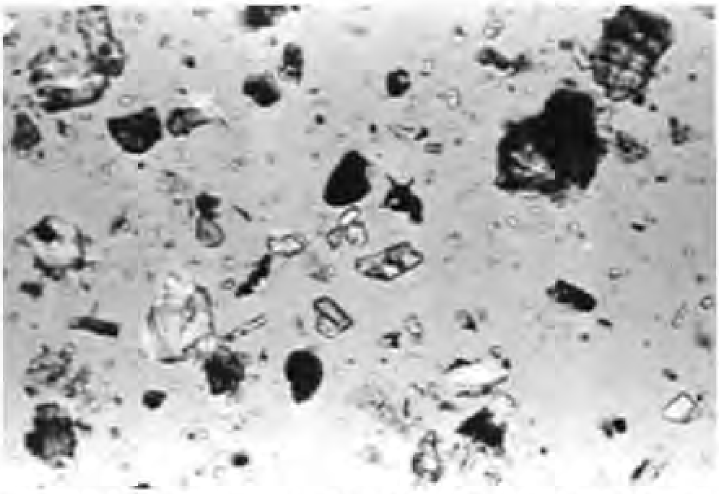


Figure 5.14 Photo-micrographic of the Filler produced by the 48VFC - magnification 200x.

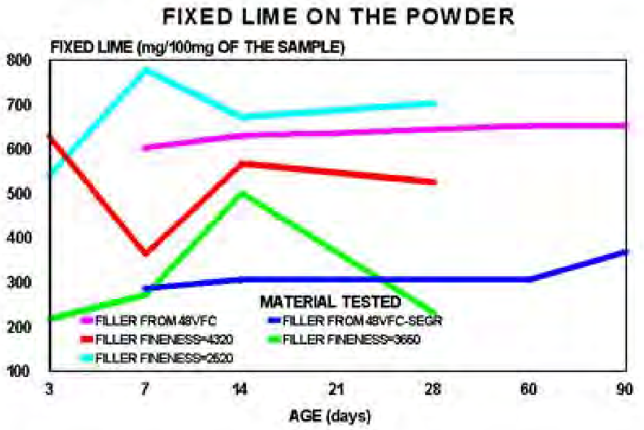


Figure 5.15 Calcium Hydroxide Fixation on Fines (Method TOCT-25094, adapted).

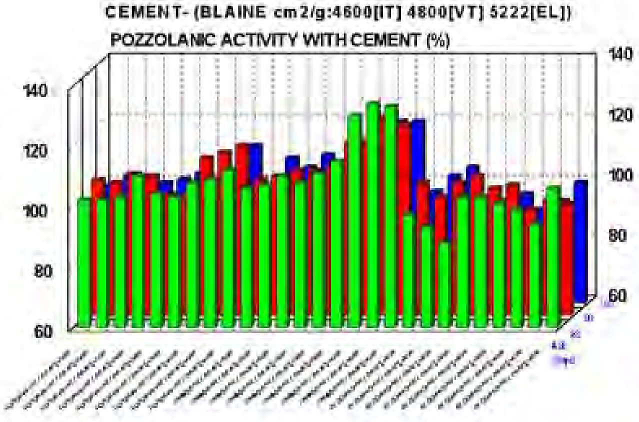


Figure 5.16 Pozzolanic Activity of the Materials, with Cement (ASTM-C-311-[5.18]).

The test for evaluation of the calcium hydroxide is carried out according to the ex-soviet TOCT-25094 method, (adapted by Dr. Albert D. Ossipov). The test comprises the $Ca(OH)_2$ measurement, established to be 20g of crushed material, finer than 0.075 mm, from a saturated $Ca(OH)_2$ solution, under a temperature of 40°C for a period of 28 days. The quantity of $Ca(OH)_2$ fixed by the aggregate fines is obtained after titration. A $Ca(OH)_2$ minimum fixation of 30mg per 100g of fine material is recommended as shown in Figure 5.15.

The Pozzolanic Activity Index of the filler with cement can be determined by the test based on the ASTM-C-311[5.18] method, to verify the pozzolanic action of the material, as depicted in Figure 5.16. The Pozzolanic Activity Index of the Filler, with Lime, is also determined by the test performed, based on the ASTM-C-311 method, bearing the same concept as above. Figure 5.17 shows the values obtained.

It is very important and must be remembered that:

"*... There is in fact a complex relation between the quantity and fineness of the reactive material, the alkali content of cement, and the degree of expansion. Thus,. ... .., pozzolans, which are reactive silicate materials, are often a corrective for alkali-aggregate expansion...* "[5.13]

"*... When the reactive mineral is powdered, it can be used in a wide range of proportions without causing expansion. This was demonstrated by Vivian [5.19] when opal was ground to pass N° 300 sieve and used in several proportions, expansion was practically zero for all proportions and the particle size of the reactive mineral is clearly an important factor...*"

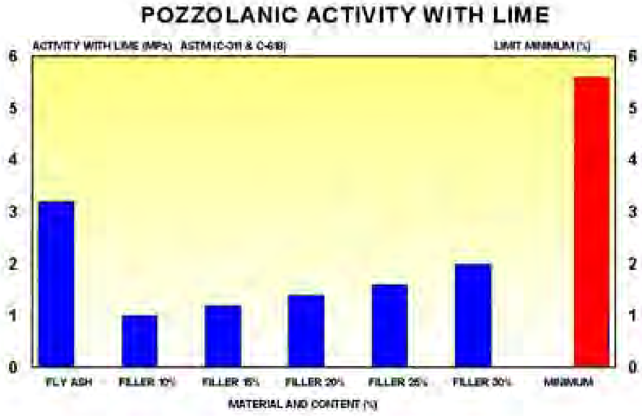


Figure 5.17 Values of the Activity with Lime (ASTM-C- 311).

"...When an aggregate contains reactive mineral and is used with an amount of alkali greater than it can tolerate, expansion can be prevented by adding an appropriate amount of pulverized reactive mineral, as has been shown by Hanna [5.20], Stanton [5.21] and others... "[5.17]

The reduction of the expansion using the aggregate fines can be determined by the joint application of the ASTM-C-441[5.22] and C-1260 [5.23] methods. Fines have also the role of a pozzolanic material, as shown in Figures 5.03 and 5.18.

Determination of potential reactivity between the cement Alkalis and the fines was carried out by means of accelerated tests, following the South African National Building Research Institute and ASTM-C-1260 method, using Pyrex glass (ASTM-C-441) for comparison. Figure 5.18 shows the results obtained.

The "crushed powder" produced from basaltic rocks and also from other rocks having a given content of silica, have properties of interest for its incorporation to the concretes. Fillers used in Jordão and Salto Caxias RCC dams, which were originally obtained by means of basalt crushing, have shown:

- Fineness similar to that of a generic cement and somewhat inferior to those of the traditional pozzolanic materials, even when produced in the conventional crushing systems and therefore there is no need for different equipment.

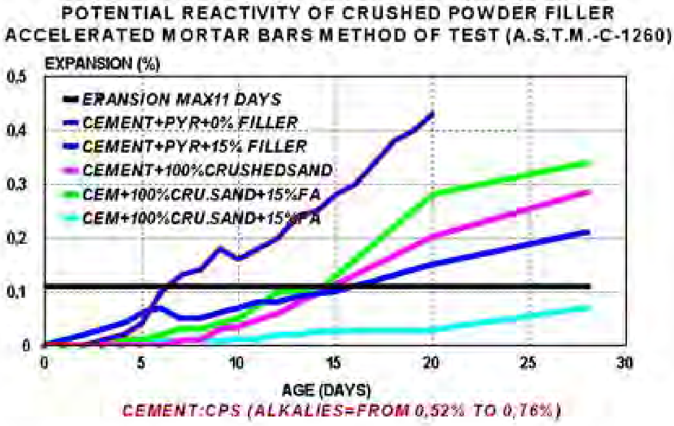


Figure 5.18 Reduction of the expansion.

· Grading curves obtained with the filler produced by distinct machines have shown differences of a certain magnitude, identified by the major concentration (70% to 80%) of grains with dimensions of about 0.040 mm, in the material produced by Barmac, in relation to a concentration of 65% for the material produced by the 48VFC Recrusher.

· Average diameters of the fillers under study are of a slightly higher magnitude (around 0.025 mm) than that of the cements normally produced (0.010-0.015 mm).

· The form of grains when analyzed under the microscope has shown differences sensitive to the electronic microscope, showing that the grains of the material produced by the Barmac are more equidimensional.

· Fillers presented Calcium Hydroxide fixation (following the Ossipov method) as can be seen by the Calcium fixation tests, thus identifying a pozzolan activity.

· Pozzolanic Activity Indexes with Lime and with various Cements (ASTM-C-311 & 618) confirm the pozzolanic activity of the Fillers studied.

· Pozzolanic Activity Indexes with various cements have proved to grow according to the age and fineness (Blaine) of the incorporated fillers.

· Fillers tested have demonstrated a substantial efficiency to reduce the expansions resulting from the Alkali-Silica Reaction thus demonstrating another important pozzolanic action, as mentioned above and recently (1996) confirmed [5.24].

5.4 Aggregates

5.4.1 General

The selection of aggregates and aggregate grading control are important factors influencing the quality and properties of RCC. The variability of aggregates during construction significantly affects the cement and water requirements, which, in turn, affect strength and yield. Requirements for compressive strength and bonding of construction joints are factors that should, therefore, be considered in aggregate specifications. If high quality concrete is required, then the specifications should reflect an appropriate degree of control of aggregate quality and grading. In less demanding situations, suitable RCC can be produced using a variety of aggregate sources that may not meet usual grading and quality requirements or other recommendations for concrete aggregates as long as design criteria are met.

For RCC, like conventionally placed concrete, aggregate quality and gradation are important factors influencing the final product. Slight differences have occurred among designers in the selection of maximum size aggregate (MSA), the proportion of sand in the RCC mix, and the percentage of fines passing a Nº200 (0.075mm) sieve for RCC mixtures when compared with CVC mixtures.

The segregation of coarse aggregate at the bottom of RCC lifts has led to decisions to reduce the MSA in some cases or to increase the proportion of sand in the mix in other cases. Most soils-approach RCC mixes have a greater percentage of fines than CVC mixes. This is particularly so if the fines are non-plastic, fill voids in the aggregate, and lead to decreased water demand and improved compactability.

A discussion of concrete aggregates is given in [5.04] and in [5.25]. In the first, deleterious substances are described as those "*that either together or separately render it impossible to attain the required properties of concrete when employing normal proportions of the ingredients*". Limits for deleterious material for RCC should be established prior to construction. These limits should be set according to their effect on all of the concrete properties required for the structure or placement involved. Some of the deleterious substances, such as material finer than Nº200 (0.075mm) sieve, in different condition than that pointed in (5.25), and some friable materials in the upper limiting quantities specified by ASTM-C-33 [5.26] may affect water requirements in CVC plastic mixtures.

5.4.2 Coarse aggregate

For RCC there is normally not enough material cost savings from using aggregate sizes larger than 76mm to offset the added batching cost and the cost of correcting the increased segregation problems associated with the larger aggregates. Bank or pit-run materials are normally batched with little or no size separation, so there is no cost savings in screening out the larger aggregates. Rounded river gravels and crushed aggregates have been used for RCC.

At Tarbela [5.04], the bank or pit-run materials contained aggregates up to 220mm in size. In much of the work, as Japanese RCD dams, MSA was limited to 150 mm. The advantage of crushing oversize cobbles in bank gravels to reduce waste, improve strain capacity, and minimize segregation should be evaluated.

Compaction of RCC is influenced by aggregate size. However, MSA has little effect when the thickness of the placement layers is more than three times the MSA, segregation is minimum, and large vibratory rollers are used for compaction. When smaller size rollers are used for compacting materials adjacent to structures and abutments where high density and strength are needed, MSA should be limited and layer thickness may have to be reduced. There is a greater tendency for aggregates larger than 38mm to segregate when placed. The prevention of segregation should be considered when selecting transporting and spreading equipment and when specifying the placing and spreading methods.

If segregation does occur, measures should be implemented to disperse the segregated particles or rock clusters evenly over the uncompacted RCC. If material cost is a principal factor in the selection of the MSA, then the cost of controlling segregation should be considered or the consequences of segregation should be recognized in establishing strength, bonding, and permeability requirements.

Figure 5.19 Segregation in RCC proportioned with the same content of 76mm aggregate as CVC.

In massive concrete placements, control of the temperature rise should have a greater significance than materials costs in the selection of the MSA. The difference in cementitious materials requirements for mixtures with MSA from 38mm to 76mm is less in RCC than in normal-slump CVC. Where pozzolanic material is used, the generation of heat may be reduced substantially. The use of aggregates larger than 76mm may not be justified on the basis of either heat reduction or material cost saving.

Aggregate grading requirements for different RCC mixtures have varied significantly. Variations in aggregate gradation in the mixture directly affect variability of the RCC. Consistency can be achieved by separating aggregates into conventional size groups and recombining them in specified proportions. Although some projects have successfully used a single stockpile with an all-in grading, stockpiles separated into two or more size groups have also been used successfully. Where separate stockpiles are used, the split can be made near the midpoint of the grading or where a natural break in size fractions occurs.

5.4.3 Fine Aggregate (finer than 5mm)

The grading of fine aggregates strongly influences paste requirements and compactability of RCC. Grading of sand within the limits shown in ASTM C 33 have been used. This sand may require more cementitious material than is needed for lean mixtures using aggregates with more fines than ASTM C 33 allows.

Unwashed aggregates with a much broader gradation range than is specified by ASTM C 33 have also been used after studies (as seen in 5.3). The aggregate grading and the type and quality of fines content affects the relative compactability of the RCC and may influence the minimum number of vibrating passes required for consolidation of the full thickness of the layer. It also affects the water and cementitious material requirements needed to fill the voids in the aggregate and coat the aggregate particles.

5.4.4 Quality

The quality of the aggregate required for the RCC need be checked by standard tests, as mentioned in Figure 5.20. Information on grading and a means of determining the quality of the aggregate are required in the early stages of project design. Past experience with an aggregate source provides an indication of its quality.

Suitable aggregates for RCC can come from a variety of sources, but the material closest to the dam site should be investigated first. At Middle Fork Dam, an on-site marlstone (oil shale) was successfully used rather than importing known acceptable river gravel from a source 32km away. The RCC had a high compressive strength versus cement content, released heat slowly and had a high ratio of tensile strength to compressive strength. Durability was not considered because the RCC was capped with CVC, air-entrained concrete using the river gravel as aggregate.

Since higher strength concrete will be required for very high RCC dams the quality of the aggregate will have a greater effect on the cementitious content of the RCC mix and consequently on the in-place cost. Likewise, thermal characteristics of the aggregate will take on greater importance because of their impact on the cracking potential.

Characteristic	Significance	Test designation	Test name
Grading	Consistency, compactability economy	ASTM-C-136	Sieve Analysis of Fine and Coarse Aggregate
		ASTM–C-117	Materials Finer than 75 mm (No. 200) in Mineral Aggregates by Washing
Resistance to abrasion	Aggregate quality, resistance of surface	ATM–C-131	Resistance to Degradation of Small Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
		ASTM-C-535	Resistance to Degradation of Large Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
		ASTM-C-295	Petrographic Examination of Aggregates for Concrete
Soundness to AAR	Aggregate soundness to AAR	ASTM-C-227	Standard test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar Bar Method)
		ASTM-C-289	Standard Test Method for Potential Alkali-Silica Reactivity of Aggregates (Chemical Method)
		ASTM-C-1260	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)
Specific gravity-absorption	Mix design calculations	ASTM-C-127	Specific Gravity and Absorption of Coarse Aggregate
		ASTM – C-128	Specific Gravity and Absorption of Fine Aggregate
Bulk unit weight or density	Mix design calculations	ASTM –C- 129	Unit Weight and Voids in Aggregate
Sulfate resistance	Soundness against weathering and chemical attack	ASTM –C- 88	Soundness of Aggregates by Sodium Sulfate or Magnesium Sulfate
Organic impurities	Strength gain	ASTM C4O	Organic Impurities in Fine Aggregate for Concrete

Figure 5.20 Standard tests recommended for aggregates.

5.4.5 Grading

Grading for both coarse and fine aggregates and the proportions used have an important effect on the properties of RCC.

The difference in mix design philosophy has produced some differing trends with respect to specifying aggregates for RCC. This is especially true with respect to maximum size aggregate (MSA), percentage of sand and fines desired, and the number of separate sizes processed and then combined to produce the desired grading.

For concrete-approach RCC mixes, aggregate requirements are very similar to those for CVC mass concrete. The most common MSA has been about 75mm, although Tamagawa Dam used 15Omm MSA [5.27; 5.29], and Upper Stillwater Dam required 50mm MSA [5.30 to 5.32]. For a 75mm MSA, four aggregate sizes have traditionally been produced, especially for large-volume RCC dams. The ranges are 38mm to 75mm, 19mm to 38mm, 4.75mm to 19mm, plus sand (less than 4.75mm). The four aggregate sizes are then blended to produce the desired grading. Another possible method of producing similar results at lower cost is to start with a crushed river-run aggregate (MSA to fines) and add one or more of the sizes to meet grading requirements.

Particle shape and gradation of the aggregate, especially the fine aggregate, are also important factors along with cementitious content in determining the workability and density of the RCC, which in turn are directly related to strength and permeability. The workability requirement also affects the selection of mixing, delivery, spreading and compaction equipment. In order to avoid segregation of coarse aggregate at lift joints, consideration should be given to limiting the maximum size aggregate and increasing the percentage of fine aggregate in the RCC mixes. Though larger aggregate and less sand might be more economical in theory, the cost savings are usually offset by the labour costs required to control segregation.

Sand percentages have generally been between 30% to 50% of total aggregate [5.33]. The percentage of fines passing the Nº 200 (0.075mm) sieve was initially limited to 3 percent of the total weight of the aggregate, but this had a new approach, as mentioned in 5.3. At Elk Creek Dam [5.34], the range of minus 200 fines required was 10% to 18% of the fine aggregate, which is calculated to be about 3 to 6 percent of the total weight of the aggregate.

Soils approach mixes specified for many early RCC dams required 75mm MSA and 30% to 35% sand. However, with these drier-consistency mixtures, there is a greater tendency for the larger particles to segregate during transport, deposition, and spreading. Segregation can be minimized by reducing the MSA and by increasing the percentage of sand. There is a trend toward 50mm MSA and sand content in the 40% to 50% range.

The amount and type of Nº 200 sieve fines allowed have varied considerably. It has ranged from 0 to15 percent of total aggregate. In many cases, an unwashed aggregate can be appropriate for RCC.

As noted in Figure 5.04**,** the allowable range for non-plastic fines was 1.5% to 10%. The allowable percentage is reduced for more plastic fine aggregates, which are defined as those having a liquid limit (LL) greater than 25% and a PI greater than 5%.

RCC mixes made with excessive amounts of clay fines have shown a higher water demand due to the surface activity of the clay minerals. The increased water content increases shrinkage in the RCC and creates a greater potential for cracking and reduced strength. The general consensus is that fines should be non-plastic and allowed only to the extent that they fill voids and reduce water requirements and improve RCC cohesiveness and compactability.

Pit-run or as-dug aggregates produced with little processing except screening of oversize rock have been used in RCC mixes, particularly for dam modification projects. The largest of these was the 2.700.000m^3 mix of RCC used at Tarbela Dam [5.04] in Pakistan. This type of aggregate would be appropriate for RCC cofferdams. Cost and resistance to overtopping are major considerations for these structures, which have a relatively short life.

5.4.6 Aggregate Proportions

The amount of effort required to compact the mixture is directly proportional to the coarse aggregate volume. If there is sufficient paste, a wide range of coarse and fine aggregate gradations is not likely to significantly affect in-place densities of RCC compacted with large vibratory equipment. This may allow the use of available aggregates that do not conform to standard concrete specifications for gradation, to produce acceptable RCC.

The grading of fine aggregate will have an effect on minimum paste requirements. In areas where pozzolans are not readily available, it has been economical and beneficial to blend sands or introduce mineral fines to reduce fine aggregate voids, as mentioned above. The proportioning of blended sands or the benefit of adding mineral fines (as previously mentioned) can be determined by their effect on minimum paste volume requirements or by evaluation of test cylinders made with them.

The in situ density of concrete will depend to a great extent on the relative density of the aggregates to be used.

Fine and coarse aggregates should be proportioned to create a well-graded combined aggregate. The addition of material finer than the 0.075mm sieve may be necessary to supplement fine aggregate in order to reduce the volume of voids within the fine aggregate and to produce a more cohesive mixture.

The grading/distribution curve normally adopted by various authors and designs [5.35 to 5.59] is similar to a cubic type curve as shown in Figure 5.21. One of the characteristics of the cubic type curve is that it requires a certain amount of material below 0.075mm (N° 200 sieve). This amount is about 8% to 12% of the total aggregates in the mixture, as illustrated in Figure 5.21.

Another characteristic approached by the cubic type curve is the reduction of the coarsest part of the aggregates, which usually causes segregation. This may be seen comparatively in Figure 5.22, while observing the curves in Figure 5.21 and the combination of aggregates, normally used for CVC mass concrete, also shown in Figures 5.21 and 5.22.

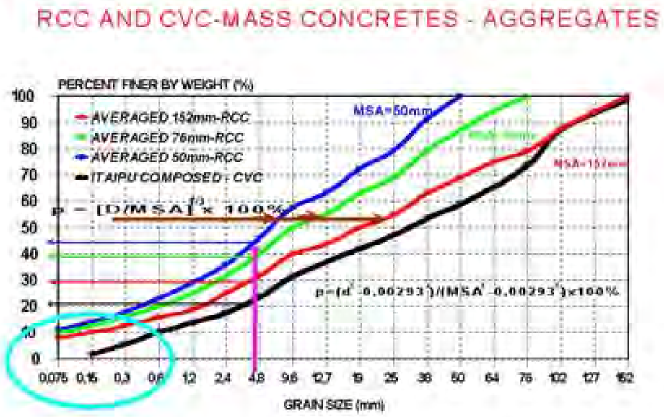


Figure 5.21 Cubic type grading curve, adopted in various designs and an aggregate combination curve for CVC mass concrete [5.35 to 5.59].

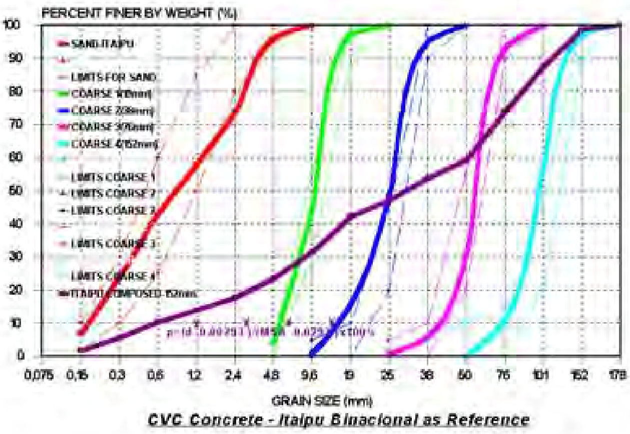


Figure 5.22 Curves of the individual fractions of each aggregate and the curve composed for CVC mass concrete (Itaipu CVC as reference).

The {sand}/{total aggregate} ratio normally considered in the CVC mass concrete studies varies for each aggregate set, considering that it reduces with the increase of MSA, as illustrated in Figure 5.22 [5.60 and 5.61]. The same may be observed for the RCC when using the cubic type curve, as illustrated in Figure 5.21.

One can observe, in Figure 5.21, when comparing the cubic curves adopted for RCC and those of the composed aggregates, that there is a greater RCC over mortared to CVC. From this observation, one may verify that the recommendation [5.27; 5.28; 5.29; 5.51; 5.52] that the {sand}/{total aggregate} relation be not inferior to 0.3, is generically followed.

In comparing the water content of the RCC and CVC of the same dams (that is with the same type of materials) (see Figure 5.23), one will observe that the RCC values are around 10% to 35% smaller, with around 30% predominance, for the RCC, which means approximately 30 l/m^3.

If this void is filled by fly ash or slag, with an absolute specific gravity around $2.2t/m^3$ to $2.9t/m^3$, this signifies about $70kg/m^3$ to $90kg/m^3$ more material in RCC. If the addition of fly ash or slag is not adopted, however using aggregates with an absolute specific gravity of $2.65t/m^3$ to $2.95t/m^3$, this signifies around $80kg/m^3$ to $90kg/m^3$ more material in RCC.

In reducing the cement content even more as in the lean RCC mixtures, the corresponding voids will need to be filled by fly ash, slag or by fine aggregate (or by aggregate filler).

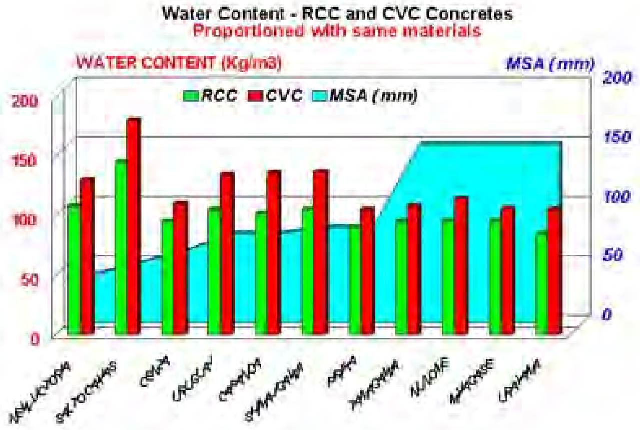


Figure 5.23 CVC mass concrete and RCC water content in the same dams.

It is at this point that the fine fraction of the cubic curve becomes important, for the fine fractions (inferior to 0.075mm) recommended in contents around 8% to 12%, serve to fill the voids previously mentioned, allowing to reach an adequate compaction ratio, consistency and cohesiveness.

There are, however, options for the filling of these voids, such as the use of fly ash, slag, or other pozzolanic material, but there is also the option of adopting the filler following the aggregate crushing, or of silt.

The fine fraction type to be used will depend on the availability for each worksite; however, it is important to remember that the choice must be made on a technic-economic basis.

5.5 Water

As RCC is a concrete, the usual requirement for water in CVC is adopted for RCC mixes. The requirement is that it is free from excessive amounts of alkalies, acids, or organic matter that might inhibit expected strength gain. Most RCC mixes require 90 to 160 kg/m^3 for MSA around 50 mm. Large amounts of fines (pozzolanic or filler) can increase the water demand. In general the quality of the water has relatively little effect on the final RCC, and is not often a source of problems.

It has been stated that most potable waters are suitable except those where the dissolved salts can exceed 1,000 ppm. It should be noted that a turbid water should be allowed to settle before use to remove suspended solids, which could have unexpected effects.

It is commonly given that if the water is potable, it is suitable for concrete, and this is true for municipal waters. However, this may be an onerous requirement for concrete; water that is not potable may still be satisfactory for making concrete.

Evaluation of unknown water may be carried out by means of chemical analyses and comparative mortar or concrete tests.

Chemical testing can provide results relatively quickly, and these limits cover the most common and deleterious impurities.

In order to conduct a comparative strength test, two sets of concrete specimens should be made, if possible using the materials and mix proportions to be used on the site. One set should be made with the suspect water and the second with water from a known, reliable source.

Sulphates can react with the constituents of hardened cement paste, causing expansion within the concrete and resultant softening and spilling. The severity of sulphate attack depends on the concentration of sulphates (as SO_3) and a limit of 500 mg/l of water is recommended to keep the concentration within harmless limits.

A content of 2,000 mg/l of sodium carbonate and sodium bicarbonate (together) has been reported as tolerable although it is recommended that comparative tests be carried out if their sum is greater than 1,000 mg/l. Other carbonates are of low solubility and have negligible effects whilst 400 mg/l of calcium or magnesium bicarbonate are reported as not being harmful.

Mineral oils are reported to have little effect and an upper limit of 2 % has been reported as acceptable. However, it should be noted that oil can be floated off the water relatively easily, and this is recommended in order to minimise potential problems.

The total amount of sugar in a mix influences the concrete. Less than 500 mg/l of sugar in the mixing water generally has little effect. However, a sugar content of 0,03% of cement weight results in a retarded set and an improvement in later strengths; 0,25 % sugar of cement weight causes rapid setting and a loss in strength.

Limits given in the literature range from 4-6 up to 8-8,5 for pH. It should also be noted that the high alkalinity of the water in the pores during hydration should neutralize any acidity in the mix water, and is little affected by alkalis in the water.

Organic acids should be avoided because their presence may affect the stability of the concrete. Seawater generally contains approximately 3.5% salts of which about 2% are chlorides. Treated effluent as mixing water has little effect on concrete. Raw effluent is also not recommended from the point of view of safety of those handling the concrete. The effect of industrial wastewaters depends entirely on the type of contaminant as well as its concentration.

5.6 Admixtures

The advantages of using admixtures that enhance workability and retard set for keeping conventional mass concrete alive and preventing cold joints, particularly during hot weather, are well established. Water-reducing and set-retarding admixtures have been used effectively in many projects mainly in China [5.62; 5.63] and Spain [5.64]. Other work in the laboratory and in field applications has indicated success with higher workability mixtures having VeBe times in the range of 10 to 30 seconds, as done at COPEL laboratory at Salto Caxias Dam site [5.65].

Plasticizers, otherwise known as water-reducing agents, have the effect of increasing the workability of the mix if the water content is unchanged. Alternatively, the water content can be reduced so that the workability is unchanged, which will result in stronger concrete with the same cement content, or both the water and the cement contents can be reduced, keeping strength and workability the same. In the latter case, the cost of the mix may be reduced (if the cost of the admixture and additional aggregates is required to maintain yield is less than the saving in cement cost).

With little success, air entraining, as well as water reducing and set-retarding, admixtures have been tried in RCC mixtures, with proportions based on soil principles. Due primarily to the dry consistency and fines content of these mixes, a proper air-void system has not been established at any application rate using normal batching or proportioning procedures.

There is a better chance for admixtures to be effective in wetter consistency mixes associated with the concrete approach. Mix design investigations revealed that the use of the water reducer retarded compressive strength development at early ages from 7 to 90 days and enhanced the strength gain after 28 days.

Figure 5.24 Consistency test of RCC mix using water-reducer /set retarder admixture.

MIX		J.2.e.6	T 7	T 4	T 6
Cement	kg/m^3	100	90	100	90
Water	kg/m^3	143	143	143	133
MSA	mm	50	50	50	50
Crushed Sand	kg/m^3	1142	1146	1141	1160
Coarse 25mm	kg/m^3	745	748	745	757
Coarse 50mm	kg/m^3	497	499	497	505
Plasticizer-Retarder	kg/m^3			1,0	1,26
Consistency	sec	32	25	29	32
Specific Gravity (theoretical)	kg/m^3	2627	2626	2627	2646
Specific Gravity (test)	kg/m^3	2606	2640	2624	2655
Compaction Ratio	%	99,2	100,5	99,9	100,3
Compressive	7 days	38	34	42	44
Strength (kgf/cm^2)	28 days	53	51	57	63

Figure 5.25 Data values from RCC consistency tests using water-reducer / set retarder admixture [5.65.].

5.7 REFERENCES

5.01 DAVIS, E. Raymond. "Historical Account of Mass Concrete", in: Symposium on Mass Concrete - Paper nº 1- ACI, SP-06 -1963.

5.02 STEELE, Byram W. "Height Limits of Dams without Longitudinal Joints or Cracks"- Symposium on Mass Concrete - Paper no. 3- ACI, SP-06 -1963.

5.03 ASTM-C- 618. "Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Concrete", in: Annual Book of ASTM Standards, 1996.

5.04 A.C.I. 207.5R – "Roller Compacted Mass Concrete".

5.05 SALLES, F. M.; OLIVEIRA, P.J.; ANDRIOLO, F.R. "Crushed Powder Filler - The Use on RCC and the Reduction of the Expansion due to the Alkalies- Aggregate Reaction". Santander Spain: International Symposium on Roller Compacted Concrete Dams, October-1995.

5.06 KREMPEL, A.F.; ANDRIOLO, F.R. "The Use of Basaltic Rock Crushed Powder (Filler) in the RCC". Santander Spain: International Symposium on Roller Compacted Concrete Dams, October-1995.

5.07 BRAGA, J.A.; ROSÁRIO, L.C.; DUARTE, J.D.C.; LACERDA, S.S. "Utilização de Finos - sub-Produto de Briatgemno Concreto Rolado e Convencional". Foz do Iguaçu, Brazil: XVIII Seminário Nacional de Grandes Barragens, 1989.

5.08 GOLIK, M.A.; ANDRIOLO, F.R."Uruguai (CCR) - "Quality Control of the Concrete Poured in the Main Branch of the Dam". Foz do Iguaçu, Brazil: XVIII National Seminar of Large Dams, 1989.

5.09 ANDRIOLO, F.R.; BRAGA, J.A.; ZANELLA, M.R.; ZALESKI, J.M. "The Use of Rolled Concrete. Capanda Project, Angola. Special Tests". Aracaju, Brazil: XIX National Seminar of Large Dams, 1991.

5.10 ANDRIOLO, F.R.; SCHMIDT, M.T. "The Capanda RCC Dam in Angola", in: International Water Power & Dam Construction, February 1992.

5.11 KREMPEL, A.F.; CREVILARO, C.C.; PAULON, V.A. "Powder Addition to the Concrete as an Economic and Durability Factor", in: 34th. Ibracon Meeting. Brazil, 1992.

5.12 CARMO, J.B.M.; NASCIMENTO, J.F.F.; FONTOURA, J.T.F.; SANTOS, M.C.; TRABOULSI, M.A. "Application of RCC with Additions",in: 35th. Ibracon Meeting. Brazil, 1993.

5.13 LEA, Frederick M. "The Chemistry of Cement and Concrete", in: Third Edition, 1970.

5.14 OLIVEIRA, P.J.; SALLES, F.M.; ANDRIOLO, F.R. "Studies of Various Types of RCC Mix Designs — Laboratory Test Results", in: International Symposium on Roller Compacted Concrete Dams. Santander, Spain, 1995.

5.15 TAVARES, M.; SCHMIDT, M.T.; RESENDE,F.; FONTOURA, P.T.; ANDRIOLO, F.R. "Capanda-Angola Hydroelectric Development — Quality Control of Materials and Conventional and Roller Compacted Concrete", in: International Symposium on Roller Compacted Concrete Dams. Santander, Spain, 1995.

5.16 ANDRIOLO, F.R. "RCC Properties", in: International Symposium on Roller Compacted Concrete Dams. Santander, Spain, 1995.

5.17 POWER, T.C.; STEINOUR, H.H. "An interpretation of Published Research on the Alkali-Aggregate Reaction", in: Journal of the American Concrete Institute, Title n° 51-26. Chigago, June 1955.

5.18 ASTM-C-311-"Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete", in: Annual Book of ASTM Standard-1996.

5.19 VIVIAN, H.E. "Studies in Cement-Aggregate Reaction: Effect on Mortar Expansion of the Particle Size of Reactive Component in the Aggregate", in: XIX Autralian Journal of Applied Science, 1951.

5.20 HANNA, W.C. "Unfavorable Chemical Reactions of Aggregates in Concrete and a Suggested Corrective", in: Proceedings ASTM- n° 47 – 1947.

5.21 STANTON, T.E. "Studies of Use of Pozzolans for Counteracting Excessive Concrete Expansion Resulting from Reaction Between Aggregates and Alkalis in Cement", in: Symposium on Use of Pozzolanic Materials in Mortar and Concretes, ASTM Special Technical publication n° 99 –1950.

5.22 ASTM-C-441. "Standard Test Method for Effectiveness of Mineral Admixtures or Ground Blast-Furnace Slag in Preventing Excessive Expansion of Concrete Due to the Alkali-Silica Reaction", in: Annual Book of ASTM Standard, 1989.

5.23 ASTM-C-1260. "Standard Test Methods for Potential Alkali Reactivity of Aggregates (mortar-Bar Method)", in: Annual Book of ASTM Standard, 1994.

5.24 BIAN Qighan; WU Xuequan; TANG Mingshu; NISHIBAYASHI, S.; KURODA, T.; WANG Tiecheng. "Effect of Reactive Aggregate Powder on Suppressing Expansions Due to Alkali-Silica Reaction", in: X International Conference on Alkali-Aggregate Reaction. Melbourne, Australia, 1996.

5.25 ACI- 221.R. "Guide for Use of Normal Weight Aggregates in Concrete".

5.26 ASTM-C-33. "Standard Specification for Concrete Aggregates", in: Annual Book of ASTM Standard, 1993.

5.27 KOKUBU, Masatane; SHIMIZU, Shigeaki; JOJIMA, Seishi. "Present State and Problems of Rationalized Construction of Concrete Dams in Japan". Lausanne: XV ICOLD, 1985.

5.28 YAMAGUCHI, Takeshi; HARADA, Joji; OKADA, Teruo; SHIMADA, Shoichi. "Construction of Tamagawa Dam by the RCD Method". Lausanne: XV ICOLD, 1985.

5.29 YAMAGUCHI, Jinro; OHYABU, Katsum; KATO, Toshiharu; KAMATA, Toshiharu. "Construction Work and Quality and Temperature Control for Tamagawa RCD Dam". San Francisco XVI ICOLD, 1988.

5.30 DUNSTAN, M. R. H. "Design and Construction Considerations for Roller Compacted Concrete Dams", in: XVI ICOLD. San Francisco, 1988.

5.31 DUNSTAN, M. R. H. "Design and Construction Considerations for Roller Compacted Concrete Dams", in: Water Power and dam Construction. London, January 1986.

5.32 DUNSTAN, M. R. H. "Rolled Concrete- With Particular Reference to its use as a Hearting Material in Concrete Dams". London: Concrete Society, 1978.

5.33 CRD-C- 161. "Standard Practice for Selectin Proportions for Roller-Compacted Concrete (RCC) Pavement Mixtures Using Soil Compaction Concepts. U.S. Army Corps of Engineers.

5.34 HOPMAN, D.R.; CHAMBERS, D.R. "Construction of Elk Creek", in: Roller Compacted Concrete II - ASCE Symposium, March 1988.

5.35 ANDRIOLO, F.R. "Contribuições para o Conhecimento e Desenvolvimento do Concreto Rolado". São Paulo, Brazil, 1989.

5.36 ELIAS, G.C.; CAMPBELL, D.B.; SCHARDER, E.K. "Monksville Dam - A Roller Compacted Concrete Water Suply Structure". Lausanne: XV ICOLD, 1985.

5.37 FORBES, B.A. "The Development and Testing of Roller Compacted Concrete for Dams in Australia", in: XVI ICOLD Congress. San Francisco, 1988.

5.38 BOUYGE, B.; GARNIER, G.; JENSEN, A.; MARTIN, J.P.; STERENBERG, J. "Construction et Contrôle d'un Barrage en Béton Compacté au Rouleau (BCR) : Un Travail D'Equipe", in: XVI ICOLD Congress. San Francisco, 1988.

5.39 BENCHEIKH, L.; TAYAE, M.; JAFRANE, S.; LAHLOU, K. "Barrage Ain Al Koreima en Béton Compacte au Rouleau, À Base D'Alluvions Naturelles Conception et Composition du Béton", in: XVI ICOLD Congress. San Francisco, 1988.

5.40 ARJOUAN, M., CHRAIBI, A.F.; EJJAOUANI, H. "Utilisation du Béton Compacté au Rouleau dans les Barrages de Faible Importance: Cas du Barrage de Rwedat", in: XVI ICOLD Congress. San Francisco, 1988.

5.41 MORSMAN, D.E.; LAWLER, L.E.; SEIMEAR, J.R. "Construction of Two Spillways Using roller Compacted Concrete", in: Roller Compacted Concrete - ASCE Symposium. May, 1985.

5.42 REEVES, G.N.; YATES, L.B. "Simplified Design and Construction Control for Roller Compacted Concrete", in: Roller Compacted Concrete - ASCE Symposium. May, 1985.

5.43 LEMONS, R.M.- "A Combined RCC and Reinforced Concrete Spillway",in: Roller Compacted Concrete II - ASCE Symposium. March, 1988.

5.44 DOLEN, T.P.; TAYABJI, S.D. "Bond Strength of roller compacted Concrete", in: Roller Compacted Concrete II - ASCE Symposium. March-1988.

5.45 OBELHOLTZER, G.L.. LORENZO, A.. SCHRADER, E.K.- "Roller Compacted Concrete Design for Urugua-i Dam", in: Roller Compacted Concrete II - ASCE Symposium. March, 1988.

5.46 BOUYGE, B.; LANGOIS A.P.; MARTIN, J.P. "Quality of Works in RCC in France", in: Roller Compacted Concrete II - ASCE Symposium. March, 1988.

5.47 DANTAS, J.E.E.; HOLANDA, F.G. "CCR- Uma Realidade Nacional Açude Público Saco de Nova Olinda- Paraíba", in: XVII Seminário Nacional de Grandes Barragens. Brasilia, Brazil, 1987.

5.48 DVORACEK, J.; HOBST, L.; PRIBYL, F. "Investigation of Gravity Dams Compacted By Rolling in High Layers", in: XV ICOLD. Lausanne, 1985.

5.49 PARENT, W.; MOLER, W.A..; SOUTHARD, R.W. "Construction of Middle Fork Dam", in: Roller Compacted Concrete - ASCE Symposium. May, 1985.

5.50 TUC-61-8005-RE. "Observações e Controles sobre o Concreto Rolado Aplicado na Eclusa 1 de Tucurui". Tucurui, Brazil, 1983.

5.51 RCD. *Concrete for Shimajigawa Dam,* 1979.

5.52 KURITA, M.; AOYAGI, Y.; ENDO, T.; OKUMURA, T. "Compaction Characteristics of Roller Compacted Concrete", in: Roller Compacted Concrete II - ASCE Symposium. March, 1988.

5.53 CROW, R.D.; DOLEN, T. "Evaluation of Cores from Two RCC Gravity Dams", in: Roller Compacted Concrete II - ASCE Symposium. March, 1988.

5.54 BAYAN, B.J. "Execution and Control of Castilblanco de los Arroyos Dam with Roller Compacted Concrete", in: XVI ICOLD Congress. San Francisco, 1988.

5.55 FUTIAN, J. "Relationship Between the Properties of RCC and Vibratory Characteristics of Vibrating", in: International Symposium on Roller Compacted Concrete Dams. Beijing, China, November, 1991.

5.56 MINGKUAN, M. "Study of Mechanism of RCC Vibration Compaction", in: International Symposium on Roller Compacted Concrete Dams. Beijing, China, November, 1991.

5.57 GAOMENG, X.; XIAOXIANG, Z. "RCC Mix Design and Application to thr Shuikou Project Diversion Wall", in: International Symposium on Roller Compacted Concrete Dams. Beijing, China, November, 1991.

5.58 YOUCHANG, L.; JIALI, H.; YANJI, H. "The Technique on RCC dam construction of Yantan Project", in: International Symposium on Roller Compacted Concrete Dams. Beijing, China, November, 1991.

5.59 ANDRADE, W.P. et alli. "Construção e Controle do Concreto Compactado a Rolo para as Ensecadeiras Galgáveis da Usina Serra da Mesa- Aproveitamento Hidreleétrico de São Felix", in: XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, 1989.

5.60 "Concreto Massa no Brasil- Memória Técnica-1 Registro Histórico", in: CBGB-Eletrobrás-IBRACON, 1989.

5.61 "ACI - Manual of Concrete Practice - Part 1".

5.62 ZENG LI and FANG KUNHE. "The setting state of RCC and the control of binding quality between the layers", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

5.63 SHEN CHONG GANG. "SPECIAL CONFERENCE- New technical progress of RCC dam construction in China", in; Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

5.64 VAL, Luis Cavero; CLAVER, Fernando Lacasta. "Aditivos Polifuncionales en las Grandes Obras Hidráulicas (Presa de Rilab)", in: Cemento-Hormigón- Instituto Español del Cemento Y Sus Aplicaciones. August, 1997.

5.65 VOCV-CX-RT-009/97. "Estudos Avançados do CCR na Margem Direita da Barragem da U.H. de Salto Caxias", in: COPEL. Paraná, Brazil, August/1997.

6

Design of Mixture Proportion

6.1 General

Roller Compacted Concrete (RCC) is a relatively easy and simple construction technique but unfortunately up to now has not yet had a consolidated methodology for design, proportioning mixes, and laboratory tests. Some authors or technical groups have shown trends or advantages in adoption a procedure for mix design. In general it could be pointed as a specific tendency or experience that cannot be accepted as a general rule.

There are a number of methods that have been used for the mixture proportions design of a RCC.

RCC mixture proportions should follow the convention used in traditional concrete that is: ***identifying the mass of each ingredient contained in a compacted unit volume of the mixture based on saturated-surface-dry (SSD) aggregate condition***. A practical reason for use of this standard convention is that most RCC mixing plants require that mixture constituents be so identified for input for the plant-control system.

A number of mixtures proportioning methods have been successfully used for RCC structures throughout the world. Projects have differed significantly due to the location and design requirements of the structure, the materials, the mixing and placing equipment, and time constraints. Approaches to mixture proportioning also differ significantly due to the philosophy of treatment of aggregates as either a CVC concrete aggregate or as an aggregate approached from the standpoint of a stabilized embankment. Mixture proportioning methods for the CVC concrete approach generally follow procedures similar to those used for mass concrete i.e., evaluating various aggregate proportions with known water to cementitious materials ratios [w/(c+pm)] to determine optimum proportions which meet proportioning requirements for strength, bond, and temperature considerations.

Emphasis is placed on determining optimum water content for compaction at fixed cementitious materials content. Selection of cementitious materials content and water content is determined from design requirements, generally compressive strength, with consideration of minimizing the cementitious materials content to avoid thermal cracking.

For a given design with structural element, environment and placement conditions, a concrete composition is defined in such a way that the evolution of its behavior conforms to what was asked of it.

It could be said that the mix design of a concrete is a process by which an adequate and economic combination of binder, aggregate, water, and admixtures can be obtained producing a concrete which performs to the required specifications throughout its service life.

There are many ways of reaching an objective, in this case the design of a RCC. The design engineer has to select structural features and options compatible with the attainable RCC mix properties. Compressive strength of RCC rarely dictates the mix proportions. Shear strengths are generally the controlling factor except where earthquakes may generate large tensile stresses. For low to moderate volume structures it is often advantageous to design a structure with sufficient section to allow RCC with low shear strength characteristics rather than to minimize the volume and require extraordinary shear strength performance. This needs to be balanced on a technical and economical basis.

It is the author's opinion that design features should take advantage of the economies of RCC construction, looking for simplicity, quality and cost efficiency. A mix design must assure the required property values, that no segregation should occur during handling operations and that performance requirements are met using the proper materials.

The diversity of structural designs, the environmental, geographical, and other conditions described in papers, justify why there are several types of concrete which differ in their composition and characteristics.

As a working system, based on some of the previous ideas, the following can be summarized:

1) Choose two continuous grading curves, one above and another below, as the theoretical reference. In that way the index coarse aggregate/fine aggregate is varied.

2) Mix according to reference curves several samples with different contents of cementitious material admixture and water.

3) For each mixture the following parameters are measured:

- Density
- VeBe consistency -time VeBe
- Mechanical strength – Compressive, Shear and Tensile
- Modulus of Elasticity
- Permeability

4) Choose the most adequate grading which minimizes the quantity of binding material for adequate time values of VeBe, and maximizes, in relative terms, the other parameters.

5) Introduce the adequate corrections, repeating the process, if it is necessary.

6) Obtain the confirmation of the chosen mix on a test slab.

RCC requires a mixture that will not subside excessively under the weight of a vibratory or other roller but which will have an appropriate grading and paste volume to consolidate adequately under the roller.

Projects which have steeper downstream slopes and smaller mass will typically require higher strength and hence more vigorous quality and production controls than dams designed with more massive, conservative sections. Similarly, higher dams will typically have zones requiring higher strength. The mixture must be proportioned by whatever means necessary to provide the strength, other material properties, and appropriate overdosing factors to meet all design requirements for stability and performance on a site-specific basis.

RCC exposed and submitted to severe climatic conditions and high seismic accelerations must be designed for durability.

Along with the various techniques of aggregate processing and stockpile control, there are various approaches to mixture proportioning. They differ primarily regarding the emphasis on theory, laboratory analysis, and practicability.

The basic considerations for selecting and proportioning RCC mixtures are gradation to minimize segregation, (as mentioned in Chapter 5), desired water content for compaction, and minimum amount of cementitious material for required mechanical properties and reduced amount heat from hydration.

The principal methods and ideas around mixing processes have numerous aspects in common such as the need to adjust the concrete to the available materials, required characteristics, and the placement as well as to the economic conditions. The backdrop to all this is the desire to obtain a compact concrete. RCC presents two fundamental differences in composition with respect to its CVC counterpart.

· First, RCC generally uses an aggregate combination that reduces the coarse fraction and increases the use of fine material. The fine fraction can be obtained by using a mixture of Portland cement and a very high proportion of pozzolanic material as cementitious material or increasing the finer portion (smaller than 0.075mm) that exists in the fine aggregate or yet, some silt-material available at the job site. The qualification and quantification of fines is a question of crucial importance. The consideration of a cubic curve type as adequate in the distribution of solid elements results in a high quantity of fines and a low coarse aggregate/sand ratio.

· Second, RCC contains a reduced quantity of mixing water, which is compatible with the transit of heavy duty earth-moving equipment over its surface, while it is still in a fresh state. This peculiarity of its placement means that RCC concrete must he studied and controlled when it is in a fresh state.

The binder plays two roles in a concrete. On one hand it is a filler and on the other hand, a cementing material. The qualification and quantification of the solids which pass through sieve n°. 200 (0.075mm) is of extraordinary importance for concrete.

Required bond strength of joints, permeability and seepage control, thermal cracking potential, and durability requirements may influence materials selection and proportioning of RCC mixtures also.

RCC has a "**no slump**" consistency and is densified by external loading and vibration of a roller. It is therefore "compacted" rather than "consolidated". This requires much lower water content than for comparable strength of conventionally placed concrete and provides the ability to support compaction or spreading equipment. Mixture proportioning procedures reflect the need for a consistency that is different from "slumpable" mixtures.

A major concern in RCC design is the potential for incomplete bonding of the layers. This problem has been accommodated by reducing the time interval between lift placement and by providing supplementary joint treatment.

6.2 Mixture Proportioning - Routines

The basic objective in proportioning RCC mixtures is to produce a concrete that satisfies the performance requirements using the most economical combination of readily available materials, placed by roller compaction methods. The desired physical properties of the mix depend on the function, location, and design chosen for the structure. The strength is dictated by minimum structural safety requirements with some overdosing factor to account for variability in the mix together with appropriate factors of safety. See Chapter 7 for RCC strength obtained at various dams.

Based on the type of structure, available materials and their cost, some considerations that need to be addressed initially include the quality and maximum size of the aggregate to be used, the type of cement, and whether pozzolanic material will be used and to what extent. All of the methods should include the preparation of trial mixes to confirm that the consistency is suitable for roller compaction. This is usually confirmed in a test section using the placing method and equipment that are planned for the dam. If the laboratory determined mix proves unsuitable for construction, the mix must be adjusted accordingly.

Just like the conventional concrete, roller compacted concrete have to comply with the following conditions:

· Density
· Watertightness
· Strength
· Durability
· The ability to be transported, spread and compacted without detrimental segregation
· Economy

All these factors depend on the porosity of the material. A concrete, being so much more resistant and durable the less its porosity. For this reason it is essential that RCC should be proportioned, mixed, and handled on the job and provided with an adequate compaction.

As it has been already indicated binding material contents are very variable oscillating between 50 and 250 kg/m^3.

Five routines for determining RCC mixture proportions for dams are normally adopted and are called:

I. Proportioning RCC to meet specific limits of consistency.

II. Trial mixture proportioning for the most economical aggregate-cementitious materials combination.

III. Proportioning using soil compaction concepts.

IV. RCD Japanese concept.

V. Army Corps of Engineers method.

6.2.1 Proportioning RCC to Meet Specific Limits of Consistency

6.2.1.1 General Concept

Proportioning for optimum workability for compaction was used as the basis of the U.S. Bureau of Reclamation's [6.01] Upper Stillwater Dam and the Corps' Elk Creek Dam. The high-paste mix design method was developed by Dunstan [6.02 to 6.06] and modified by the U.S. Bureau of Reclamation for its design of Upper Stillwater Dam. In designing a mix for a high-paste-content RCC dam two conflicting requirements must be resolved. The method points that sufficient cementitious material is needed to achieve a low permeability and assure the bond (and cohesion) between successive lifts of RCC. At the same time, the volume changes produced by heat generated by the cementitious materials must be minimized. The problem in this proportion mix method has been solved with substantial substitution of cement by pozzolanic material **as long as a suitable pozzolanic material is available at a reasonable cost**.

The modified VeBe compactability test [6.07; 6.08] is used as the basis for determining workability and optimizing aggregate proportions.

The modified Vebe apparatus consists of a vibrating table of fixed frequency and amplitude with a 0.01m^3 container attached to it. A loose RCC sample is placed in the container under a surcharge at either 9.0 or 22.5 kg (this is one of the differences between the routines) and the sample is vibrated until "fully" (there is another difference here) consolidated.

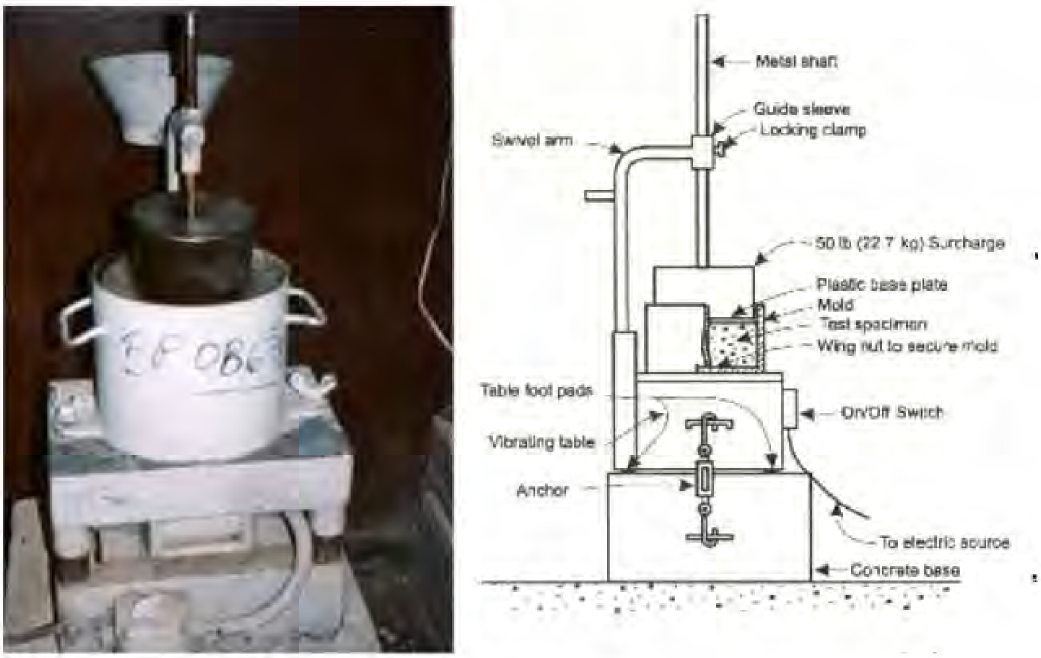


Figure 6.01 Modified VeBe apparatus.

MIX		**E-5913**	**E-5906**	**E-5907**	**E-5908**	**E-5912**	**E-5926**	**E-5917**	**E-5918**	**E-5919**	**E-5920**
Cement	kg/m^3	100	100	100	100	100	120	120	120	120	120
Water	kg/m^3	120	130	140	150	160	120	130	140	150	160
MSA	mm	50	50	50	50	50	50	50	50	50	50
Crushed Sand	kg/m^3	1153	1140	1126	1112	1098	1044	1032	1021	1009	997
Coarse 25mm	kg/m^3	790	781	772	762	752	844	833	823	813	802
Coarse 50mm	kg/m^3	527	521	514	508	502	563	555	548	542	535
Consistency	sec	35	32	20	14	7	40	26	21	15	9
Specific Gravity (theoretical)	kg/m^3	2690	2672	2652	2632	2612	2691	2670	2652	2634	2614
Specific Gravity (test)	kg/m^3	**2637**	**2654**	**2653**	**2648**	**2676**	**2711**	**2723**	**2705**	**2673**	**2670**
Compaction Ratio	%	98,0	99,3	100,0	100,6	102,5	100,7	102,0	102,0	101,5	102,1
Compressive	7 days	49	46	41	39	29	73	65	52	46	41
	28 days	75	73	58	53	44	120	95	86	76	69
Strength (kgf/cm^2)	90 days	121	104	89	76	69	168	128	124	107	98

Figure 6.02 Water content and maximum densities.

The VeBe time is determined and compared with on-site compaction tests with vibratory rollers. The optimum time can be determined based on density tests and evaluation of core samples. This optimum VeBe time will be influenced by mixture proportions particularly water content, MSA, sand content, and fines content under 0.075mm (№ 200 sieve). Mixtures generally require a VeBe time of 20 to 30 seconds to compact for samples with 38mm to 50mm MSA.

6.2.1.2 Water content

The effect of vibration time and water content on the compacted density of RCC is shown in Figure 6.02. Maximum densities in percentage (air free) occurred at a vibration time of 50 seconds with very little density increase, if any, under extended vibration time.

If the water content is too reduced there will be a point at which the strength will no longer increase with a decrease in w/(c+pm) ratio. This is because aggregate voids will no longer be filled with paste and entrapped air will be enclosed.

6.2.1.3 Cementitious Materials Content

The cementitious materials content should be based upon laboratory tests or test fills where cement content is varied for an aggregate gradation that will not segregate. The cementitious materials content will be dependent upon required strength, bond, and thermal considerations. Higher strength mixtures will require higher cementitious materials content at a desired water content. Greater use of a pozzolanic material may be required to minimize heat generation.

6.2.1.4 Proportioning Coarse Aggregates for Minimum Mortar Requirements

The proportioning of coarse aggregates depends upon the combined effects of aggregate voids, surface area, and particle shape. When grading is controlled by screening and dividing the aggregates into separated size fractions the void content may be controlled within limits. Dry-rodded densities and combined grading control are dependent upon the proportioning and number of separated sizes and the variation of grading within the individual sizes. Provided the grading control is satisfactory the dry-rodded density will increase with maximum aggregate size. Therefore, since void content decreases with increased dry-rodded weight, the void content of aggregates with the same specific gravity in each size range will decrease with increased aggregate size. It is also well established that the total surface area of the aggregate will decrease as the proportions of large aggregate per unit volume are increased. Compactibility increases with rounded and cubical shapes and decreases with flat shapes.

Segregation problems may be encountered with skip grading due the increased proportion of the larger size particles. In conventional concrete the proportions of smaller sizes are generally increased to reduce segregation. It is also economical to utilize all size groups and reduce waste of the smaller aggregate fractions.

6.2.1.5 Proportioning Fine Aggregate for Minimum Paste Requirement

The void content of fine aggregate as determined in dry-rodding weight measurements normally ranges from 34% to 42 %. The actual void content may be somewhat smaller due to the inefficiency of the measurement. It makes though little difference since the minimum cement, pozzolanic material, air, and water contents required to achieve a solid volume must fill all the fine aggregate voids and coat all the aggregate particles. The minimum paste volume can thus be determined by maximum density curves in much the same way as optimum water content is determined for soils. The procedure is as follows:

I) Using the water-cement ratio or water total cementitious material ratio requirements of the mixture, add fine aggregate in equal increments and measure the density of specimens using soil compaction procedures or extended vibration.

II) Plot density versus the calculated paste volumes.

III) Determine the paste volume producing maximum density of the mortar specimens. This paste volume, as a ratio of the total mortar volume, should be increased from 5 to 10 % in proportioning the mass mixtures. For special mixtures designed as bedding mixtures for construction joints, this minimum paste volume ratio should be increased from 20 to 25 %.

6.2.1.6 Selecting RCC Mixture Proportions

The consistency of no-slump mixtures proportioned in accordance with [6.09] will not carry the weight of large vibrating rollers without some alteration of the procedure.

Because all of them are based on a VeBe time (or VC value)- indicating full consolidation of the RCC- the basic premise of these methods is that the volume of paste must exceed the aggregate voids. Therefore, there is a greater need to closely control the aggregate grading to minimize voids and the amount of paste required. All involve proportioning mixes using absolute volume concepts in which the weights and specific gravity of all materials are used to calculate a unit volume of concrete. The final mix therefore consists of batch weights to produce a cubic meter of RCC.

Concrete approach mix design methods usually involve fixing all but one of the basic materials (cementitious materials, water, or aggregate content) and then varying that component until the desired consistency or required properties are achieved. Each variable can be adjusted this way to optimize all mix components.

The steps in the mix design procedure used by this approach are:

(a) In addition to determining densities and thereby specific gravity of the cement (c), pozzolanic material (pm), coarse aggregate (ca), water (W), and sand, the void ratio of total aggregate is determined. The "ca" and sand conform to standard gradations for conventional concrete.

(b) Determine a required w/(c+pm) ratio by weight based on the design compressive strength requirements at a certain age. For 29.7MPa at one year, a w/(c+pm) of 0.5 is required, whereas for 15.9MPa at one year the w/(c+pm) is 0. 7.

(c) Determine a relationship of "c" to "mp" that will produce the desired compressive strength within a specified time.

(d) Determine a mortar percentage based on the requirement that the volume of mortar should exceed the volume of voids by 5% to 10%.

(e) The coarse aggregate percentage can now be calculated by subtracting the mortar percentage from 1.0.

(f) It is assumed an entrapped air volume of 1.5%.

(g) All the necessary values have been determined to calculate batch weights for 0,5m^3 of RCC based on saturated surface dry (SSD) condition of the aggregates.

(h) A trial mix is proportioned in the laboratory and a VeBe time is measured. If the VeBe time is not within the desired range, adjustments are made in the mix, mainly in water content. A water content change initiates revisions in other material proportion and the mix is adjusted until all basic requirements are satisfied including consistency

(i) The mix can be further refined by more testing. In order to study various combinations of components such as pm/c, w/(c+pm), (c+pm)/sand, or various sand gradations, mortar specimens can be used, while changing one variable and keeping the others constant.

6.2.2 Trial Mixture Proportioning for the Most Economical Aggregate-Cementitious Materials Combination

6.2.2.1 General Concept

This proportioning method is generally associated with low-cementitious content mixtures. Aggregates selected for use in this proportioning method were usually those with minimal or no processing. Cementitious materials, water and fines are proportioned to yield the necessary strength, workability and paste volume requirements based on experience. Mixtures are proportioned to the desired workability level for a range of cementitious content and pozzolanic material substitution, fines contents, and other variables. The resulting family of performance curves is then used to determine the materials proportion that will exhibit the desired properties.

Designers of a number of RCC structures have proportioned the concrete mixtures using a relatively fixed grading of aggregates while varying cementitious contents. The minimum cementitious content which provides the required design strength and a field usable mixture is then selected for the project. This procedure has been used extensively with cementitious materials contents ranging from about 30kg/m^3 to 300kg/m^3 giving strengths at one year ranging from about 4MPa to 40MPa.

6.2.2.2 Water Content

The water content is controlled to achieve maximum density during compaction. During the first few batches of RCC the water content is varied to establish the optimum moisture. Once the water content is established it typically will vary little or not at all as the cement content is changed through a wide range of values. During construction control of water content is largely visual as determined by the placing inspection for optimum compaction and confirmed by density test. The amount of water added at the plant should allow for whatever loss occurs by evaporation during transport and placement.

6.2.2.3 Cementitious Materials

Usually, trial mixtures varying pozzolanic material contents are made to optimize the most economical cement and pozzolanic material combination that meets design requirements. When the option to produce or excavate suitable natural fines exists. A series of mixtures can be made to establish what reduction in cement or pozzolanic material might be achieved by adding more fines.

6.2.2.4 Aggregates

With the borrow sources available (gravel, quarry materials, river sands, and silts), the most economical combination of raw materials to produce a smooth overall grading within the general broad limits if a curve type p = $[\{d/MSA\}^{1/3}]$ +/- 5% is used as a fixed grading for the project and the basis for mixture proportioning. Experience has shown that any smooth grading within this band will produce a compactible RCC.

The admissible fines content depends on plasticity. If the fines are non-plastic greater percentages are convenient and allowed. As much as 10% fines by weight of total aggregate have been used successfully in some RCC mixtures. More than four times the normally allowed graded sand in concrete. Adding well-graded non-plastic fines may improve compactibility, impermeability, and strength.

The sand content is usually higher than that of CVC mass concrete ranging from 30% to 50%. This provides cushioning for the larger sized aggregate, minimizes breakage from compaction, minimizes segregation, and aids in compaction.

6.2.2.5 Selection of the Project Mixture

The two mix design routines (6.2.2 and 6.2.3 ahead) that fall within the soil approach are quite similar. They both start with a desired grading for the aggregates and involve the preparation of cylinders with varying cementitious contents to determine strength or other properties. **Differences in the two methods center on how the moisture or water content for the mix is determined and on laboratory method of specimen preparation.**

This method starts with a fixed aggregate grading. It varies cementitious contents and compares results, primarily compressive strength, with the project requirements. A continuous aggregate-grading band is typical of this method. A 75mm MSA is usually selected for what is termed the most economical usable gradation. The amount of water used for laboratory trial mixes is determined by observing the consistency of mixes of varying water content and by relying on past experience. The water content is set somewhere between the point on the dry side where voids are no longer visible on the side of laboratory cylinders and on the wet side before the mix has a rubbery appearance.

With the aggregate grading and water content now fixed laboratory specimens are prepared with varying cementitious content using a pneumatic pole tamper. Most mixes that have resulted from this method have varied from 60 to 150 kg of cement per cubic meter except for special mixes. This level of cement content provides a good starting point for laboratory mix design investigations. If use of a pozzolanic material is desired, another set of specimens should be prepared using a set percentage of pozzolan with respect to total cementitious content. This percentage usually varies from 25% to 50%. Typically the laboratory mix design program consists of two cylinders prepared for testing at 3, 7, 14, 28, 90, 180, and 365 days. If there is insufficient time to obtain results at later ages, the compressive strengths can be estimated based on the curve shape for the early ages, test results from previous projects using the same method, or by accelerated test methods.

Using the test data a family of graphs can be drawn showing the effect of these variables as well as age on material properties. The mix design program thus provides a family of curves that indicate the effects of various cementitious contents on compressive strength at various ages. The cement content can be selected to meet project requirements with consideration of factors of safety and coefficients of variation. Once a cement content is selected, additional tests may be run varying aggregate type or grading, especially the percentage of fines passing the Nº 200 (0.075mm) sieve.

6.2.3 Proportioning Using Soil Compaction Concepts

6.2.3.1 General Concept

This method is a geotechnical approach similar to that used for selecting mixture proportions of soil-cement and cement-stabilized base mixtures. Instead of determining the water content by VeBe time or visual performance the desired water content is determined by water content/density relationship of compacted specimen [6.13].

The same fundamentals have been the basis for determining cement content for soil-cement mixes for more than 50 years. The basic method is quite similar to the previous method. It starts with a fixed aggregate grading and performs a test program of varying cementitious content and comparing results once water content is determined. Rather than a visual determination of water content the "optimum moisture content" is determined by the moisture-density principles using impact compaction with a standard hammer or hammer dropped a prescribed number of times. A modified Proctor compactive effort of 2693kJ/m^3 has been used for most current projects, although some researchers have suggested some lower compactive effort. A 4.5kg hammer dropping from 450mm height per unit volume defines the compactive effort.

RCC mixtures have successfully been proportioned using soil compaction procedures. This method involves determining the maximum dry density of materials using modified compaction procedures and can be considered an extension of soil-cement technology. Optimum water contents are established using procedures to determine optimum water contents of soils. Compaction test equipment for RCC requires modification. A cylindrical container and an equivalent modified AASHO procedure can be used to determine the dry density curve for RCC. In order to determine a distinct peak to the maximum density curve, the cementitious material content of all specimens should be constant and the aggregate grading should be in the mid-range of the specification limits. Variable results may be expected unless the gradation and moisture content of the aggregates are maintained relatively constant. The peak of the density curve indicates the point corresponding to the minimum paste volume needed to fill all aggregate voids.

Variations of this method have been used depending upon the mixture composition and nominal maximum size of aggregate. Compaction equipment may be Standard Proctor or some variation of this equipment to better suite large aggregate mixtures. An alternative tamping/vibration method that simulates field compaction equipment and obtains similar densities has also been used.

In this method a series of mixtures varying water content within a range are prepared and batched. Each mixture has a cementitious content and is compacted with a standard effort. The maximum density and optimum water content are determined from a curve of density versus water content, one for each cementitious content.

The actual water content used is usually slightly higher (about 1%) than the optimum value determined in the laboratory to compensate for moisture loss during transporting, placing and spreading. RCC specimens are then made at optimum or the designated water content for strength testing at each cementitious content.

RCC has also been proportioned using soils compaction equipment similar to the ASTM-D-1557 (Modified Proctor) test method. Modifications were made to compact specimens in a 150mm by 300mm mold rather than the 100mm by 200mm mold used for larger sized aggregate. The compaction depends upon the energy imposed to the specimen. As mentioned, density with the compactive effort of modified Proctor test of 2693kJ/m^3 has been found close to in-place measurements, provided that water content is near optimum.

6.2.3.2 Water content

The optimum water content in the soil compaction methods will depend on the aggregates, the cementitious materials content, and the compactive effort applied. It represents the minimum paste volume required to fill voids at a compactive effort. Loss of strength will occur with a water content bellow optimum due to the presence of entrapped air as well as above optimum due to a higher w/(c+pm) ratio. Water content is expressed as percent of moisture weight by dry weight of solids. It will vary with the specific gravity of materials and values of absorption. Therefore, it is difficult to compare strengths at different mixtures due to the variation of w/(c+pm) which depends on the dry (SSD) water content.

6.2.3.3 Cementitious materials content

The cementitious materials content is determined by compressive strength at optimum water content for different mixtures. Cement and pozzolanic have been used for this mixture proportioning method and are again expressed as a percentage of dry weight of solids. Cementitious materials contents have ranged from 7% to 15% by dry weight of solids which have dry densities ranging from 1920kg/m^3 to 2240kg/m^3 (this is another difference). The range may correspond to approximately 150kg/m^3 to 300kg/m^3 when expressed in solid weight per unit volume.

6.2.3.4 Aggregates

The work performed at Tarbela Dam used an MSA ranging from 150 to 230 mm. In the USA the MSA has been generally limited to 51mm to 76mm and the full RCC mixture can be used in density testing. It is important that fines content under 0.075 mm (Nº. 200 sieve) should be sufficient to apply soil compaction procedures. The average grading specified is shown in Figure 6.03. Fines content has averaged approximately 12% of the total aggregate content while fine aggregate content is 35%approximately. Variation in aggregate materials and moisture content will lead to variation in densities achieved and corresponding concrete properties.

Size (mm)	Specified Range - % Passing	Average Range - % Passing
50	100	100
19	56 to 91	70
9.5	38 to 80	49
4.75	26 to 65	35
2.00	10 to 49	25
0.425	12 to 25	18
0.075	9 to 16	12

Figure 6.03 Aggregate grading for RCC aggregates using modified soil compaction methods cumulative percent passing [6.10].

6.2.4 Japanese RCD-Roller Compacted Concrete for Dams

6.2.4.1 General Concept

RCD should be lean concrete in order to prevent temperature cracks due to heat of hydration of cement. It should be extremely stiff concrete for the compaction by vibrating rollers. At the same time, RCD has plenty of cement filling the void between aggregates and satisfying the strength requirement. The RCD method of optimizing the mixture proportions is based on considerable experience acquired during the construction of many RCD dams in Japan. Though similar to the "concrete" approach it makes greater use of the VC consistency apparatus [6.15]. There are two different apparatus: the standard and a larger. The VC testing device with the standard container is in general use.

6.2.4.2 Consistency of RCD

The consistency of RCD can be measured by two VC testing devices [6.15]. In the standard VC test the RCD with its aggregates larger than 40 mm removed by wet- screening, is poured into the standard container. The RCD in the container is then vibrated. The time in seconds when the paste covers up the entire surface of the specimen is defined as a standard VC value. The optimum VC value of RCD compacted by vibratory roller has been determined as 20 seconds. A larger apparatus is used for RCD with full size aggregates. This VC value is called the large-sized VC value. A 60 second vibration time with the larger apparatus has been found to be equivalent (so, why use 2 different apparatus ?!) to a 20 second vibration time on the standard apparatus.

The standard VC testing device consists of a standard container with inside diameter of 24 cm and inside height of 20 cm. The large VC testing device has a container with inside diameter of 48cm and inside height of 40 cm. The VC testing device with a standard container as shown in Figure 6.04 is used in general.

Figure 6.04 VC testing device with standard container.

In the VC test with a standard container, RCD whose aggregates larger than 40 mm were wet-screened, is poured into a standard container. Then RCD in the container under a weight of 20kg is vibrated on the vibrating table of the VC testing device. The table vibration has a 3000 cpm frequency and 1mm of full amplitude. The time needed by the paste to come up over the whole RCD surface in the container is measured in seconds and is defined as a standard C value or a VC value. The optimum VC value of RCD compacted by vibrating rollers is 20 seconds.

The large container is used for RCD of full size aggregates. The vibration specification and surcharge of the large specimen is the same as that of the device with a standard container. The VC value which is measured by the VC testing device with a large container is called "Large-Sized VC" value. The 60 seconds of a large-sized VC value is equivalent to 20 seconds of a standard VC value. The VC testing device with a large container is used occasionally when the optimum sand aggregate ratio of RCD is examined.

The procedure for the design of the mixture proportions of RCD is summarized in Figure 6.05 and as follows:

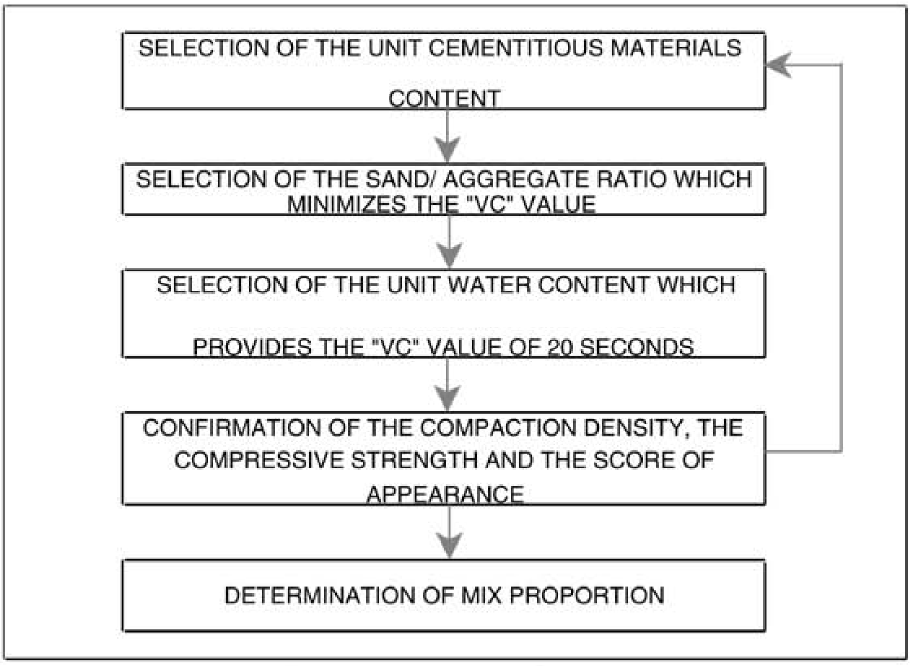


Figure 6.05 Procedure of mixture design of RCD [from 6.15 to 6.19].

(a) Select the cementitious material content: A cementitious content of 120 kg/m^3 is used for most dams although 130 kg/m^3 [6.16; 6.17] is used for high dams and for those requiring higher strengths. Cement content should be as low as possible while being consistent with strength requirements. Some fly ash should be used as an admixture to reduce heat of hydration and mixing water requirements. Thirty percent of the cementitious material is usually fly ash, although ground-granulated blast-furnace slag has been used in a recent dam [6.18; 6.19]. In usual cases, 30% of cement is replaced by fly ash to reduce the hydration heat.

(b) Select the fine aggregate/coarse aggregate ratio giving the minimum VC value: In the procedure of the mixture design of RCD the optimum sand aggregate ratio is selected first. The optimum sand aggregate ratio is defined as the sand aggregate ratio that minimizes the VC value. Figure 6.06 shows the typical result of the VC test determining the optimum sand/aggregate ratio. The large VC testing device is occasionally utilized to determine the optimum sand aggregate ratio. A sand/aggregate ratio higher than for conventional mass concrete should be used to reduce segregation and to facilitate compaction by a vibratory roller. The grading of coarse aggregate for maximum unit weight is determined by unit weight tests using a vibrating table with varying percentages of the particle sizes of coarse aggregate. VC values are determined for each mixture. The sand/aggregate ratio producing the lowest VC value is selected. Tests in Japan indicate that there is a sand/aggregate ratio that produces a minimum VC value using a large container. This ratio is in the range of 30% to 32%. A cement content versus compressive strength test series then is used to determine the final cementitious- content and the mix is ready for field trials.

(c) Select the water content that corresponds to a VC (standard apparatus) of 20 seconds: Next, the optimum unit water content is selected. The optimum unit water content is defined as the unit water content that provides a VC value of 20 seconds. Figure 6.07 shows the typical result of the VC test determining the optimum unit water content.

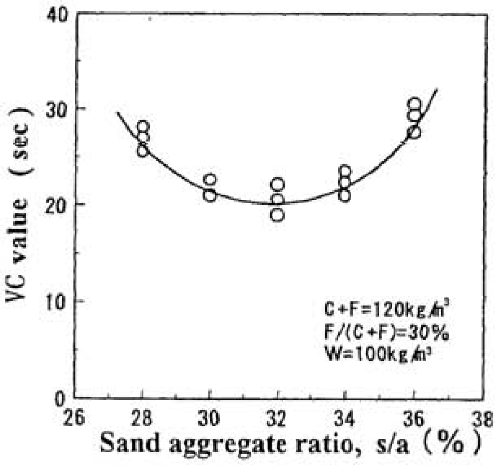


Figure 6.06 Relationship between sand aggregate ratio and VC value (large container) [from 6.15 to 6.19].

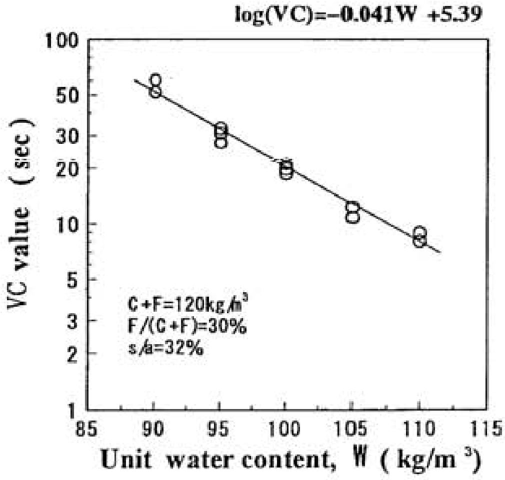


Figure 6.07 Relationship between unit water content and VC value [from 6.15 to 6.19].

(d) Review the density: The compaction test of RCD is conducted in order to confirm the compaction density, the strength, and the watertightness of RCD. The field compaction device has been developed and is utilized efficiently in the compaction test of RCD. Figure 6.08 shows the large-sized specimen compaction device. In the compaction test, full-sized RCD is poured into a container with inside diameter of 50 cm and inside height of 45 cm and is compacted for 60 seconds by a vibrating compactor which simulates an actual vibrating roller. The vibrating compactor has a mass of 648kg and can generate a compaction force of 3,109kgf with frequency of 1,900cpm and full amplitude of 2.4 mm;

(e) Choose the final mixture proportions.

(f) **Undertake trial compaction of large-sized specimens in the larger VC apparatus.**

In addition to the above procedures, the use of limestone dust as mineral fines in the fine aggregate in RCD mixtures has been investigated. It showed significant benefits regarding consistency and strength [6.20].

Figure 6.08 Large-sized specimen compaction device.

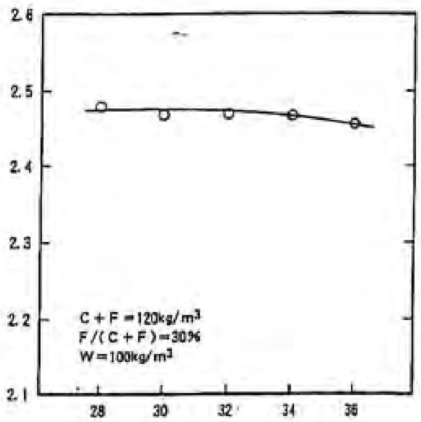


Figure 6.09 Relationship between Sand Aggregate Ratio and Compaction Density [from 6.15 to 6.19].

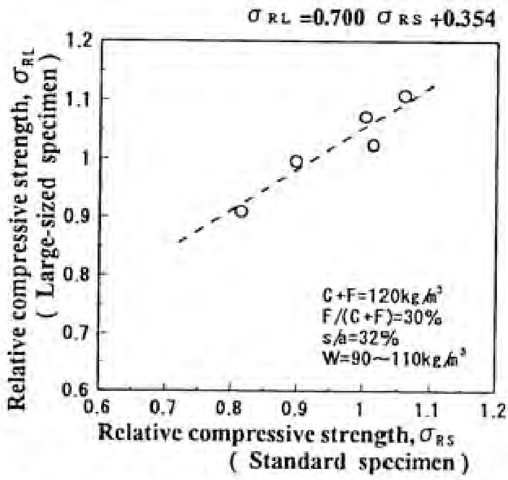


Figure 6.10 Relationship between Relative Compressive Strength – Standard and Large sized Specimen [from 6.15 to 6.19].

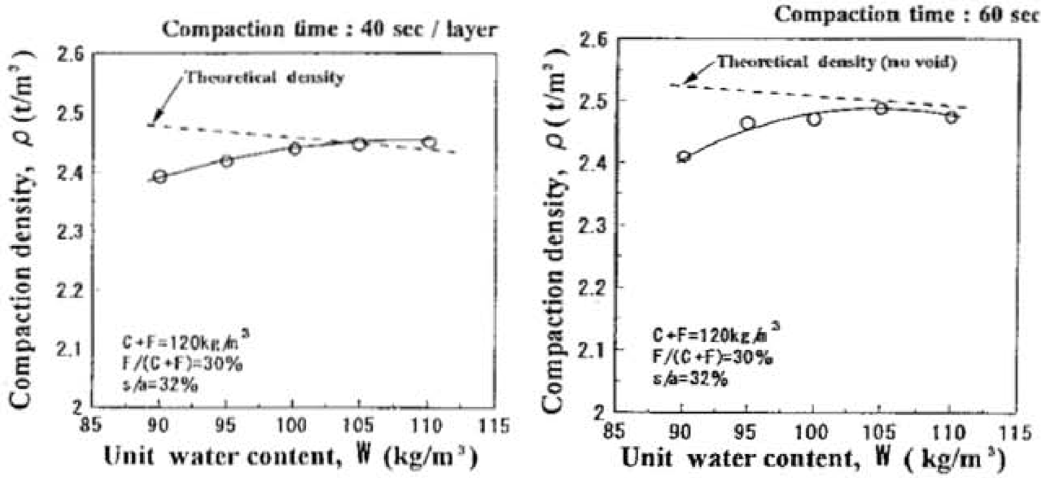


Figure 6.12 Relationship between Unit Water Content and Compaction Density [from 6.15 to 6.19].

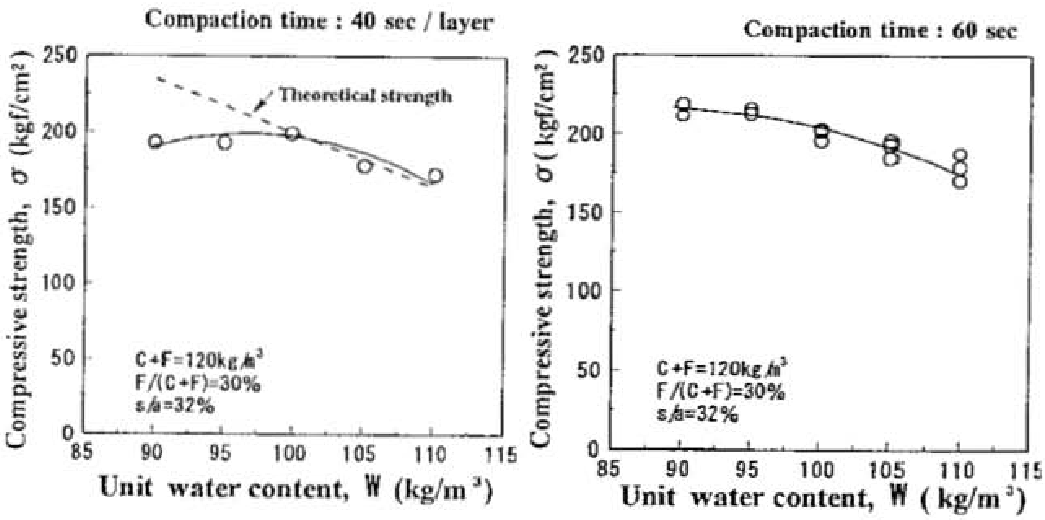


Figure 6.13 Relationship between Unit Water Content and Compressive Strength [from 6.15 to 6.19].

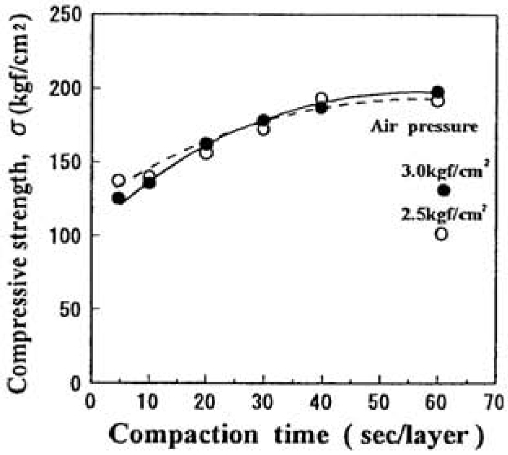


Figure 6.11 Relationship between Compaction time and Compressive Strength [from 6.15 to 6.19].

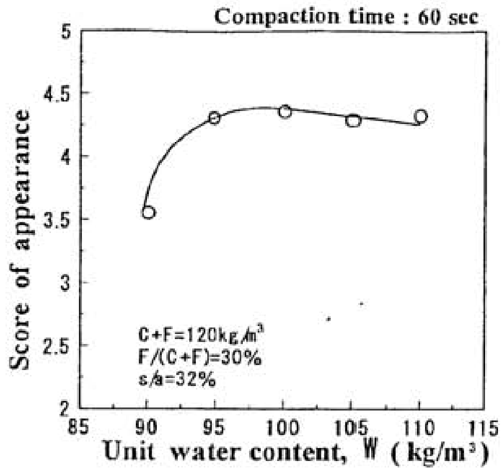


Figure 6.14 Relationship between Unit Water Content and Score of Core Surface [from 6.15 to 6.19].

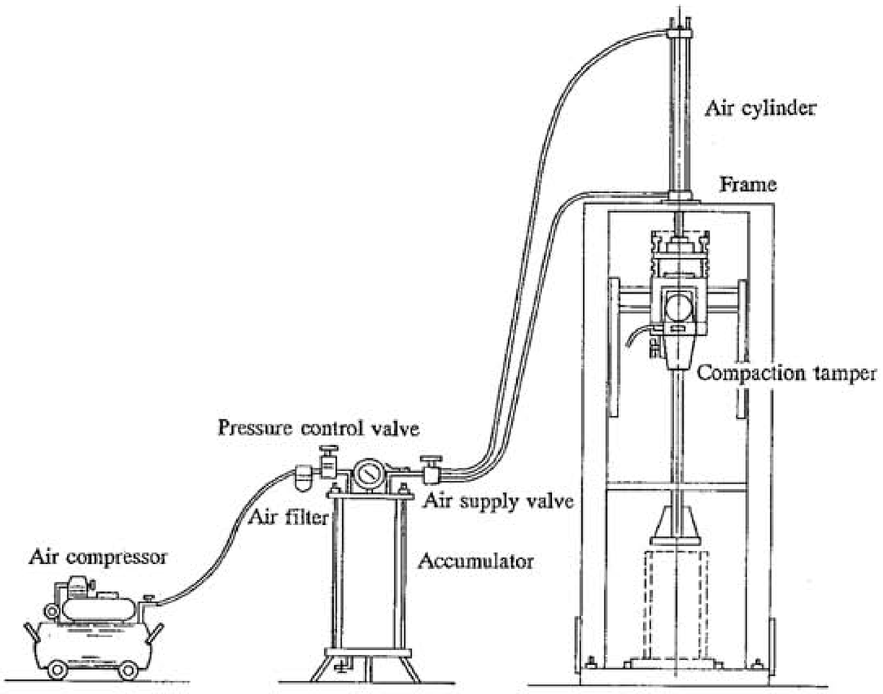


Figure 6.15 Standard Specimen Compaction Device.

6.2.4.3 Compaction Test by Large-Sized Specimen Compaction Device

The compaction test of RCD using a large-sized compaction device consists of a test for determining sand/aggregate ratio of RCD and a test for determining unit water content of RCD. RCD is compacted for 60 seconds by a vibrating compactor and the settlement of the RCD surface is measured during the compaction. RCD density can be calculated from the settlement. Then RCD is cured for 28 days in the container with filling water and four core samples are drilled out from the specimens. The core samples are cured in the water and the uniaxial compressive strength test is conducted in the 91st day. At the same time the density of core samples is measured and the surface condition of core samples is evaluated. Figure 6.16 shows the criteria describing RCD quality and the surface condition of the core samples.

Score	Description
5	Concrete surface is as fine as conventional concrete surface.
4	Concrete surface is slightly porous or slightly rough.
3	Concrete surface is porous.
2	Concrete surface looks like a honeycomb.
0	Concrete is not consolidated.

Figure 6.16 Score of Core Surface.

a) Test for Determining Sand/Aggregate Ratio: This test is performed in order to determine the optimum sand/aggregate ratio of RCD which provides the required compaction density, strength and permeability. The test is conducted for RCD mixtures of various sand aggregate ratios around the optimum value derived from the mentioned VC test. Figure 6.17 shows the typical test results. The optimum sand/aggregate ratio is determined so that the best surface condition of core sample can be obtained while the compaction density and the strength of core samples satisfy the design requirements.

MSA-Maximum Size of Coarse Aggregate (mm)	"VC"Value (sec)	Fly Ash Ratio (%)	Water Cementitious Material Ratio (%)	Sand Aggregate Ratio (%)	Water (kg/m³)	Cementitious Content (kg/m³)	Fine Aggregate(kg/m³)	Coarse Aggregate (kg/m³)	Air Entraining (kg/m³)
80	57	30	75	32	90	120	725	1551	0,24
80	30	30	79,2	32	95	120	721	1543	0,24
80	20	30	83,3	32	100	120	717	1532	0,24
80	13	30	87,5	32	105	120	713	1523	0,24
80	8	30	91,7	32	110	120	708	1514	0,24

Figure 6.17 Typical test results [from 6.15 to 6.19].

b) Test of Determining Unit Water Content: This test is performed to determine the optimum unit water content of RCD which provides the required compaction density, strength and permeability. The test is conducted for RCD mixtures of various unit water contents around the optimum value derived from the mentioned VC test. Figure 6.17 shows the typical test results. The optimum unit water content is determined so that the best surface condition of core sample can be obtained while the compaction density and strength of core samples satisfy the design requirements.

6.2.4.4 Details Related to RCD Mix

Maximum Size of Aggregate: The maximum size of aggregate has a large influence on unit water content of RCD. In general the larger the maximum size of aggregate is the smaller the unit water content that provides adequate consistency. It means that the unit cement content for the required strength can be reduced while the potential of temperature cracks is reduced when larger maximum size of aggregate is adopted. However, the risk of greater segregation becomes significant when the maximum size of aggregate is too large. A maximum size of 80mm is generally adopted in RCD mixture regarding reduction of both the temperature cracks potential and segregation.

Fine Particle Content in Sand: The fine particles in the sand, smaller than 0.15 mm, have an important role, as to improve the RCD consistency, since RCD is a lean mixed concrete. It is understood from a number of RCD mixture tests that the optimums content of fine particles smaller than 0.15 mm is 10 to 15% of the total sand mass. When fine limestone particles were added in RCD mixture its consistency was splendidly improved during Chiya Dam construction.

Use of Finely Crushed Blast-furnace Slag: Fly ash is often used as admixture material in RCD. However, the lack of high quality fly ash in recent days enforces the development of new admixture material added in RCD mixture. Finely crushed blast-furnace slag was used as admixture material in RCD in Satsunaigawa Dam construction.

Use of Admixture Agents: Effective use of low quality aggregate is a great concern regarding construction economy. Several admixture agents have been developed to improve RCD with low quality aggregate properties. Admixture agents can be also available to prevent the increase of a VC value with time and to improve construction efficiency. Water reducing admixture and retarding admixture were used in order to improve RCD quality in several RCD dams.

Standard Specimen Compaction Device: Mixture design of RCD has been simplified and still reliable with the large-sized specimen compaction device development. However, there is still a strong demand to establish more simplified mixture design procedure of RCD because it is widely adopted in concrete dam construction in Japan. The standard specimen compaction device shown in Figure 6.15 has been developed in order to meet such a demand [6.20]. The compaction energy is precisely controlled in this device and the effect of consistency on the compaction density and strength of RCD can be accurately evaluated even in the standard specimen test. The standard specimen compaction device is utilized in RCD quality control during field construction too.

6.2.5 Army Corps of Engineers Method

6.2.5.1 General Concept

Specific mixture proportioning RCC methods have been developed by the U.S. Army Corps of Engineers [6.21; 6.22; 23].

Properly proportioned RCC is workable, free of segregation, and easily consolidated using external vibratory compaction. The RCC mix must contain sufficient paste (cement, pozzolanic material, fines under Nº.200 sieve, mineral filler, water, and entrapped air) to fill voids within the mortar (bellow No. 4 sieve aggregate, fines, and paste), and must contain sufficient mortar to fill voids within the coarse aggregate. The mortar provides cohesion and workability to the mix during placement and determines the resulting strength, bonding potential, durability and permeability of the hardened RCC. The coarse aggregate provides stability to support placing and compaction equipment.

A minimum ratio of paste volume to mortar volume V_{pa}/V_{mo}, of 0.42 is required to ensure that voids within the fine aggregate (typically 35% to 40% of total aggregate) are filled and so that the mix contains enough paste to be thoroughly distributed throughout the mixture during mixing, placing, and compaction. Specific testing may show that a lower V_{pa}/V_{mo} is satisfactory: 0.42 is conservative in the absence of such testing. In order to meet the minimum V_{pa}/V_{mo}, sand for RCC may contain a higher percentage of under Nº. 200 sieve fines, or may be supplemented with mineral filler, fly ash or other non-plastic under Nº. 200 sieve fines. Mixes containing low cementitious material contents require more fines under Nº. 200 sieve or mineral filler in order to meet the minimum paste volume requirements.

Mortar contents for RCC mix vary depending on the maximum size and shape of coarse aggregate, whether it is crushed or rounded. Typically, RCC mixtures contain 2% to 4% higher sand content than do equivalent conventional concrete mixtures.

The selection of a suitable aggregate source is an important step in RCC mix design process since the type and quality of aggregate will directly effect the quality and economy of the resulting RCC. Available aggregate sources should be assessed for suitability and structural design parameters, determined accordingly.

Fine aggregate, aggregate passing Nº 4 sieve, will contain a higher percentage of fines under Nº 200 sieve than for conventional concrete. They may be processed as a single size fine aggregate or may be conventional graded material enriched with fines passing Nº 200 sieve, either natural non-plastic fines, pozzolanic, or mineral filler. The use of plastic fines and clay in RCC often results in lower strength as water demand increases. It may lead to balling of fines and unworkable sticky mixtures that are difficult to place and consolidate.

RCC mixtures, both structural and mass applications, are designed for Vebe consistency times of 10s to 40s using the Modified VeBe Test Apparatus with a 12.5kg surcharge [6.21].

At this consistency RCC is stable enough to bear heavy placing and compaction equipment. The paste is sufficiently fluid to be fully distributed throughout the concrete mass during mixing and RCC is workable allowing consolidation with vibrator rollers. The quantity of cementitious material in a RCC mix depends on the water:cement "w/c" ratio selected to meet strength or durability requirements. Fly ash is normally used in RCC as partial replacement for cement to reduce heat generation and cost. Fly ash may also be used instead of some fines (under Nº 200 sieve) in order to meet paste requirements and improve workability. Fly ash has been used up to approximately 80% of the total cementitious content (cement + fly ash) but at levels above approximately 50% of fines replacement. Additional fly ash will not significantly contribute to strength gain.

The use of a retarding admixture (ASTM-C-494 [6.24], Type B or D) is beneficial for increasing placing time and bond at the lift joint by maintaining the surface in a plastic condition prior to the following lift placing. The extended workability is especially helpful during placement in hot weather and during RCC start-up when placement rates are low. Dosage rates should be based on laboratory mix proportioning studies. As with CVC concretes, laboratory evaluation of admixture compatibility with the cement is necessary. Air within RCC has not been evaluated in full scale field mixing and placement.

CVC concrete mixes cannot be reproportioned to produce RCC by any single action such as reducing water content, altering the proportion of fine aggregate or mortar, or reducing the W/C ratio. The following is a step by step procedure for proportioning RCC for structural or mass concrete applications.

The method is based on experience with mix designs for RCC projects. It basically follows ACI-211.3 "Standard Practice for Selecting Proportions for non standard -Slump Concrete"[6.09]. The manual includes several tables developed from the Corps' experience with RCC. The mix-proportioning method can be used with a wide range of materials and project requirements. The steps to be taken after determining the required concrete properties and the properties of the proposed materials are:

Project	MSA- Maximum Size Aggregate (mm)	Cementitious Content (kg/m³)	Cement (kg/m³)	Pozzolanic Material (kg/m³)	Aproximate Water (kg/m³)
Willow Creek	75	66,5	47,5	19	107
Willow Creek	75	103,9	103,9		110
Willow Creek	75	151,4	103,9	47,5	110
Elk Creek	75	78,3	55,8	22,5	101
Lost Creek	75	119,8	41,5	78,3	83
Lost Creek	75	139,4	139,4		83
Upper Stillwater	50	231,4	71,8	159,6	104
Upper Stillwater	50	246,2	76,5	169,7	107
Galesville	75	74,2	43,9	30,3	113
Middle Fork	75	71,2	71,2		80
Monksville	75	62,3	62,3		122
TVA	38	223,5	44,5	179	85
TVA	75	132,8	55,8	77	77

Figure 6.18 Typical values for use in estimating RCC mixture proportions for trial mixture design [6.23].

(a) Determine all requirements related to the properties of the RCC mixture including:

- Required/specified strength and age
- Expected exposure time and conditions
- Water: cement ratio limitations
- Admixture requirements
- Maximum size of aggregate, source and quality

(b) Determine the essential properties of materials. Obtain representative samples of all materials in sufficient quantities to provide verification tests by trial batching. Proportion RCC with an appropriate amount of pozzolanic material or cement replacement materials that will satisfy strength, durability, and economic requirements. From the materials submitted to the test program, determine the grading, specific gravity, and absorption of aggregates and the specific gravity of the cementitious materials.

(c) If the w/c ratio has not been predetermined, select the maximum possible w/c ratio for the particular exposure and conditions. Compare this w/c ratio with the w/c ratio required based on the average strength. Use the lowest w/c ratio. Determine the maximum w/c ratio for the particular exposure or other conditions from the project document, the Corps, or ACI tables. The w/c ratio can be converted to a w/ (c+pm) ratio if required using the ACI 211.1-89 [6.09] report.

(d) From Figure 6.18 estimate the water requirement and entrapped air content for the maximum size aggregate being used. Estimate the water requirements for a certain MSA and modified VeBe time from a table. For a 75mm MSA and a VeBe time of 20s to 24s, the mixing water range is 94kg/m^3 to 119kg/m^3 with an average of 109kg/m^3.

U.S. Standard Sieve- Size	Aproximate Sieve Size (mm)	Percent Passing	Cumulative Percent Retained	Percent Retained
4 in	100	100	0	0
3 in	75	98--100	0--2	0--2
2 1/2 in	63	95--99	1--5	1--3
2	50	86--96	4--14	3--9
1 1/2 in	38	75--90	10--25	6--11
1 in	25	63--77	23--37	12--13
3/4 in	20	56--69	31--44	7--8
3/8 in	10	43--53	47--57	13--16
N°. 4	4,8	33--43	57--67	10
N°. 8	2.4	25--35	65--75	8
N°. 16	1.2	19--29	71--81	6
N°. 30	0.6	14--24	76--86	5
N°. 50	0.3	10--18	82--90	4--6
N°. 100	0.15	6--13	87--94	4--5
N°. 200	0.075	4--10	90--96	2--3

Figure 6.19 Coarse and Fine Aggregate Grading for RCC [6.23].

MSA - Maximum size Aggregate (mm)	6 in. 152 mm	4 1/4 in. 106 mm	3 in . 75 mm	1 1/2 in. 38 mm	3/4 in. 20 mm	3/8 in. 10 mm
Absolute Volume, percent of unit concrete volume	37--36	39--37	43--39	48--44	54--48	58--52

Figure 6.20 Aggregate Combination Summary [6.23].

(e) Compute the required weight of cement from the selected w/c ratio and water content requirement (Steps c and d). If pozzolan is being used compute the cement and pozzolanic material weight based on the equivalent absolute volume of required cement.

(f) Compute the required coarse aggregate proportions that best approximate the ideal coarse aggregate grading shown in Figure 6.19. Proportions of coarse aggregate and fine aggregate are either determined by comparison with tables or by computation if RCC is to be made with conventionally graded aggregates.

(g) Compare the available fine aggregate gradation to the recommended fine aggregate grading shown in Figure 6.19**.** If the fine aggregate is lacking fines passing Nº 200 sieve, pozzolanic or other non-deleterious natural fines may be used as a supplement. From Figure 6.20, select the fine aggregate content for the maximum size aggregate being used.

(h) Compute the absolute volumes and weights for all of the mix ingredients from the information obtained in step (b) through (f). Determine the absolute volume of total aggregate by subtracting the absolute volumes of materials calculated in the previous step. If the aggregate is pit-run or an all-inclusive gradation produced by minimal processing, trial batches are required.

(i) Compute the mortar content and compare with values given in Figure 6.20. Mortar volume includes the volume of all aggregate smaller than the Nº 4 sieve, cementitious materials, water and entrapped air. Adjust sand content if required. Entrapped air content is assumed to be 1% of total volume. From the absolute volumes previously computed the mortar (c+pm+air+sand) can be computed and compared with a table. For a 75mm MSA, the mortar content should range between 0.415 and 0.467 of absolute volume with an average of 0.444 of absolute volume.

(j) Compute the volume of paste and the ratio of paste volume to mortar volume $\mathbf{V_{pa}/V_{mo}}$. For paste include the volume of all aggregate and mineral filler finer than the No. 200 sieve, cementitious materials, water and entrapped air. The minimum $\mathbf{V_{pa}/V_{mo}}$ ratio should be 0.42 to ensure that all voids are filled. Adjust cementitious material content or increase quantity of aggregate and mineral filler finer than Nº 200 sieve, if required. Evaluate the aggregate. If plastic fines are suspected, determine the "Liquid Limit" (LL) and "Plasticity Index" (PI) of the fine aggregate and compare "LL" and "PI" with the maximum allowable percentages of fines passing Nº 200 (0.075-mm) sieve, usually 4% to 7% for non-plastic fines.

(k) Convert all absolute volumes to batch weights and prepare trial batches to determine VeBe time consistency and measured air content.

(l) Evaluate the workability and strength of the RCC mixture by trial batching. For RCC containing large aggregate, remove by wet sieving the fraction over 38mm, and test for modified VeBe time and air content. Mold specimens for strength tests. ASTM-C-192 [6.25] describes a procedure for molding nominal 150x300mm cylinders for concretes which have low water contents but which using external vibration and a surcharge can consolidate. A surcharge heavier than 4.5kg, as suggested in the test method, may speed consolidation of RCC. No standardized method currently exists for the determination of the air content of RCC. The pressure method described in ASTM C-231[2.26] has been used by consolidating the concrete into the bowl using external vibration on the VeBe table combined with a surcharge. A strike-off plate, such as that described in ASTM-C-138 [2.27], should be used to strike off the top surface of the concrete. The unit weight and air content of the sample may then be determined following procedures given in ASTM-C-138 and C-231, respectively.

(m) Adjust the mix as necessary to produce the desired consistency.

All RCC laboratory cast and in-situ specimens should meet the minimum size and dimensions requirements as specified in the testing standards for conventional concrete. In general, cylinders, cores, beams, and blocks will preferably have a minimum dimension of at least three times the nominal maximum size of coarse aggregate in the concrete. All RCC laboratory cast specimens should be moist cured and in-situ samples should be kept moist as conventional concrete.

Compressive strength tests are normally made on laboratory cast 150x300mm cylinders, or on drilled cores following standard ASTM testing procedures. During construction RCC may be sampled and compressive strength cylinders cast at a frequency and at test ages similar to conventional mass concrete. The curing and preparation of cylinders, mixture adjustments, and statistical control procedures are the same as for conventional concrete.

6.3 Comments, Comparison and Discussion

6.3.1 Main Remarks

Which type of mix is the most suitable for a job? Low cement content, high paste content, RCD, lean RCC?

Ideally the design method should determine the minimum-cost solution that leads to all the concrete requirements.

The properties of RCC (see Chapter 7) in place depend on the quality of the used materials, mixture proportions and the degree of compaction or consolidation. Because a wide range of materials and mixes has been used, there are no typical values for RCC properties that fall within a narrow range. RCC properties that are aggregate-dependent such as elastic and thermal properties are similar to conventional concrete made from the same aggregate.

The degree of compaction plays a greater role in producing strength for these mixtures. The voids are produced by particle-to-particle contact of the aggregate without sufficient fines or paste to fill all the voids. Increased compaction tends to decrease these voids producing a denser RCC with a corresponding increase in strength. Poorly graded aggregates or those with a high percentage of coarse aggregate may have an aggregate matrix that is fully compacted and yet have a relatively high percentage of voids resulting in lower density and strength. Even though there may be greater volume of voids in a soils approach mix where all aggregate contacts are cemented together.

The compaction of a no-slump RCC mixture by rolling produces a material that is anisotropic for many of its properties if no care is taken, considering segregation and/or absence of fines. This is especially true for watertightness where the permeability in the vertically compacted direction can be appreciably less than in the horizontal direction, mainly at the bottom of the RCC layer. Most testing has been performed on cores and cylinders in only one direction. However very little data is currently available on the anisotropic properties of hardened RCC.

No matter how good the laboratory properties of an RCC are, if the material segregates when transported, spread or compacted, the in-situ properties will fall below those achieved in the laboratory. A major objective in RCC mixture proportioning is to produce a cohesive mixture with the least possible tendency to segregate. Low cementitious content mixtures if not proportioned properly tend to segregate more because of the more granular nature of the mixture. This can be controlled to a certain extent by the aggregate gradation and by the addition of fines. Higher cementitious content mixtures are usually more cohesive and less likely to segregate. The total gradation and shape of the aggregate should therefore be carefully considered in order to maximize the loose bulk density of the coarse aggregate and thus reduce the potential for segregation. Limiting the maximum size of aggregate also helps to reduce segregation. In addition it has been found that the more workable the RCC the less likely it is to segregate. Reducing segregation during transportation and placement is essential to eliminate rock pockets at the joint interface. Consequently the need for bond between the layers must be considered at all stages of design process. Alternatively, the dam cross section has to be designed so that no bond strength is required across lift joints.

Sufficient workability is necessary to achieve compaction or consolidation of RCC. Workability is most affected by the paste portion of the mixture i.e. cement, pozzolanic material, water, admixtures (if used) and the fines. Workability of RCC mixtures is normally measured using a modified VeBe apparatus or the VC test in Japan as previously mentioned. These tests produce a vibration time for the specific mixture that is a measure of RCC workability, and it is used as a control similar to the slump test used for CVC. The tests also allow to estimate the fresh density of the concrete. Adequate RCC mixtures have workability, necessary to ensure compaction ease, produce uniform density from top to bottom of each lift, good bonding with previously-placed lift, and bear compaction equipment. Their typical VeBe time is 10 to 30 seconds or a VC time of 20 seconds.

The size, shape, texture and gradation of aggregates and the volume and nature of the cementitious and fine materials will influence the water demand for a specific level of workability.

Construction requirements and equipment should be considered during the design of the mixture proportions. For example, if air temperatures at the site are particularly high, care should be taken to design a mixture that will maintain its workability over time with as much retardation as possible. When successive layers are placed, the horizontal joint between them will not reach an unsafe bond condition.

6.3.2 Laboratory

The primary purpose of laboratory mix design is to provide proportions that when mixed and placed in field will perform as required. Unfortunately it is difficult to duplicate field conditions in the laboratory. For example "pugmill" mixing or twin shaft mixing of RCC is often more efficient than small laboratory drum or pan mixers. Field haul and transfer of RCC can be more deleterious than laboratory handling, resulting in more aggregate segregation. Field compaction is poorly modeled by vibrating table compaction when elapsed time, moisture loss, and rolling patterns are considered. In spite of all these shortcomings laboratory mix design has proven to be an effective means to assure RCC performance and to minimize field adjustments. However, as with conventional concrete, the mix must be adjusted in the field to compensate for its changing conditions and undesirable observed performance.

The water content of RCC vary widely depending upon many factors including the maximum size of aggregate, the gradation and shape of the aggregates (particularly the fine aggregate), the amount and quality of any mineral fines in the mixture, the amount, proportions and quality of the cementitious materials, and whether any admixtures are being used. Nevertheless the initial water content of the mixture should be determined by experience of the materials being used or similar materials previously used or from Figure 6.21.

The proportion of cement, pozzolan, and water can then be obtained by comparison with previous mixtures with similar materials or from standard curves. Having estimated the proportion of the paste they must be proved in laboratory trial mixes.

The void ratio of fine aggregate as determined using the compacted bulk density test normally ranges from 30% to 50%. The minimum paste volume can thus be determined by maximum density curves in much the same way as optimum water content is determined for soils.

Project	MSA-Maximum Size Aggregate (mm)	Admixture	Aproximate Water (kg/m³)
Tamagawa	150	Yes	95
Urayama	150	Yes	85
Miyagase	150	Yes	95
Nunome	150	Yes	115
Santa Eugenia	100	No	95
Sakaigawa	80	Yes	105
Shimajigawa	80	Yes	105
Shiromizugawa	80	Yes	102
Willow Creek	75	No	110
Winchester	75	No	104
Elk Creek	75	Yes	101
Urugua-i	75	No	105
Les Olivettes	63	No	125
Salto Caxias	50	No	140
Tashkumir	50	Yes	105
Copperfield	50	No	130
Castilblanco	40	No	102
Los Morales	40	No	101
Bucca Weir	40	No	110
Stacy Spillway	38	No	154

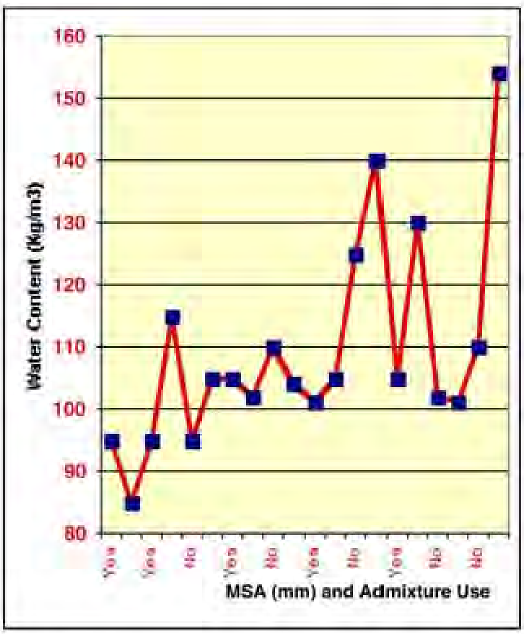


Figure 6.21 Approximate water content of an RCC relative to the maximum size of aggregate [6.23].

For any gradation of aggregate the minimum aggregate volume producing no-slump consistency can be established by proportioning the mortar fraction to yield the approximate strength required and adjusting the proportions of coarse aggregate and mortar to achieve a zero slump. The proportions of fine aggregate, cementitious material, water, and any entrapped air should remain in a fixed relationship during these adjustments. Vibration time required to fully consolidate this mixture will generally correspond to the minimum stiffness necessary to bear the vibratory equipment. To determine the vibration time the proportions of the mortar should be kept constant and the coarse aggregate volume is increased as the mortar volume decreases in equal increments. The vibration time should be determined using the VeBe test for each increment change. The limit of mortar volume for consistency will be recognized when the incremental increase in coarse aggregate proportion results in a substantial decrease in density for a given compactive effort.

J. Diez-Cascón et al [6.28] published an alternative consistency measuring method **(UC)** to the VeBe and a mixing method based on it after classifying concrete consistencies in the laboratory. The main idea behind this dosification process is to define both a mixture with a minimum post-placement porosity and to qualify the fine aggregate in accordance with the required performance.

The alternative method is developed to measure the consistencies of concretes with the aim of clearly overcome inconveniences observed in currently used methods until now. In the proposed method the consistency is measured as the slump produced in the specimen of fresh concrete submitted to an external compression and vibration over a determined period of time. Interesting conclusions have been drawn from the comparative analysis of the results obtained using this and the Modified Vebe method. These clearly show the advantages of the proposed method. For example, it serves as a quantity control of cement and filler present in the mixes.

Based on this method a straightforward and convergent way of dosing concrete is proposed which does not rely on experience as its basis. The mixes designed using this method present characteristics which agree with current tendencies in mixes for these concretes. With the application of this method it has been possible to obtain a hierarchy of the useful RCC concretes.

It is recommended that a series of mixtures were proportioned and investigated in the laboratory to encompass the potential range of performance requirements. This practice will later allow modifications or adjustments to the mixture proportions without necessarily repeating the trial mix program.

Several characteristics can be determined by visual examination of laboratory-prepared trial mixtures. Distribution of aggregate in the mixture, cohesiveness, and tendency to segregate can be observed by handling the RCC in the laboratory. The texture of the mixture whether it is harsh, unworkable, gritty, pasty, smooth, etc. can be seen and felt with the hand. These characteristics should be recorded for each mixture.

Laboratory tests including temperature, consistency, unit weight, and air content, should be performed on fresh RCC produced for each trial mixture. In addition specimens should be prepared for compressive strength testing at various ages, usually 7, 14, 28, 90, 180 days and 1 year to derive the strength-gain characteristics of each mixture. These specimens can also be used for determination of static modulus of elasticity and Poisson's ratio at selected ages. Additional specimens should also be manufactured for indirect (Brazilian) tensile strength and/or direct tensile strength at various ages to establish their relationship to compressive strength and to provide the structural analysis parameters. Permeability can be performed on 25x50cm RCC test specimens in accordance to the method CRD-C-48 [6.29].

On major projects, specimens for thermal properties are usually manufactured from one or more selected RCC mixtures. Tests include adiabatic temperature rise, thermal expansion coefficient, specific heat, and diffusivity. Specimens for special tests such as creep, strain capacity, and shear strength may also be manufactured for selected mixtures (see Chapter 7).

RCC diffusivity can be evaluated from time temperature readings taken on test cylinders brought to a constant temperature and then immersed in high temperature water bath according to the method CRCD-C-36 [6.30]. The adiabatic temperature rise of RCC can be evaluated over a 15 or 30 days period on sample sealed in a metal container placed in an adiabatic calorimeter room in accordance with CRD-C38 [6.31]. Thermal expansion coefficient of the hardened concrete can be evaluated by direct physical measurement of a series of prisms over a temperature range of 4°C to 38°C, in accordance with CRD-C-39 [6.32]. Specific heat of the hardened RCC can be evaluated in an adiabatic calorimeter testing apparatus according to CRD-C-124 [6.33]. Creep values can be obtained from full RCC mixes cylinders (25x50cm), according to CRD-C-54 [6.34] procedures.

6.3.3 Aggregates

Since rock characteristics in aggregate deposits and quarries vary and production operations change, the processed material will rarely be uniform. It is necessary to monitor these aggregate trends and adjust RCC aggregate proportions. Generally, grading adjustments are made to maintain a consistent coarse to fine aggregate proportion and consistent proportion of fraction passing Nº 200 sieve.

Moisture adjustments are a common routine procedure in concrete production. With the increased use of continuous mixers, new procedures must be used or more appropriately accepted. There is no doubt that a person experienced in visual quality of RCC exiting a plant can adjust the added moisture to the appropriate level to compensate moisture variations load by load. These moisture adjustments must be made and verified when appropriate by sampling and testing.

6.3.4 Field Trial Adjustments

Prior to placement in the dam it is recommended that the proposed RCC should be proportioned and mixed in the concrete plant and placed, spread, and compacted in a full-scale test using the specified construction procedures and equipment and the personnel that will run the dam construction. The full-scale test should provide valuable information on the need for minor modifications to the mixture proportions and can be used to determine the compactive effort (number of passes of the vibratory rollers) required for full compaction of the RCC. A full-scale test can also be used to visually examine the potential for segregation under specific conditions, the lift surfaces condition and their treatment methods, and any other construction aspect that requires review.

Final adjustments of mixture proportions should be made based on full-scale test batches using the materials and the concrete plant that will eventually be used the dam construction. These trials can investigate the following:

- ✓ Adjustment of aggregate gradations based on real materials from the stockpiles of each individual size. Starting aggregate production well in advance of RCC placement makes it possible.
- ✓ Correction of batch weights for aggregate moisture contents.
- ✓ Adjustment of water content for the desired consistency or degree of workability based on RCC compactibility.

Good performance at lift joints is significantly affected by the condition of the finished surface. Rollers that "track", create ridges of over 2cm to 3cm deep, result in dry cracked rows of RCC that must be removed prior to the next lift. The surface mortar from some mixes that contain too many fines, too much water, or are over-rolled, will stick to the roller drum after maximum density is achieved. This will result in a torn surface sprinkled with small chunks of RCC mortar. This roller pickup must be eliminated by modifying its procedure or by mix adjustment of fines and/or water.

Field handling of mixes often causes more segregation than observed in the laboratory. Field measure to this problem is to reduce the coarse aggregate content. This may in part be a solution. However, a fines increase and possible modification of handling procedure may be enough to hold the aggregate in place.

While laboratory proportioning of RCC cannot model all factors, likewise field adjustments must not be done arbitrarily or against the mix design. Compounding mix adjustments can occasionally result in mixes that do not exhibit the required performance, i. e. , shear strength, permeability, joint integrity, etc.

Figure 6.22 Preparation for a RCC test fill.

Figure 6.23 Trench at test fill during RCC compaction.

Figure 6.24 Test fill during RCC compaction.

6.3.5 Summarized Routine Design of Mixture Proportions

As described, there are several methods that use the 'concrete' approach to design the mixture proportions of RCC including that used for RCD mixture design. All the methods have similarities as shown in Figure 6.25 and follow similar procedures although there are minor differences. The table of the Figure 6.25 shows the main conceptual points of the mentioned routines. The general procedure is as follows :

1) Optimize the gradation of fine and coarse aggregates to produce minimum voids rate. Use additional mineral fines in the fine aggregate or available pozzolanic material if necessary (see 3 bellow). The mixes are proportioned in attempt to reach the maximum specific gravity so the aggregates can be combined to adjust as near as possible from a typical curve.

$$p = (d/MSA)^{1/3} \times 100\%$$, where :

p = % finer than "d" size of mesh;
d = dimension of mesh (mm);
MSA = maximum size of the aggregate;

2) Portland cement, pozzolanic material (if any), water and admixture (if any) should be proportioned to obtain the required mean strength and determine the paste proportions. This can be modified to choose the minimum cost mixture. For example, if pozzolanic material is cheap relatively to cement and/or available fine material (silt; crushed powder filler; or other equivalent), it should be used in a higher proportion of cementitious content . If its cost were near to that of Portland cement, a lower proportion would be used. As the proportion of pozzolanic material in the cementitious content increases, the cementitious content itself usually has to increase in order to meet the required strength. In addition the water content will frequently have to be reduced to maintain the same workability.

3) Check that there is sufficient cementitious material (and a proportion of mineral fines, if used) to provide the design permeability and durability.

4) Check that the fine aggregate/coarse aggregate ratio is close to the optimum.

5) Check that hydration heat is within the expected limits.

6) Make any adjustments that are necessary (laboratory and field) and re-check the design.

Figure 6.25 Conceptual points of RCC proportioning mix routine.

6. 3.6 Typical Mixture Proportions

Figure 6.26 shows mixture proportions of most of the RCC dams completed and under construction by the end of 1997.

Project	MSA-Maximum Size Aggregate (mm)	Aproximate Water (kg/m³)	Admixture (kg/m³)	Cement (kg/m³)	Pozzolanic Material (kg/m³)	Cementitious Material (kg/m³)	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³)
Tamagawa	150	95	0,87	91	39	130	657	1544
Urayama	150	85	0,33	91	39	130	674	1572
Miyagase	150	95	0,65	91	39	130	652	1568
Nunome	150	115	0,3	88	42	130	608	1670
Santa Eugenia	100	90		125	90	215	430	1835
Erizana	100	100		90	80	170	532	1668
Sierra Brava	80	110		80	140	220	610	1590
Puding	80	84	0,85	54	99	153	768	1512
Sakaigawa	80	105	0,33	91	39	130	704	1546
Shimajigawa	80	105	0,33	91	39	130	749	1476
Shiromizugawa	80	102	0,67	96	24	120	673	1527
La Manzanilla	75	109		135	135	270	851	1338
Shuikou	75	85	0,4	76	74	150	626	1627
Monksville	75	136		63		63	1376	890
Elk Creek	75	101	1,6	70	33	103	728	1439
Urugua-i	75	105		60		60	1247	1298
Ceñza	60	95		70	130	200	740	1524
Salto Caxias	50	140		100		100	1142	1242
Upper Stillwater	50	100	0,5	95	208	303	688	1270
San Rafael	50	110		90		90	1077	1234
Lake Robertson	40	120	3,3	85	85	170	620	1430
New Victoria	40	108		79	147	226	957	1217
Castilblanco	40	102		102	86	188	673	1452
Los Morales	40	101		69	153	222	655	1420
Pangue	38	145		160	194	354	565	1295

Figure 6.26 Values of some ratios between parameters of RCC mixtures for dams.

6.4 References

6.01 RICHARDSON, ALAN T. *"Upper Stillwater Dam Roller Compacted Concrete Design And Construction Concepts"*, in: XV ICOLD. Lausanne, 1985.

6.02 DUNSTAN, M.R.H. *Rolled concrete for dams - construction trials using high flyash content concrete.* London: CIRIA Technical Note 106, May 1981.

6.03 DUNSTAN, M.R.H. *A method of design for the mix proportions of roller-compacted concrete to be used in dams. Q.57-R.41.* Lausanne: XVth ICOLD Congress, 1985, vol. 2.

6.04 DUNSTAN, M.R.H. *Expert summary to Topic D of Q.57 Q.57-D.20*. Lausanne: XVth ICOLD Congress, 1985, vol. 5.

6.05 DUNSTAN, M.R.H. *Discussion to Q.62 XVIth*. San Francisco: ICOLD Congress, 1988, vol. 5.

6.06 DUNSTAN, M.R.H. *The state-of-the-art of RCC dams*. London: International Journal of Hydropower and Dams, March 1994.

6.07 BRITISH STANDARDS INSTITUTION. *Methods of testing concrete: Part 104: Methods of testing fresh concrete*. BS1881:1983.

6.08 ASTM-C-1170 "Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table". Annual Book of ASTM Standard, 1991.

6.09 ACI Committee 211, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete", in: ACI Manual of Concrete Practice, Part 1, American Concrete Institute, MI. Detroit, 1991.

6.10 ACI- Committee 207- "Roller-compacted concrete". Chicago, 1989.

6.11 ACI Committee 214- "Recommended Practice for Evaluation of Strength Test Results of Concrete". Chicago, 1990.

6.12 CRD-C-161. "Standard Practice for Selecting Proportions for Roller-Compacted Concrete (RCC) Pavement Mixtures Using Soil Compaction Concepts", in: Handbook for Concrete and Cement, 1992.

6.13 CRD-C- 162. "Standard Test Methods for Moisture –Density Relations of Soils and Soil-Aggregate Mixtures Using 4.54Kg Rammer and 457mm Drop", in: Handbook for Concrete and Cement, 1992.

6.14 ASTM-C-1557- "Standard Test Methods for Moisture – Density Relations of Soils and Soil-Aggregate Mixtures Using 4.54Kg Rammer and 457mm Drop", in: Annual Book of ASTM Standard, 1990.

6.15 JAPANESE MINISTRY OF CONSTRUCTION. *Design and Construction Manual for RCD concrete*. Tokyo: Technology Centre for National Land Development, 1981.

6.16 KOKUBU, Masatame; SHIMIZU, Shigeaki; JOJIMA, Seishi. "Present State and Problems of Rationalized Construction of Concrete Dams in Japan", in: XV. Lausanne, 1985.

6.17 YAMAGUCHI, Takeshi; HARADA, Joji; OKADA, Teruo; SHIMADA, Shoichi. "Construction of Tamagawa Dam by RCD Method", in: XV ICOLD. Lausanne, 1985.

6.18 SHIMIZU, S. and YANAGIDA, T. *Large-sized specimen compaction device in RCD construction method Engineering for Dams*, nº 26, 1988.

6.19 NAKAMURA, E. and HARADA, T.-*The properties of RCD with blast-furnace cement Engineering for Dams*, Extra issue, 1991.

6.20 FUJISAWA, T., NAGAYAMA, I. and WATANABE, K. - *A study on mixture design of*

RCD concrete using standard specimen compaction device. Florence: C.5, IXXth ICOLD Congress, 1997.

6.21 USACE-*Roller-compacted concrete*. Washington D.C.: Engineer Manual nº 1110-2-2006, February 1992.

6.22 TATRO, S.B and HINDS, J.L.- *Roller-compacted concrete mix design in Roller-compacted concrete III*. New York: ASCE, 1992.

6.23 JAMES Hinds. "Roller Compacted Concrete Mixture Design for Mass and Structural Applications"- Proceedings of the I Conferências Portuguesas Sobre Barragens de Betão Compactado com Cilindros (BCC). Lisboa: Laboratório Nacional de Engenharia Civil- November/1996.

6.24 ASTM-C-494- "Standard Specification for Chemical Admixtures for Concrete". Annual Book of ASTM Standard, 1990.

6.25 ASTM-C-192- "Practice for Making and Curing Concrete Test specimens in the Laboartory", in: Annual Book of ASTM Standard, 1995.

6.26 ASTM-C-231- "Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method", in: Annual Book of ASTM Standard, 1991

6.27 ASTM-C-138- "Standard Test Methods for Unit Weight, yield, and Air Content (Gravimetric) of Concrete", in: Annual Book of ASTM Standard, 1992.

6.28 J. DÍEZ-CASCÓN, J.A. POLANCO and R. García de ARRIBA. "University of Cantabria methods for measuring the consistences and mix design of roller compacted concretes". Spain: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, October/1995.

6.29 CRD-C-48- "Method of Test for Water Permeability of Concrete", in: Handbook for Concrete and Cement, 1973.

6.30 CRD-C-36- "Method of Test for Thermal Diffusivity of Concrete", in: Handbook for Concrete and Cement, 1973.

6.31 CRD-C-38- "Method of Test for Temperature Rise in Concrete", in: Handbook for Concrete and Cement, 1973.

6.32 CRD-C-39- "Test Method for Coefficient of Linear Thermal Expansion of Concrete", in: Handbook for Concrete and Cement, 1981.

6.33 CRD-C-124- "Method of Test for Specific Heat of Aggregates, Concrete, and Other Materials (Method of Mixtures)", in: Handbook for Concrete and Cement, 1973.

6.34 CRD-C-54- "Standard Test Method for Creep of Concrete in Compression", in: Handbook for Concrete and Cement, 1989.

7

Properties

7.1 General

RCC is a concrete thus, significant material characteristics and properties of RCC include:

✓ Fresh RCC: consistency and unity weight;

✓ Hardened RCC: specific gravity, absorption, compressive strength, tensile strength, modulus of elasticity, tensile strain capacity, Poisson's ratio, biaxial and triaxial shear strength, volume change (thermal, drying and autogenous), coefficient of thermal expansion, specific heat, creep, thermal conductivity, thermal stress coefficient, diffusivity, permeability and durability.

Since the completion of Shimajigawa Dam in Japan in 1980, RCC dams structures have gained wide acceptance over the world. Since 1973 [7.01], several test results from laboratories and test-fill studies were published. Nevertheless, some doubts and questions remain.

Questions like these:

· Are there RCC dams higher than 100m?

· What would be the maximum height to be reached by a RCC Dam?

· How does RCC compare with CVC as a suitable material to build high and large gravity or arch-gravity dams with the same durability and quality as in existing dams that have performed well for several decades?

· How should be the construction joint treatment?

· And so on.

From a general point of view, these questions are raised by some technicians inexperienced in correlating and comparing RCC data with those of CVC concrete, or of dams with the CVC mass concrete.

It means that, beside the available data, there is no familiarity with the RCC properties. Based on these doubts, this chapter intends to discuss the RCC properties and quality in comparison with CVC properties, considering all the data obtained at the job construction and similar materials used for proportioning-mix studies.

Differences between the hardened properties of RCC and CVC are primarily due to differences in mixture proportion, grading and voids content. A wide range of RCC mixtures can be designed, just as there is a wide range of mixtures for conventionally placed concrete. It is difficult to quantify typical values for either of them. In general, RCC will have lower cement, paste, water contents and no entrained air. It may also use silt or other non-plastic fines to fill aggregate voids.

Aggregate quality, grading and physical properties have a major influence on the physical properties of CVC. They can be even more important for RCC. Because some RCC mixtures make use of marginal or inferior aggregate (by conventional standards), the range of properties for RCC goes well beyond the range of normal properties of CVC.

The *in situ* properties of RCC depend on the quality of the materials used, or the proportions of the mixture and the grade of compaction that is achieved. Given that, very diverse mixtures have been employed, from lean mixes to mixes with a high cementitious content, and the values obtained in a series of properties have also varied very extensively. Mix properties depend on the aggregates nature, such as their elastic or thermal characteristics, are influenced by these latter, similarly to what occurs with CVC.

7.2 Laboratory Facilities and Standard

7.2.1 Procedures

Most of the laboratory tests currently used for RCC are standard tests developed for the CVC or, in some cases, for soils. They include tests to check the acceptance and properties of materials, as well as methods of handling and testing specimens. However, there are two different procedures being used to test RCC: specimen preparation and consistency tests.

7.2.2 Specimen Preparation

At present, there are no generally recognized standards for laboratory preparation of specimens and determination of RCC fresh mix properties. There is no laboratory specimens preparing that produces properties nearly the same as RCC placed in the field, where heavy equipment (trucks, dozers and vibratory rollers) compact and consolidate the mix. It is properly assumed that density is proportional to another desired property of the mix, its compressive strength.

Most specimens have been prepared in standard d: 150mm by h: 300mm concrete cylinders, which are readily available and can accommodate full mix with MSAs up to 40mm-50mm. For RCC mixes using larger MSAs, aggregates larger than 40mm-50 mm can be wetscreened out or larger custom-fabricated molds can be used.

Cylinder preparation falls into three basic methods: impact compaction, vibration and tamping.

7.2.2.1 Impact Compaction Specimens

Impact compaction methods for the preparation of specimens have been used in preparing test cylinders and the number of layers has varied from three 100mm high layers to six 50mm high layers. The number of layers is not as important as the type of hammer or rammer used and the amount of compactive effort or energy applied to the material in the rigid cylinder.

Most of the procedures for specimen preparation have used impact compaction. The amount of aggregate fracturing or gradation change during impact compaction tests is a function of the aggregate nature. Hard, sound aggregate should be able to absorb more energy without breakdown.

Figure 7.01 Pneumatic pole tamper to prepare RCC cylinders.

Figure 7.02 Electric pole tamper to prepare RCC cylinders.

7.2.2.2 Vibrated Specimens

Vibrated test specimens are used primarily for concrete approach RCC mixtures designed to have more paste than aggregate voids. A 150mm by 300 mm steel cylinder is rigidly clamped to the same vibrating table used in the VeBe test and filled with three equal layers. A 9kg weight is placed on the top of each layer and the cylinder is vibrated until the paste is formed around the surcharge edge. After the third repetition, the excess concrete is struck off and the cylinder is capped for later testing. This method is described in the U.S. Bureau of Reclamation Standard 4906-86 [7.02].

A similar method is used for the RCD method in Japan, except for the size of the specimen, which is approximately 240 mm in diameter with a 200 mm height (as seen in Chapter 6).

Figure 7.03 Large Vibrating table for RCC cylinder preparation.

7.2.2.3 Tamped specimens

Another method for producing RCC cylinders involves tamping, which can be accomplished by two distinct methods:

a) Use of a pneumatic pole tamper, and
b) Use of an electric-powered vibrating rammer.

7.3 Fresh RCC Properties

7.3.1 Consistency Tests

The main purpose of consistency tests is to adjust and determine the water content required to produce a mix suitable for compaction by external rolling and to obtain the desired strength properties. The water content of the mix is determined by using a vibrating table to achieve the desired time for the paste to start appearing on the surface of the RCC mixture.

There are a number of similar tests to measure this consistency. They all follow three basic steps:

(a) A container is loosely filled with uncompacted concrete, leveled off, and a surcharge is applied to the RCC;

(b) The cylinder is attached to a vibrating table at constant frequency and amplitude. The specimen is then vibrated with the surcharge on the surface until it is fully consolidated;

(c) The time in seconds is noted when a ring of paste is completely formed around the inside edge of the cylinder. This time is the measure of consistency or workability of the mix.

The basic consistency test for no-slump RCC was conceived during the 1970's by Cannon [7.03] of the Tennessee Valley Authority, using a non-standard vibrating table, a cylinder filled up to the top and no surcharge. Most laboratories now use a modified VeBe test. This test employs a container and a vibrating table (made by Dynapac Maskin AB of Sweden- 3600 cycles per minute-see Chapter 6), as the ones used in the Cannon Test. The modification made is a surcharge addition to the loose, leveled concrete. The total weight of the used surcharge varies considerably, as shown below:

Japan	20	kg
Corps of Engineers	12.5	kg
Bureau of Reclamation	22.7	kg

As the surcharge weight increases, the Vebe or VC time tends to decrease for the same mix.

RCD consistency tests in Japan are done using tables that vibrate at 4000 cycles per minute as well as two sizes of containers. The standard container for RCD has about the same volume as the standard VeBe container, however it is about 200mm high and has a 240mm diameter. It is used for preliminary mixture proportioning studies and for quality control during construction. To test mixtures with MSAs up to 150 mm, a larger container is used as mentioned in Chapter 6.

A number of mix proportion factors affect the VeBe time. Any factor that tends to stiffen the mix, such as a higher sand content and a higher temperature, increases the VeBe time. Still, the primary factor is the amount of water in the mix. Lower VeBe times indicate a greater water content, thus producing a more fluid consistency. The relationship between water content and consistency values of different RCC mixes turns to be very difficult because of the factors above and the different apparatus.

7.3.2 Water Content (Moisture)-Density Relationship

The same specimen compacted and used for consistency can be useful for moisture-density tests. After the consistency test, the container is weighted and the optimum water content (moisture) can be determined so as to produce a maximum dry density. A five-point curve is a general practice.

Optimum water content (moisture) is thus determined for construction and should be in the mix when the compaction occurs and not when the mixing occurs. Therefore, it may be necessary to introduce more water than optimum during the mixing to account for moisture losses during handling, evaporation and early hydration of cement. Also, field adjustments may have to be made to produce a more compactable mix, as determined by a test section construction.

7.3.3 Water Content-DMA-Brazilian Method

Pacelli *et al* [7.04] developed a very simple and rapid test method to determine the water content and the unit weight of RCC. Aiming at establishing an alternative to usual methods, a procedure for controlling the unit water of RCC and the unit weight of fresh concrete has been developed. Such method, known as "Water Measurer Device - WMD" (DMA in Portuguese), allows the prompt control of unit water during the RCC fabrication.

This method has been conceived based on a physical principle – the density of materials compounding concrete. Therefore, as water is a material with a lower density, the higher the water amount in a RCC mix, the lower its density.

The test consists in determining the water volume displaced when a concrete sample of a known weight is placed in a container (WMD), which contains a known water volume. The higher the water content in a RCC sample, the higher the water volume displaced by the sample.

A specific calibration curve should be made for each RCC mix. This curve is obtained in laboratory by simulating the conditions of water variation of the RCC mix established to be used on the site.

Such simulation is carried out by batching at least five RCC mixes with the same cement content per cubic meter. The unit water undergoes variation, the corresponding mix is calculated again and the determinations to which the water volume displaced (ml) x unit water kg/m^3) x unit weight (kg/m^3) will be correlated.

An example of the calibration curves is shown in Figure (7.04).

Theoretical Unit Water (kg/m^3)	Measured Water Content (kg/m^3) WMD-"DMA"	Measured Specific Weight (kg/m^3) WMD-"DMA"	Measured Specific Weight (kg/m^3) Nuclear Densimeter
120	120,67	2727	2710
130	141,51	2695	2721
140	134,16	2705	2705
150	144,58	2688	2672
160	159,29	2665	2670

RCC Mix	
Material	kg/m^3
Cement	120
Crushed Sand	1040
Coarse Aggregate	1405
Theoretical Specific Weight	2705

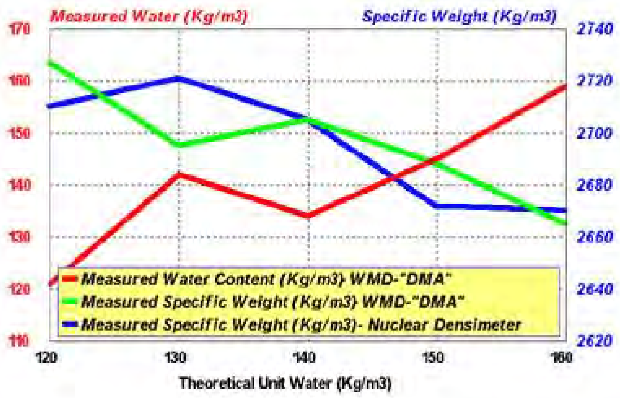


Figure 7.04 Measured Volume (WMD) * Unit Water [7.04].

Laboratory tests showed that needs have been met by using this device, as confirmed at COPEL's Salto Caxias Dam, in Brazil.

The apparatus used for these tests to measure the liquid displaced by the RCC is the same one used before, at concrete batchers, to determine sand content. The time spent in carrying on each test is about 8±2 minutes.

The device is shown in Figure 7.05 below.

Figure 7.05 Device to determine unit weight and unit water of RCC.

7.3.4 Specific Gravity-Density at Field Construction

RCC specific gravity density at field construction and the compaction ratio reflecting the Quality Control performance are discussed in Chapter 9.

7.4 Hardened RCC Properties

7.4.1 Unit Weight-Specific Weight-Specific Gravity-Density

The specific gravity of RCC is either the same or somewhat (2% to 4%) greater than that of CVC with the same materials. The aggregate volume in a concrete mix is about 80%, so the concrete specific gravity depends mostly on the aggregate specific gravity. RCC has a low air content (generally 1% to 2%) and a low initial water content, so more solids occupy a unit volume. The main reason for a higher RCC specific gravity is its lower water content and the compaction ratio. Figure 7.06 shows some typical RCC and CVC test-values, used in some projects [7.05 to 7.14].

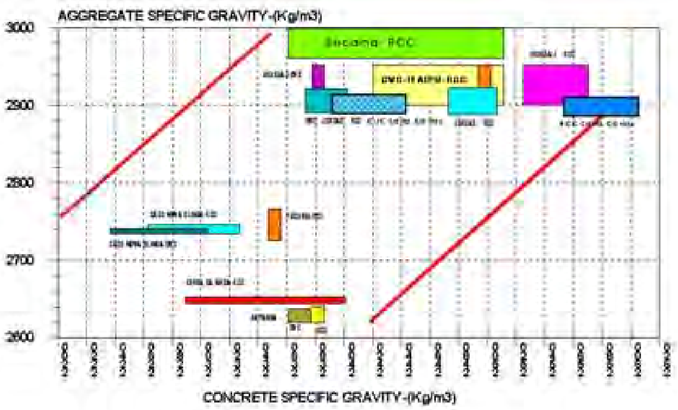


Figure 7.06 Specific gravity of concretes related to aggregate specific gravity [7.05 to 7.14].

7.4.2 Strength

7.4.2.1 Compressive Strength

Compressive strength is normally required because it is relatively easy to determine. Many other properties are directly related to the concrete unconfined compressive strength at a certain age. A design age of 90 or 180 or 360 days is usually required for RCC dams, and 28 days age for RCC pavements. These ages, for RCC dams, allow for part of long-term strength development of concretes containing pozzolanic material. The choice of a design age at a specific site depends upon the loading time of the structure, the mixture proportions used, etc.

The RCC strength depends on the aggregate quality and grading, cement proportions, pozzolanic material, water and compaction degree. For most mixtures, the compressive strength of RCC is a function of the water/cementitious ratio (w/(c+p)), similar to the traditional concrete.

The compressive strength of RCC is usually measured by cylinder or cube shaped specimens.

The compressive strength increases with a reduction in water content as long as RCC is fully compacted. The maximum compressive strength for a certain mix is obtained at the optimum water content consistent with a specified compactive effort. Water content less than optimum produces lower compressive strength. This indicates that the presence of voids in the mix has a greater negative effect on the strength than the positive effect of water reduction. For most RCC dams, the consistency tests establish a relatively fixed water content based on a VeBe time or VC value. However, once a water content and a compactive effort are established, the concrete compressive strength depends on the cement or the cementitious (cement plus pozzolanic material) content. The compressive strength increases with time and the amount of cementitious materials in the mix.

With regard to the compressive strength, its evolution with age can be seen in a series of dams, classified according to their binding material content. In general, and as it was expected, by increasing binding material content the strength also increases. On the other hand, and in accordance with the high proportions of the active additives usual in these concretes, the development of the strength is relatively slow at early ages, speeding up later: thus, in some cases, strength increase of the order of 50% has been observed between 28 and 90 days, as well as between 90 and 365 days.

It is very difficult to discuss the compressive strength in general, because it depends on the cementitious content (cement+pozzolanic material). A normal way that could be used to correlate these parameters is based on a **mix efficiency = η factor:**

η † [Compressive Strength (kgf/cm^2)] / [Cementitious materials (cement + pozzolanic materials in kg/m^3)].

"Mix Efficiency" at various ages for 28 RCC dams and 8 CVC dams or studies [7.05 to 7.40] is plotted in Figure 7.07 where RCC and CVC using the same constituents could be compared based on the data available for Capanda, Itaipu, Upper Stillwater, Urugua-i, Jordão and Salto Caxias.

In general, a "mix efficiency" at later ages is higher for RCC than comparable CVC, meaning that a desired compressive strength of RCC can be obtained by using lower cementitious content, particularly Portland Cement, and higher pozzolanic material content. These types of mixes develop more strength due to the best combination of cement and pozzolanic material.

Dam	Cement	Poz. Mat.	TOTAL	Mix Efficiency [(kgf/cm²)/(kg/m³)]				
	kg/m³	kg/m³	kg/m³	7 days	28 days	90 days	0,5 year	1 year
TAMAGAWA	91	39	130	0,85	1,08	1,52	1,94	2,26
SAKAIGAWA	91	39	130	0,39	0,82	1,54		
MYAGASE	91	39	130			2,54		
URAYAMA	91	39	130	0,61	1,15	1,85		
YUGOSLAVIA	100	60	160		0,86			
URUGUA - i	60		60	0,94	1,24	1,63		
WILLOW CREEK	47	19	66	0,43	0,85	1,25		2,81
WINCHESTER	104		104		1,7		2,06	
MIDDLE FORK	66		66		1,5	2,22		
GALESVILLE	54	52	106					1,45
MONKSVILLE	64		64	0,52	0,73	0,78		1,85
UPPER STILLWATER	80	173	253	0,35	0,58	0,96	1,28	1,42
NORTH LOOP	119	56	175	0,67	0,82	1		
CEDAR FALLS	140	92	232	0,66	0,85			
LOWER CHASE	64	40	104	0,69	0,96			
COPPERFIELD	95	15	110		0,42	0,67		
CRAIGBOURNE	70	60	130		0,68	1,22		
BUCCAWEIR	90	90	180		0,67	1,11		
MISTRAAL	58	58	116		1,81			
ZAAIHOEK	36	84	120		1,67			
OLIVETTES	88	47	135	0,39	0,94	1,14		
RWEDAT	60		60	0,4	0,8	0,88		
ITAIPU	91	26	117	0,41		1,11	1,27	
SACO NOVA OLINDA	75		75		0,65			
TUCURUI	58	34	92		1,11	1,43		
CAPANDA	70		70	0,79	1,15	1,35	1,48	1,62
JORDÃO	75		75	0,43	0,61	0,84	1,02	
SALTO CAXIAS	100		100	0,41	0,56	0,85	1,15	1,33
ERIZANA	90	90	180		0,84			
SANTA EUGENIA	130	110	240		1,07			
RCC - Average				0,56	0,97	1,29	1,46	1,82
ITAIPU				0,4	0,8	1,38	1,58	1,62
ILHA SOLTEIRA				0,82	1,45	1,76	1,83	2,1
TUCURUI				0,75	1,05	1,33	1,38	
MYAGASE						1,76		
URAYAMA				0,65	1,25	1,8		
UPPER STILLWATER				0,55	0,9	1,25	1,42	1,5
URUGUA-i				0,75	1,03	1,27		
CAPANDA				0,62	0,94	1,1		
JORDÃO				0,55	0,79	0,92	0,99	1,07
SALTO CAXIAS				0,56	0,78	0,97	1,07	1,22
ERIZANA					0,89			
SANTA EUGENIA					1,22			
Conventional -Average				*0,63*	*1,02*	*1,56*	*1,38*	*1,50*

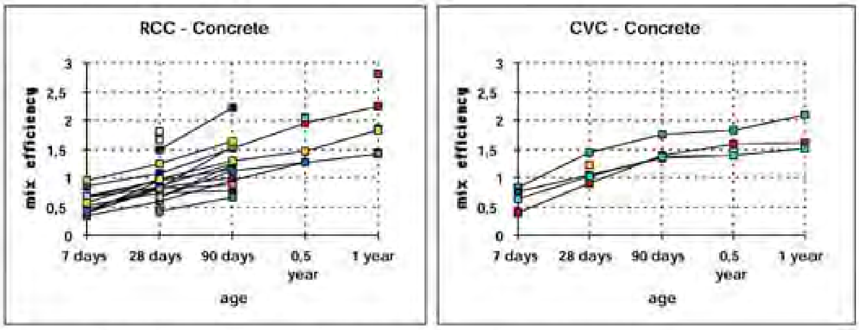


Figure 7.07 Mix efficiency for RCC and CVC concretes.

7.4.2.2 Tensile Strength

The ratio of tensile strength to compressive strength for RCC mixtures has typically varied depending on aggregate quality, age, cement content and strength. Tensile strength of RCC can be determined by tests either by measuring direct tension or splitting (indirect) tension. The splitting tension test is also known as the Brazilian test.

Like the compressive strength, the tensile strength of RCC and CVC also depends on the cementitious content and age. For CVC, the tensile strength is considered to be 10% to 15% of the compressive strength. Data from 22 dams or testing programs [7.18 to 7.44], showing the ratio of splitting tensile strength to unconfined compressive strength presented in Figure 7.08, indicates that the RCC average tensile strength is also 10% to 15% of its compressive strength.

Because of its steep downstream slope, Upper Stillwater is the only [7.20; 7.45] RCC gravity dam built up now for whom the direct tensile strength of the RCC was the primary design criteria. A minimum direct tension of 1.24MPa at one year was required.

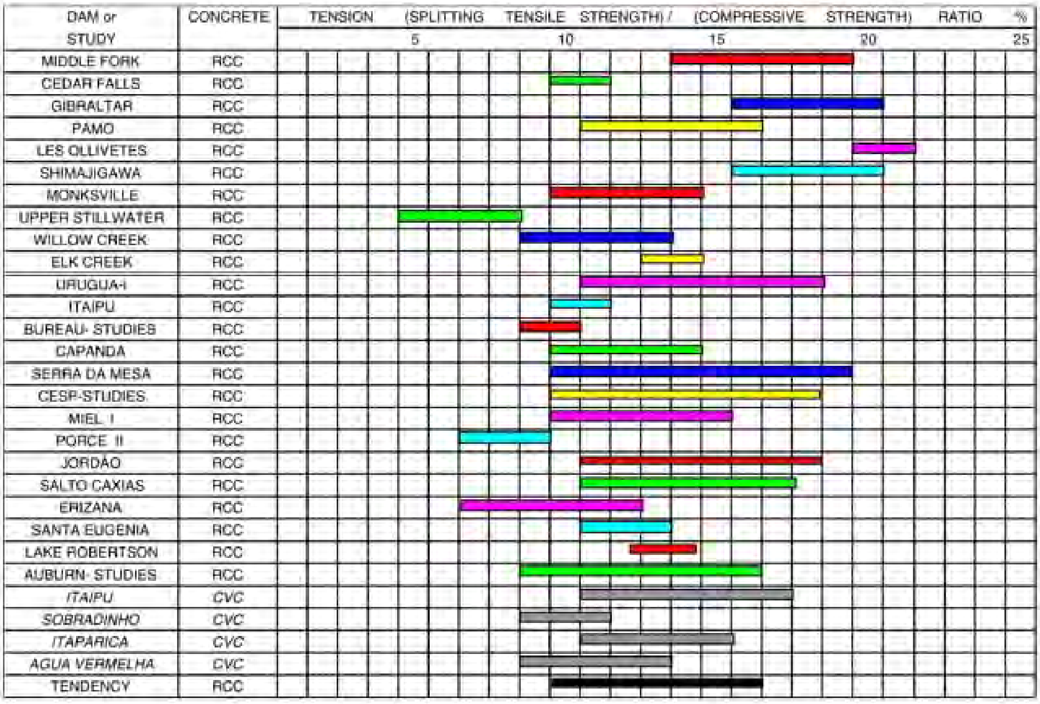


Figure 7.08 Splitting tensile strength as a percentage of compressive strength of RCC and CVC.

7.4.2.3 Shear

The shear strength of RCC depends on its tensile bond properties (cohesion) and internal friction angle. Minimum strength occurs at construction joints and along the interface between lifts of RCC. Constructing a concrete dam by using RCC methods produces a structure with lift lines every 0.3m to 1.0m vertically. The shear strength at the compacted lift surface is more important to the designer than the shear strength of the parent material.

A typical construction joint in a mass concrete dam is the horizontal surface of an existing concrete which has become so rigid that a newly placed concrete cannot be entirely incorporated to the previous one. Such construction joints are sometimes called "lift joints" or "cold joints". Since it is unpractical to continuously place concrete in the entire body of a large dam without lengthy interruptions, the formation of some construction joints is unavoidable. Even in an RCC construction, if the elapsed time between lifts is excessive, construction joints may occur, as previously mentioned in Chapter 4.

✓ **Necessity of joint treatment**

Ideally, mass concrete in a dam body should be monolithic. A construction joint, whether planned or unexpected, if untreated, can become a discontinuity or a weakness plane in the concrete mass.

External and internal loads, including those due to temperature changes, imposed upon a monolithic concrete dam, are distributed throughout its entire body and transferred to its foundation and abutments by its elastic response. This structural response results in deformations and stresses caused by flexure, transverse shear, compression and tension. In an arch or three-dimensionally monolithic gravity dam, torsional and longitudinal shears also occur. Thus, a typical horizontal construction joint would be subjected to stress combinations comprising horizontal shear, flexural tension and compression (see Figure (7.09) [7.46]). Near the upstream face the joint will also be subjected to internal hydraulic pore pressures, possibly of a greater magnitude and over a larger area than in the adjoining concrete.

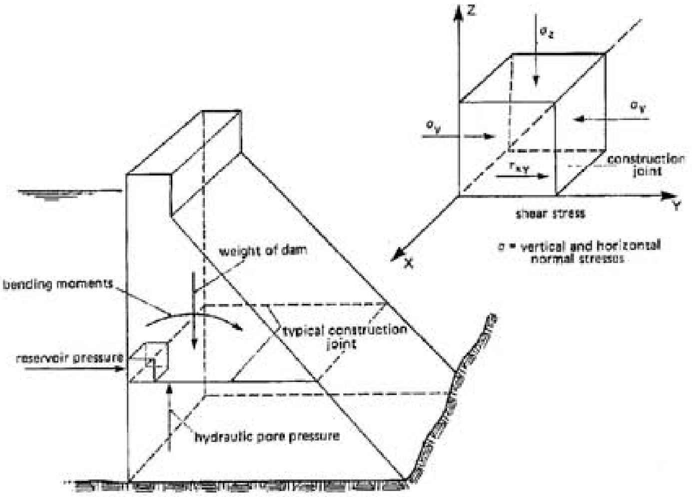


Figure 7.09 Stresses in and loads on typical construction joints [7.46].

A construction joint cannot fully transmit these stresses from one part of the concrete to the other, unless its effective bond, flexural, tensile and shear strengths are greater than the corresponding stresses. Frictional resistance alone is not sufficient to ensure monolithicity at an untreated construction joint, because without an adequate bond it will tend to open at the upstream face, and the pressure of water into the open joint will increase further the tensile stresses at the joint. In the long term it can weaken the concrete, alter the distribution of stresses in the structure, impair its stability and require strengthening and rehabilitation.

Therefore, it is necessary to prepare, clean and treat each construction joint before placing a new concrete lift, in such a manner that the joint would have adequate bond and shear strength to assure integral elastic behaviour of the entire concrete structure.

✓ **Construction Joint investigations**

Case histories regarding the performance of construction joints in five large concrete dams [7.46], a RCC cofferdam and two RCC dams (see Figure 7.10) are discussed in this section: Ilha Solteira, Brazil; Itaipu, Brazil-Paraguay; Itumbiara, Brazil; Jupia, Brazil; Ross Dam, USA; Serra da Mesa RCC cofferdam; Jordão and Salto Caxias RCC dams, Brazil; and Capanda dam, Angola:

Dam	Dworshak	Ilha Solteira	Itaipu	Itumbiara	Jupiá	New Bullards Bar	Revelstoke
Location	USA	Brazil	Brazil-Paraguay	Brazil	Brazil	USA	Canada
River	Clearwater	Paraná	Paraná	Paranaíba	Paraná	Yuba	Columbia
Power Plant Capacity (MW)	800	3200	12600	2100	1400	330	2700
Constructed	1965-1974	1965-1973	1975-1983	1973-1980	1962-1968	1966-1970	1977-1984
Type	PG	TE/PG; ER	TE/PG; ER/CB	TE/PG	TE/PG; ER	VA	PG
Height (m)	219	74	196	106	43	194	175
Crest Length (m)	1002	6185	7297	6780	5604	689	472
Concrete Volume (1000m ^{3})	5024	3676	12686	2081	1500	2000	2275
Mass Concrete Mix (kg/m ^{3})*	150	84	87	112	150	180	138
PG= Gravity; TE= Earthfill; CB= Hollow Gravity, Buttress; VA= Arch							
* Minimum cementitious content (Cement + Pozzolanic Material) and MSA= 152mm							

Figure 7.10 Dams where waterblasting was used for joints treatment [7.46].

⇒ **Ilha Solteira dam (3,675,600m³ CVC)**

During construction (1965-1973) of this gravity dam (where greencutting and waterblasting were mostly employed for joint preparation), in order to compare the efficacy of various joint treatments, test panels were prepared in four lifts of the transition walls between the concrete dam and the rockfill wing dams. The lifts were placed after nominal clean up with air and water jets: in some test panels, the joints were not subjected to any treatment. The construction joints in other designated test panels were prepared by greencutting and waterblasting prior to placement of new concrete. Cores, with a diameter of 250mm, drilled along the joints, were obtained from the test panels with concrete ages ranging from 60 to 90 days.

The 250mmx400mm and 250mmx500mm core samples, with a construction joint located in the central part of the specimens, were prepared and tested in accordance with ASTM-C-496 [7.47] procedures. In all cases, the break occurred at the joint, indicating that the joint was weaker than the monolithic concrete. Test results are summarised in Figure 7.11, [7.48].

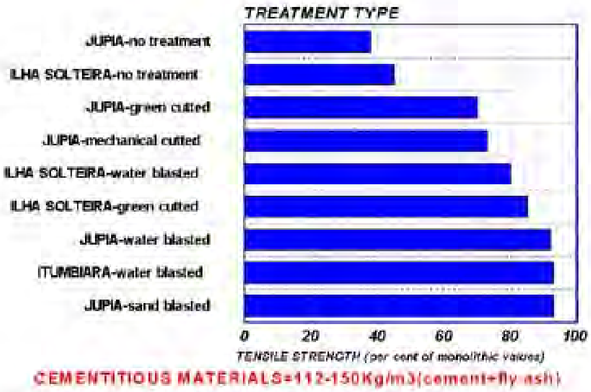


Figure 7.11 Test results on core samples from Ilha Solteira Dam [7.48].

The average compressive strength of the monolithic concrete at 90 days was 145kgf/cm^2. Analyses of a large number of various types of tests, for concrete tensile strength, have shown that it is about 10% to 12% of its corresponding compressive strength [7.49]. The Ilha Solteira tests demonstrated that, with greencutting or waterblasting, a high degree of bond was obtained and the average splitting tensile strength of the joint was about 90% of the tensile strength of the concrete (parent) itself.

⇒ Itaipu Project (13,000,000m^3 CVC)

Considering the large sizes and heights of the Itaipu dams, the complex shape of the hollow gravity dam [7.50], the relatively thin upstream heads of the buttresses and the anticipated fast rate of concrete placement, great emphasis was placed on the treatment and performance of the construction joints.

To determine the most satisfactory method of joint treatment from the structural viewpoint, which would also be economical, comprehensive field and laboratory investigations were carried out on dam blocks during the early stage of the project construction in 1977-1978.

Construction joints were designated for one of the following types of treatment:

- No treatment (only nominal clean-up);
- Waterblasting; and
- Greencutting

For each type of treatment, four alternatives of joint surface condition were considered:

I. Plane surface or
II. Rough surface; and
III. With a mortar layer or
IV. Without a mortar layer

For greencut and waterblasted joints, additional alternatives were for dry, surface saturated dry, and excessively cut conditions. Thus, 12 alternatives of joint treatment were evaluated. These comprehensive investigation involved a total of 330m of cores extracted from selected test blocks; 145 laboratory samples from the joints tested; 432 laboratory samples tested from monolithic concrete (cast and drilled core); 36 joint specimens, and 142 monolithic concrete specimens tested for splitting tensile strength according to ASTM C-496; 34 joint specimens plus 132 monolithic concrete specimens tested for shear strength according to CRD C-90 USCE [7.51]; and 15 joint specimens plus 120 monolithic concrete specimens tested for compressive strength according to ASTM C-39 [7.52].

The construction joint surfaces were prepared in two blocks of the dam. Each one of the 12 alternatives had an area of 3mx3m in plan, on the boundary part of the blocks, and CVC was placed in five 0.5m thick layers with a total lift height of 2.5 m and consolidated as specified for the dam. The concrete mix comprised the following (all in kg/m^3):

Cement		104
Fly-ash		30
Water		89
Aggregates - natural sand		166
- crushed sand		388
- crushed coarse basalt		
	19mm	364
	38 mm	365
	76 mm	465
	152 mm	641
Slump (wet screened portion)		4.0 $\pm$ 0.5 cm
Air entrained (wet, screened)		7.0% $\pm$ 0.5%
Placement temperature		7°C

A total of 280m^3 of concrete were placed above and below the surfaces to form the construction joints test area. The cores were drilled horizontally in the concrete and the construction joint, when the age of the joint and the concrete was 60 to 80 days. The drilled cores had a diameter of 250 mm and the tests were carried out at 90 days age. The 250mmx400mm or 250mmx500mm size samples were prepared with a construction joint located approximately in the central part of the specimens.

Figures 7.12 to 7.14 show the average splitting tensile and shear strengths of construction joints subjected to the 12 types of treatment studied. Stress values are shown as percentages of the comparable values for monolithic concrete. The permeability coefficient of the tested construction joints, discussed ahead, ranged from $1x10^{-9}$ to $1x10^{-11}$ m/s, which is comparable to that of the concrete.

⇒ **Itumbiara dam (2.080.789m^3 CVC)**

Concrete placement in this 106m high gravity dam commenced in 1975. Benefiting from the experience gained at Dworshak, Jupia, Ilha Solteira and New Bullards Bar dams (as seen in Figure 7.10), high-pressure waterblasting was specified and employed for treatment of all construction joints in Itumbiara dam.

Cores of 200mm diameter were drilled from 55 randomly selected locations, with a total length of 70m. The cores were horizontally extracted from the blocks of the transition wall between the concrete and the rockfill dam with a construction joint along the core. The samples were prepared, being cut with a diamond saw, at ages of 150 to 360 days.

Randomly selected specimens were tested [7.53] for splitting tensile strength of the joint in accordance with ASTM-C-496 [7.47]. The average tensile strength of the treated joints exceeded 90% of that of the monolithic concrete (see Figure 7.11), indicating that an almost full monolithic action would develop across the construction joints.

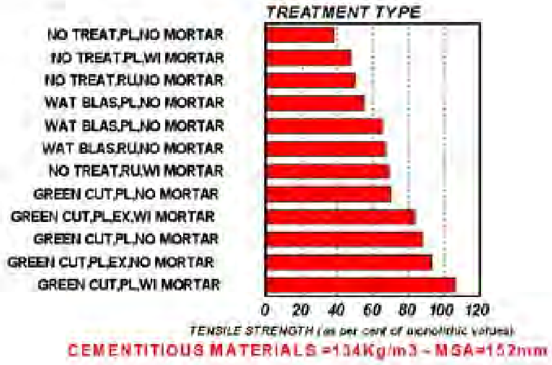


Figure 7.12 Itaipu Project - Tensile strength – Construction joints [7.43].

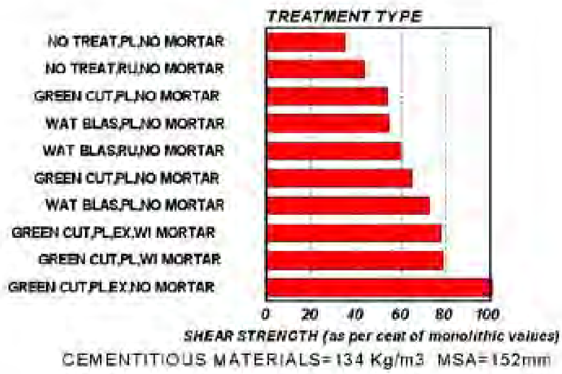


Figure 7.13 Itaipu Project - Shear strength - Construction joints [7.43].

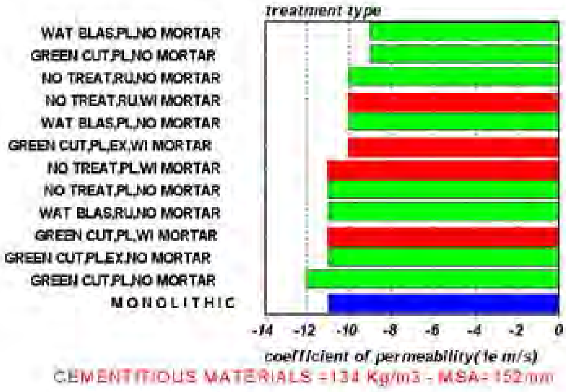


Figure 7.14 Itaipu Project - Permeability - Construction joints [7.43].

⇒ **Jupia dam (1,500,000m3 CVC concrete)**

During the initial period of construction (1960's) of Jupia dam, 30 test blocks were cast to verify the suitability of greencutting, waterblasting, sandblasting and mechanical cutting.

The typical joint test surface was 0.4mx0.4m in area in the middle of a block of 0.4mx0.4mx1.3 m. In addition to the four areas where the various types of joint treatment were applied, three joint test panels received no treatment other than a nominal air-water jet clean-tip, and three other blocks were cast without a joint to be compared with monolithic concrete. A total of 38 beams (0.4mx0.4mx1.3m) were tested according to ASTM-C-78 (Standard Test Method for Flexural Strength of Concrete) using a simple beam with three-point loading.

The results of the tests for the five alternatives are shown in Figure 5.15. It was concluded that joints treated either by greencutting or mechanical cutting would develop a tensile strength (modulus of rupture) of at least 70% of that of the concrete. Results of waterblasting were as good as those obtained by sandblasting, developing a tensile strength equal to 90% of that of the concrete. Considering the low height of the gravity dam, the degree of monolithicalty developed by greencutting was considered acceptable when the new concrete was placed within 5 days. The remaining construction joints, particularly when more than 5 days elapsed before placing new concrete, were treated by waterblasting.

⇒ **Ross dam (670,000m^3 CVC)**

The Ross concrete arch dam was completed at a height of 165m in 1949. During 1968 to 1975, extensive engineering studies were performed to raise the dam [7.54] at a height of 202 m. A critical concern in the proposed design was that the new concrete should adequately bond to the old, so that the two parts of the dam would respond to the external and internal loads as one elastically integral monolithic structure.

Field tests [7.54] were performed by casting concrete panels against the vertical surface of the "dimples" originally formed in the downstream face of the dam (Figure 7.15). Twelve test specimens each, with a contact area of $0.14m^2$, were placed after the contact surface of the old concrete was chipped to a depth of 38mm, sandblasted and kept damp for 48h. The test panels were cured with water spray for 28 days and then covered with a sealing compound.

Two series of tests were carried out on the same surface. The first series was with a 10mm thick layer of cement-sand mortar applied to the contact surface just before the test panel of concrete was cast. After completion of the first series, a second set of 12 panels was cast, except that the mortar layer on the prepared contact surface was omitted.

On 9 panels in each series, the load was applied along the plane of the contact to induce failure by direct shear, and on three panels the load was applied with an eccentricity of 38mm out of the plane of the contact surface.

The panels were tested for failure at ages of 28 to 90 days under rapid and slow loading conditions. While these *in situ* tests were performed under difficult field conditions, where the same degree of quality control could not be maintained as in a laboratory, the data obtained are useful and pertinent to evaluate adequacy of treatment construction joints.

The principal conclusions derived from Ross dam tests were:

· The treatment and preparation of the existing concrete must produce a clean, fresh, sound, moistened surface, and the new concrete must be carefully placed, consolidated and cured to obtain a satisfactory bond.

· An adequate bond can be achieved between the old and the new concrete without using mortar or grout on the contact surface.

· Bond or shear strength, on a properly prepared (even vertical) surface, is about 10% of the unconfined compressive strength of the (new) concrete at an age of 28 to 90 days.

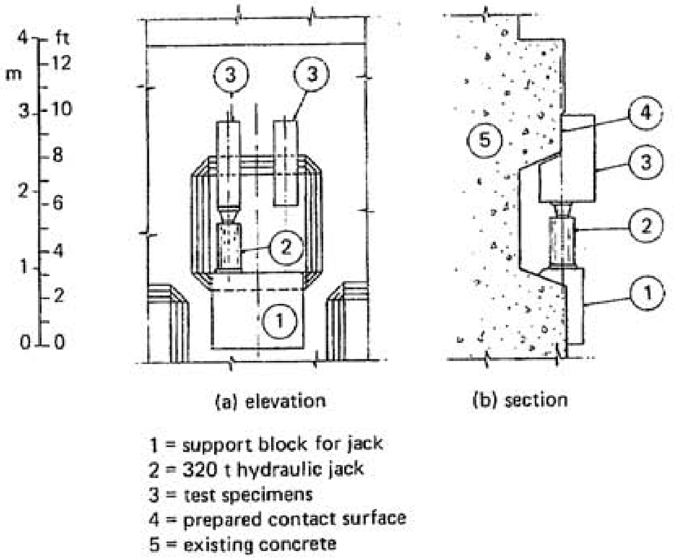


Figure 7.15 Ross dam. *In situ* bond test arrangement [7.43].

✓ **Construction Joints in RCC dams**

⇒ **Serra da Mesa Cofferdam Investigations**

Under ideal conditions, in a RCC dam, a zero-slump concrete is placed in thin layers and compacted by vibrator rollers, in a continuous operation with successive layers being placed without significant interruption. However, for large RCC placements, a continuous operation may not be feasible and some cold or construction joints are likely to occur. How should these joints be treated?

The cofferdams for the Serra da Mesa rockfill dam are RCC gravity dams constructed in 1988 [7.55]. These cofferdams, overtopped by river flow, have the following main characteristics:

Cofferdam	Height (m)	Crest length (m)	Volume (m^3)
Upstream	25.mai	160	21 000
Downstream	16.mai	180	12 500

The following six different types of joints treatment (see Figure [7.16]) between the layers of RCC were investigated on two large scale test fills, 4mx27m in area, each containing 150m^3 of RCC. The RCC was placed and compacted in layers ranging from 0.25m to 0.5m in height, with 10t vibrator rollers. All the important construction elements of the RCC dam were used in the test fill (see Figure 7.17).

Type	Compacted surface clean up	Mortar or bedding mix	Interval between layers (hours)**
I	No	None	< 8
II	No	None	> 8
III	No	Yes	< 8
IV	No	Yes	> 8
V	With low pressure water jet*	None	> 8
VI	With low pressure water jet*	Yes	> 8
* Pressure about 7 kgf/cm^2			
** Placement of new layer after compaction of preceding layer			

Figure 7.16 Serra da Mesa Cofferdam- Types of joints treatment [7.43].

Two RCC mixes with the following cementitious content were used for the tests:

60 kg/m^3 cement + 100 kg/ m^3 milled blast furnace slag
60 kg/m^3 cement + 60 kg/ m^3 milled blast furnace slag

The average joint surface area of each test was about 100m^2, and 90m of cores were extracted for all the tests on the joints. For each alternative, six samples were tested to obtain the direct tensile strength of the joint.

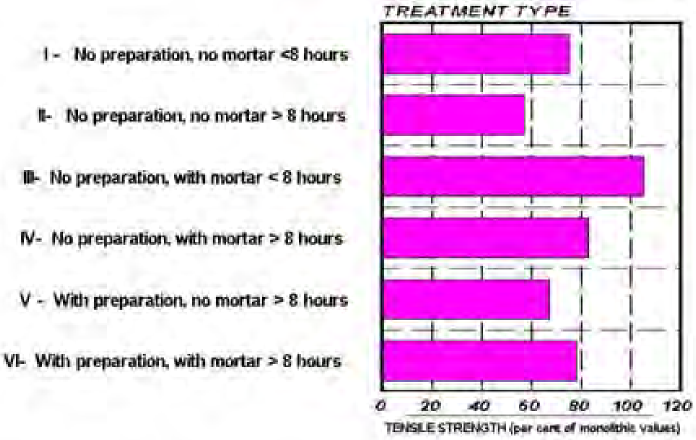


Figure 7.17 Serra da Mesa cofferdam tensile strength results [7.43].

The tensile strength of the RCC joints for the six treatment conditions are compared with the tensile strength of monolithic RCC in Figure 7.17.

These investigations indicated the following, regarding the performance of joints between successive layers of RCC subjected to different types of treatment:

· If the time interval between layers exceeds 8 hours, without any treatment, there would be a 25% reduction in the effective bond strength of the joint.

· The use of a bedding-mix would improve the strength of the joint more than 34% regardless of the time interval between lifts.

· The clean up of the RCC joints with low-pressure air-water jets showed only a small improvement in joint strength (16%, comparing conditions V and II in Figure 7.17).

⇒ **TVA field tests**

It is interesting to review the results of field tests performed on RCC by the Tennessee Valley Authority [7.03] in 1971, when RCC dam technology was in its infancy.

The test fill was 10m long, 5m wide and 1.2m thick. The lean no-slump concrete used 75mm maximum size aggregate and contained 56kg/m^3 of cement plus 77kg/m^3 of fly ash.

RCC was placed in two 60cm thick lifts and compacted with a 15t vibrator roller. The lifts were placed 24h apart, forming a horizontal construction joint at mid-height, which was untreated. When the concrete was 3 months old, 12 widely spaced vertical cores were taken from the full depth of the fill and 2 horizontal cores were taken at the construction joint from the full 5m width. On randomly selected specimens obtained from the cores, the following tests were performed in laboratory: 24 compressive strength tests; 16 tensile strength tests; 25 shear strength tests; and 7 tests for permeability of the joint.

These investigations showed the following results:

Average compressive strength of RCC concrete	(kgf/cm^2)	219
Average shear strength of untreated construction joint	(kgf/cm^2)	21
Tensile strength of the construction joint as % of Tensile strength of concrete (approximately)	(%)	80

The results of these early pioneering investigations are in good agreement with those of the Serra de Mesa project (Figure 7.17).

⇒ Capanda Project (757,000m^3 RCC and 397,000m^3 CVC)
⇒ Jordão dam (570,000m^3 RCC and 77,000m^3 CVC)
⇒ Salto Caxias Project (1,000,000m^3 RCC and 450,000m^3 CVC)

The total shear strength can be determined by using Coulomb's equation:

$\tau = \mathbf{C} + \sigma\mathbf{tan}(\Phi)$ where
τ = unit shear stress;
C = unit cohesion;
σ = unit normal stress; and
Φ = internal friction angle

The cohesion **C** is also called the bond stress, while **stan(Φ)** defines the sliding friction resistance. A direct shear test is the usual method to obtain cohesion and friction angle data using various normal loads. The break bond shear strength may also be called the peak strength, and the "sliding friction" values indicate the residual shear strength.

These tests are done to get the Mohr-Coulomb Envelope, and so the cohesion **C** (shear strength) and the friction angle **Φ**. The laboratory tests on monolithic-RCC-specimens could be done:

- In a triaxial chamber similar in aspect, but greater in dimensions than the one used for soil-mechanics or rock-mechanics. In this way it is possible to change the confining pressure and determine the axial compressive value, as shown in Figure 7.18; or
- by A Direct Biaxial Shear test, often used in rock-mechanics, when a normal load is applied and the shear (with a little angle of the plane due the methodology) load can be measured (see Figures 7.19 to 7.21); or
- by a Direct Unconfined Shear test, based on the CRD-C-90, Corps of Engineers Test Method [7.51], where the shear load is applied in a single and non-confined plane.

The specimens from the RCC Construction Joints could be tested by:

- a Direct Biaxial Shear test - "in laboratory"- as shown in Figures 7.19 to 7.21, on core specimens drilled from a trench, or from a large scale test-fill, or from a large specimen (for instance, by casting a 45x90cm specimen with a construction joint in the central part and after drilling a core throughout the construction joint); or

➢ a Direct Biaxial Shear test - ***in situ*** - in a large scale test-fill, as it was done at Urugua-i and Capanda dams and shown in Figures 7.22 to 7.25.

Typical values of shear strength parameters for some RCC and CVC dams and studies [7.19 to 7.43] are shown in Figure 7.28. The Figure 7.29 shows some values from Figure 7.28 compared with shear tests from the rock (meta-sandstone) foundation contact at Capanda dam. It is very important to emphasize this, because it is possible to see that:

- The shear (cohesion and friction) values at the construction joint (normally well treated and with bedding mix) are greater than the ones obtained for the rock foundation contact;
- The shear values at construction joint, without bedding mix, are in the same range as the one obtained for the rock foundation contact;
- The results of direct, biaxial and triaxial tests performed on cores obtained from test fills and completed dams, including *in situ* tests, indicate that the shear strength components **C** and **Φ** are comparable to the CVC ones made from similar aggregates. While cohesion is dependent on the cementitious content, the quality and gradation of the aggregates affect the friction angle.

From the shear tests, one can learn that, when it is enriched by increasing unnecessarily the cementitious content of the bedding-mix, the shear values in general will not increase because the failure surface will be just near the construction joint (closely above or below) at the weakest RCC point or surface, as it can be seen in Figure 7.27. The values in this case will be more or less the same as the monolithic RCC values.

Figure 7.18 Triaxial chamber used for concrete tests at Ilha Solteira and Itaipu laboratories.

Figure 7.19 System used for biaxial shear test on rocks and concrete specimens, at Itaipu laboratory.

Figure 7.20 Modification in the apparatus shown in Figure 7.19, by changing the shear load angle, at Itaipu laboratory, as suggested by Bureau of Reclamation [7.56].

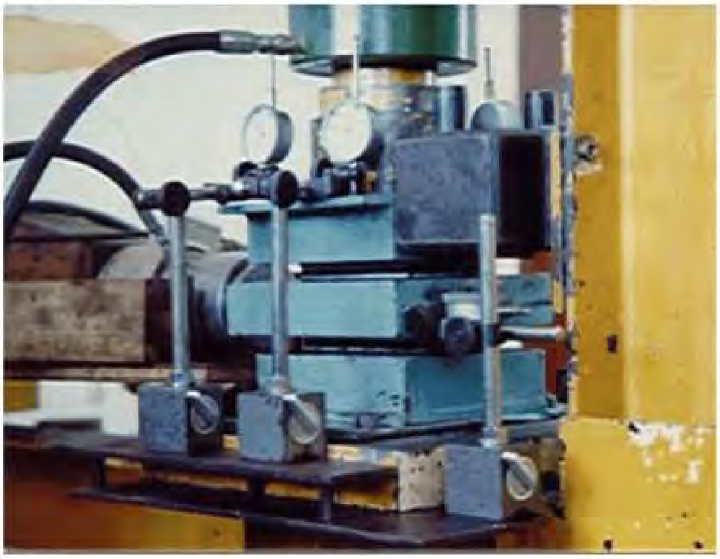


Figure 7.21 Detail from the test shown in Figure 7.20.

Figure 7.22 Rock surface preparation for RCC test-fill at Capanda job site.

Figure 7.23 RCC placement at the test-fill at Capanda job site.

Figure 7.24 RCC block-specimens being cut by diamond saw blade, at Capanda job site.

Figure 7.25 Biaxial shear - *in situ* - test undertaken at Capanda test-fill.

Figure 7.26 Core drilled from the RCC test-fill, showing the action of the bedding mix placed on the construction joint of Capanda dam.

Figure 7.27 RCC blocks specimens after tested, showing that the bedding mix works well and the failure surface occurred immediately below the construction joint.

Dam	Order	Type	kg/m³	kg/m³	kg/m³	Treatment	Cohesion kgf/cm²	Friction Angle	Cohesion kgf/cm²	Friction Angle
Tamagawa	1	RCD	91	39	130	Mortar	30	49		
Tamagawa	2	RCD	91	39	130	Monolithic	33	52		
Upper Stillwater	3	RCC	80	173	253	No treated	34	64	2.5	47
Upper Stillwater	4	RCC	80	173	253	Monolithic	21	57	2.3	44
Copperfield	5	RCC	95	15	110	Global Values	0.2--1.5	46--51		
Galesville	6	RCC	54	52	106	No bedding mix	7.6	67	5.6	40
Galesville	7	RCC	54	52	106	Monolithic	23.3	52	4.9	43
Galesville	8	RCC	54	52	106	No treated	26.6	33	6.7	45
Elk Creek	9	RCC	70	36	106	No treated	1.1	41		
Elk Creek	10	RCC	70	36	106	No clean + Mortar	6	62		
Elk Creek	11	RCC	70	36	106	Water jet + Mortar	4	56		
Elk Creek	12	RCC	70	36	106	Monolithic	8	67		
Urugua-í	13	RCC	60		60	No bedding mix	3.8--4.6	54--59	3.2--3.5	40--47
Urugua-í	14	RCC	60		60	200 oC + No bedding mix	2.9--3.1	40--44	3.3--3.4	36--40
Urugua-í	15	RCC	60		60	500 oC + No bedding mix	4.2--4.4	33--37	3.6--3.9	30--35
Urugua-í	16	RCC	60		60	780 oC + No bedding mix	2.5--2.7	39--42	3.6--3.7	32--37
Urugua-í	17	RCC	60		60	Monolithic	24.6	48		
Serra da Mesa	18	RCC	60	140	200	Monolithic	22	58		
Capanda	19-(1)	RCC	100		100	Monolithic	31.7	42		
Capanda	19-(2)	RCC	60		60	Monolithic	15.7	49		
Capanda	19-(3)	RCC	100		100	Monolithic	38.3	46		
Capanda	A-(1)	CVC	140		140	Monolithic	36.5	42		
Capanda	A-(2)	CVC	140		140	Monolithic	29.9	43		
Capanda	A-(3)	CVC	180		180	Monolithic	38.5	41		
Jordão		RCC	75--100		75--100	Monolithic	19	50		
Jordão		RCC	75--100		75--100	Water jet	12	48		
Jordão		RCC	75--100		75--100	Water jet + Concrete Bedding	14	58		
Jordão		RCC	75--100		75--100	Water jet + Mortar Bedding	22.5	50		
Salto Caxias		RCC	100		100	Water jet + Concrete Bedding	16	49		
Ilha Solteira	B-(1)	CVC	200--350		200-350	Monolithic	55--70	31--44		
Ilha Solteira	B-(2)	CVC	109		109	No treated	5.5	57		
Itaipu	C-(1)	CVC	100--350		100--350	Monolithic	22--96	40--42		

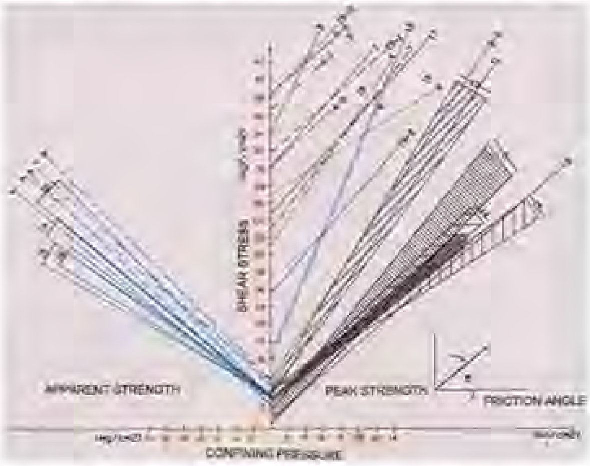


Figure 7.28 Shear strength values of RCC and CVC.

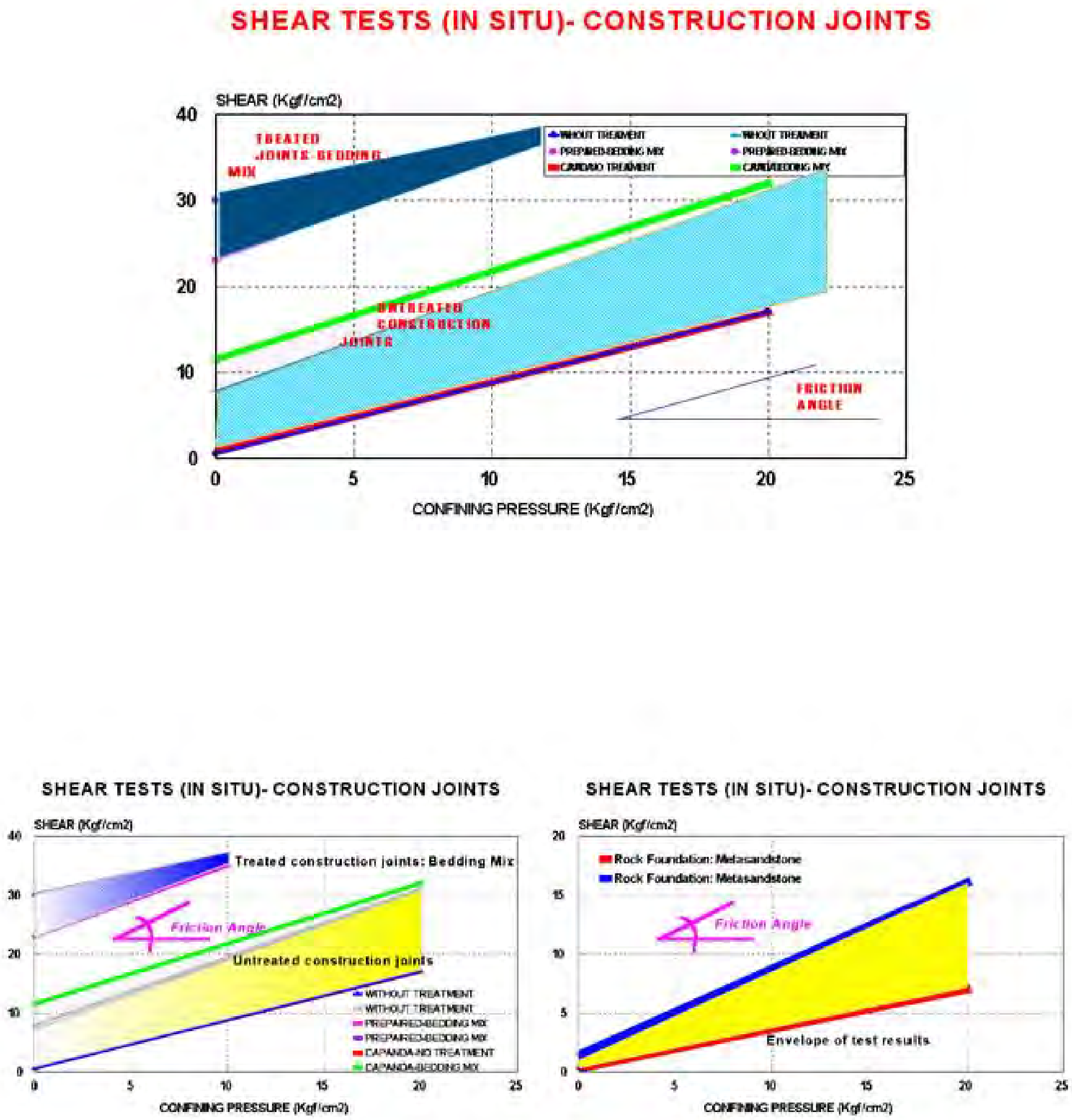


Figure 7.29 Shear strength values of RCC and rock-foundation contact.

Comparison

CVC mass concrete

· For a satisfactory treatment of construction joints, high pressure waterblasting is as effective as wet sandblasting;

· Properly controlled greencutting performed at an early age (within 5 days) will produce a construction joint surface almost as good as the one obtained by waterblasting;

· A construction joint prepared by either greencutting or waterblasting, without a mortar layer, will have effective shear, bond and tensile strengths equal to at least 85% of those of the concrete, which would adequately ensure monolithic performance of the joint;

· The roughness of the joint surface does not have a significant influence on its strength or performance;

· A mortar layer has some beneficial effect on the joint strength only if the surface clean-up is not performed;

· The permeability coefficient of construction joints without any treatment and without a mortar layer is about 10^{-10}m/s or 90% of that of the concrete. With greencutting or waterblasting and without a mortar layer, the construction joint would be essentially as impervious as the concrete.

Roller Compacted Concrete

· If the time interval between successive RCC layers is more than 8 hours, without any treatment or bedding mix, the joint would be 25% weaker than if the time interval was less than 8 hours;

· The use of a bedding mix or mortar layer would increase the bond strength of the joint by 30%, regardless the time interval between RCC layers;

· The clean up of joint surface with low-pressure air-water jet would improve the bond strength of the joint by about 16 per cent.

7.4.3 Modulus of elasticity

The modulus of elasticity "E", also known as Young's modulus, is the ratio of normal stress to its corresponding strain for compressive or tensile stresses below the proportional elastic limit of the material.

The main factors that can affect the modulus of elasticity of RCC and CVC values are:

- Age of tests - The modulus increases with age up to a maximum value corresponding to the maximum that could be reached by the mortar or the aggregate (which is lesser);
- Aggregate type (and its modulus) - At large ages, the concrete modulus could be similar to the one of the aggregate if a rich mortar is used;
- Water to cement ratio (or paste proportioning) - As concluded from the above mentioned, rich mix has high values and poor mix has low values.

Aggregates, such as quartzite and argillite, can generally produce higher than average elastic modulus values for a given strength concrete. Similarly, a lower elastic modulus results from the use of a sandstone or similar aggregate. RCC mixtures made with conventional concrete aggregate and a relatively high content of cement or cement plus pozzolanic can develop moduli similar to those obtained in conventional concrete.

In most mass uses, a low modulus is desired to decrease the crack potential. Lean RCC mixtures using natural or manufactured fines as filler have resulted in very low moduli. Typical elasticity moduli for a variety of RCC mixtures are shown in Figures 7.30 and 7.31, illustrating the increase in elasticity modulus with age for 5 CVC and 13 RCC dams or test programs [7.20 to 7.43]. It is seen that the modulus of elasticity of RCC is considerably lower than that of CVC; about 50% at 7 to 28 days and about 65% at 90 days and later. Tests on core samples obtained from RCC used as backfill at Itaipu Project showed the same modulus at the age 3090 days as CVC with the same mix materials.

As seen in the Figures, extremely low elasticity values are possible with RCC. Lean mixtures with low strengths made with fines for filler material can have values of 75,000 kgf/cm^2 or less.

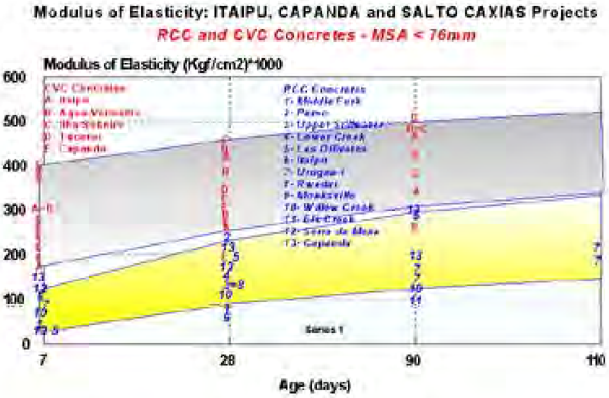


Figure 7.30 RCC and CVC modulus of elasticity values.

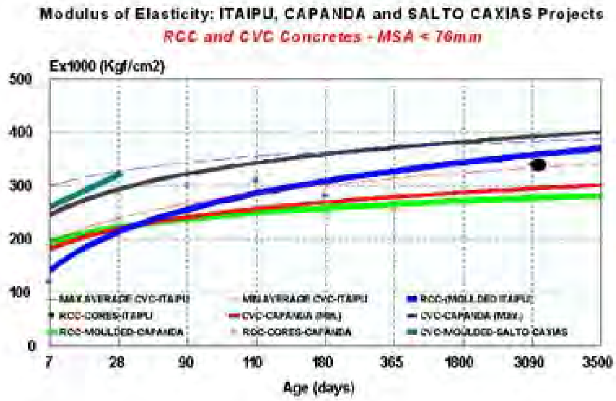


Figure 7.31 RCC and CVC modulus of elasticity tested at various ages.

7.4.4 Poisson's ratio

Poisson's ratio value is the ratio of the transverse (lateral) strain to the corresponding axial (longitudinal) strain, resulting from the uniformly distributed axial stress below the proportional limit of the material. It seems that the values for RCC are similar to the values reported for CVC mixtures. A range from about 0.17 to 0.22 has occurred.

7.4.5 Creep

When the concrete is subjected to a load, the deformation caused can be divided into an immediate deformation, such as an elastic strain (related to the modulus of elasticity) and a time-dependent (related to the period of time under load) compressive deformation called creep. Creep begins immediately and continues at a decreasing rate for as long as the load remains on the concrete.

Figure 7.32 Capanda RCC and CVC specimens under a creep test, at Itaipu concrete laboratory.

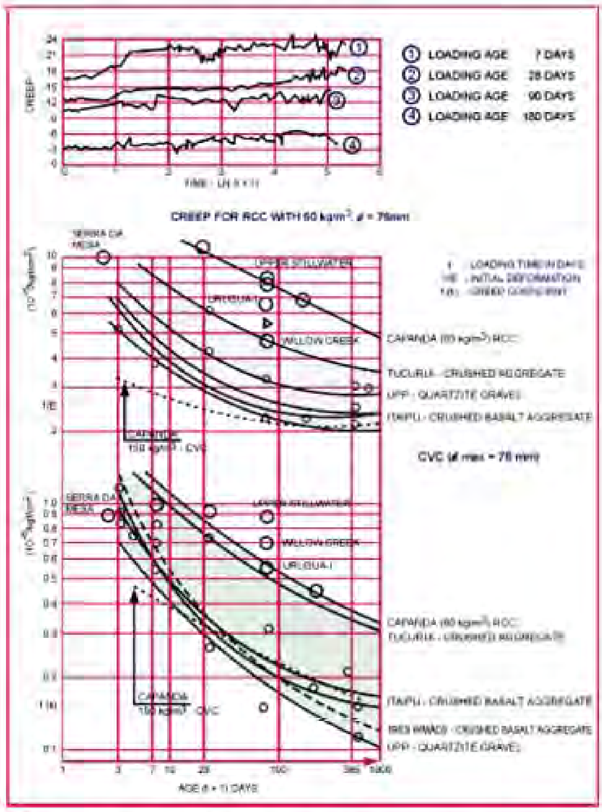


Figure 7.33 RCC and CVC Creep values.

The total creep is mainly affected by the aggregate modulus of elasticity and by the filler material that was used in the concrete proportioning mix. The scheme adopted for the creep test at CESP (Ilha Solteira- São Paulo- Brazil) and ITAIPU Laboratories could be seen in Figure 7.32. The main difference, when compared with creep tests on CVC, is that the deformations of the RCC specimens under load were measured on the surface, instead of by strain-meters embedded in the specimen body, as normally used for CVC specimens. This is due to the difficulties that could occur during the compaction of the RCC (by pneumatic hammer).

Figure 7.33 shows some [7.32 to 7.43] values in comparison with creep values of CVC. It can be noted that, from the creep equation $\boldsymbol{\varepsilon = \{[1/E] + [f_{(k)}] x [\log (t+1)]\}}$ normally used, the ratio **1/E** of RCC mixes - at early ages - is greater than that of CVC mixes, due to the higher mortar content of RCC. Due to the larger content of mortar in RCC mixes than that of CVC mixes, the coefficient of creep "$\mathbf{f_{(k)}}$" of RCC is higher than the one obtained for CVC made of similar aggregates.

In general, aggregates with a low modulus of elasticity will produce a concrete with a high creep. For most mass concrete applications, the ability to relieve sustained stress is desirable to relieve thermal stress. Higher strength mixtures have generally a more rigid cementing matrix and a lower creep, resulting in an increased thermal stress. Lean mixtures and those made with inert fillers of natural or manufactured fines have a creep higher than normal.

7.4.6 Tensile Strain Capacity

The strain capacity is considered as the ultimate deformation under tension before the rupture. Strain is induced in concrete when a change in its volume is restrained. When the volume change results in tensile strains that exceed the capability of the material to absorb the strain, a crack occurs. The threshold strain value just prior to cracking is the strain capacity of the material. Tensile strains in concrete can also be developed by external loads and by volume changes induced through drying and autogenous shrinkage.

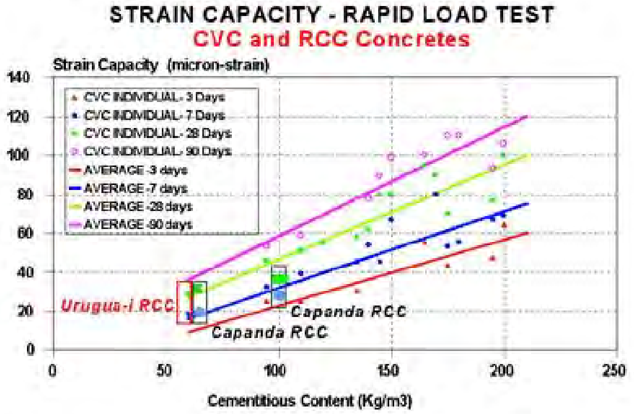


Figure 7.34 RCC and CVC Tensile strain capacity.

Figure 7.35 Tensile strain test - General view.

Figure 7.36 Tensile strain tests – Close view showing the wire strain gage on RCC specimen surface.

As with other material properties, strain capacities of RCC can vary considerably with the wide range of mixture designs and usable aggregates. The major factors affecting strain capacity are the loading rate, type of aggregate, shape characteristics (angular as produced by crushing versus natural rounded) and the cement content. The hard brittle aggregates, such as argillite and quartzite, generally produce a lower strain capacity. Crushing or addition of crushed material usually improves strain capacity by increasing tensile strength.

Test data for tensile strain capacity for RCC from Capanda and Urugua-i dams [7.06; 7.10 to 7.12], as compared to that for CVC, are plotted in Figure 7.34. It seems that the strain capacity of the two types of concrete using the same amount of cementitious materials, at various ages, is about the same.

7.4.7 Adiabatic Temperature Rise

The adiabatic temperature rise, due to the heat of hydration, for both types of concrete is obtained by the same way, by using a large dimension calorimeter. The adiabatic temperature rise for both types of concrete is essentially proportional to the cementitious content of the mix.

The values can be shown in two different ways. One in terms of temperature degrees, in an absolute value range. The other gives a simple way to general comparisons by a ratio between temperature degrees of adiabatic rise, per cementitious (cement plus pozzolanic material) content, which is called coefficient **of temperature rise** and is shown in Figure 7.37 [7.06 to 7.13]. The most important is to get the maximum **mix efficiency** (as described in 7.4.2) and the minimum **coefficient of temperature rise.**

RCC produces an adiabatic temperature rise in a similar way to CVC.

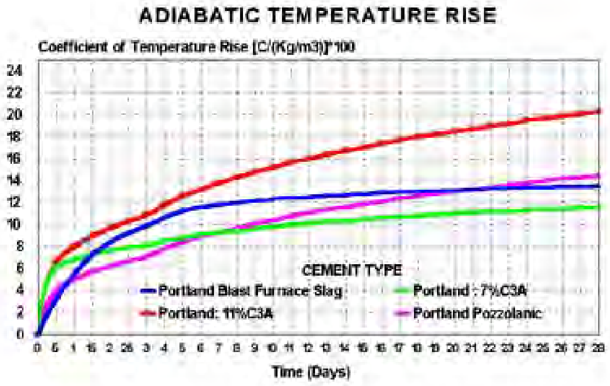


Figure 7.37 RCC and CVC Adiabatic temperature rise in terms of "coefficient of temperature rise" values.

Figure 7.38 Adiabatic temperature rise test - Specimen preparation.

Figure 7.39 Adiabatic temperature rise test - Specimen inside the adiabatic room.

7.4.8 Thermal Properties

The thermal properties - Diffusivity, Specific Heat, Conductivity and Coefficient of Thermal Expansion - depend mostly on the aggregates thermal properties and the saturation degree in the hardened RCC. The RCC properties that may be needed in a thermal analysis include specific heat, diffusivity, conductivity and coefficient of thermal expansion, together with a tensile-strain capacity. Typical values for RCC are very similar to values for CVC made with aggregate from the same source. RCC mixes show practically the same values as the CVC mixes, proportioned with the same type of materials as shown in Figure 7.40 [7.07 to 7.13].

COEFFICIENT OF THERMAL EXPANSION					
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT	COEFFICIENT OF THERMAL EXPANSION
				kg/m^3	10-6/C
URUGUA-i	PM - 60	RCC	BASALT	60	7.41
URUGUA-i	PM - 90	RCC	BASALT	90	8.33
ITAIPU	76 - D - 04	CVC	BASALT	189	8.0
ITAIPU	76 - D -04	CVC	BASALT	162	7.71
			SPECIFIC HEAT		
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS	SPECIFIC
				CONTENT	HEAT
				kg/m3	cal / g.C
URUGUA-i	PM - 60	RCC	BASALT	60	0.238
URUGUA-i	PM - 90	RCC	BASALT	90	0.233
ITAIPU	76 - D - 04	CVC	BASALT	189	0.243
ITAIPU	76 - D -04	CVC	BASALT	162	0.242
LAKE ROBERTSON	RCC-1	RCC	GRANITE-GNEISS	170	0.225
LAKE ROBERTSON	FC- 3	CVC	GRANITE-GNEISS	320	0.225
CAPANDA	RC - 60	RCC	META-SANDSTONE	60	0.221
CAPANDA	152 - 150 - B	CVC	META-SANDSTONE	150	0.228
CAPANDA	152 - 100 - A	CVC	META-SANDSTONE	100	0.223

THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY						
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS	THERMAL	THERMAL
				CONTENT	CONDUCTIVITY	DIFFUSIVITY
				kg/m^3	10-3(cal /cm.s.C)	10-3(m^2 / day)
URUGUA-i	PM - 60	RCC	BASALT	60	4.76	0.066
URUGUA-i	PM - 90	RCC	BASALT	90	4.22	0.060
ITAIPU	76 - D - 04	CVC	BASALT	189	4.41	0.062
ITAIPU	76 - D -04	CVC	BASALT	162	4.60	0.063
LAKE ROBERTSON	RCC-1	RCC	GRANITE-GNEISS	170	4.05	0.086
LAKE ROBERTSON	FC- 3	CVC	GRANITE-GNEISS	320	4.05	0.086
CAPANDA	RC - 60	RCC	META-SANDSTONE	60	6.0	0.093
CAPANDA	152 - 150 - B	CVC	META-SANDSTONE	150	7.0	0.111
CAPANDA	152 - 100 - A	CVC	META-SANDSTONE	100	7.4	0.116

Figure 7.40 RCC and CVC Thermal property values.

Figure 7.41 Specific heat test.

Figure 7.42 Linear expansion test.

Figure 7.43 Diffusivity test.

7.4.9 Volume change

In any massive concrete structure, the understanding and design of volume changes are necessary to minimize uncontrolled cracking. The volume reduction due to thermal or drying shrinkage, or autogenous volume, is of concern in the design of RCC dams.

7.4.9.1 Drying shrinkage

Volume change from drying shrinkage in RCC is minimized by virtue of the reduced water content. Increases in moisture cause the expansion of the concrete and decreases in moisture cause its shrinkage. In the cement hydration process, the water combines with the cement so the basic process is a moisture loss or shrinkage. In any concrete mix, it is only the paste that shrinks. So, for a constant cemetitious content, the drying shrinkage rate depends primarily on the amount of water in the mix. Though RCC requires less water when marginal aggregates with a high water demand and resulting drying shrinkage are used to produce RCC, it will have a corresponding volume reduction with a moisture loss.

7.4.9.2 Autogenous Volume Change

Autogenous volume change is primarily a function of the aggregate and its long-term stability with the cement being used. Each job should be evaluated after a review of a petrographic analysis of the aggregate, review of historical information and tests, if appropriate. Lower cement factor mixtures tend to be more stable. Natural fines used in RCC may also affect the volume change and should be taken into account. As with conventional concrete, the change can generally be expected to be minor, but it should be considered.

7.4.10 Permeability

The permeability coefficient is obtained by tests using an apparatus like the one shown in Figure 7.44. Permeability coefficient of RCC and CVC mixes are shown in Figure 7.45 [7.05 to 7.20; 7.29 to 7.31; 7.38 to 7.40; 7.55; 7.57]. It could be noted that there are three main groups of values.

- **Conventional Concretes** - This groups represents CVC-Permeability Coefficient values;
- **RCC-Pioneer Generation** - This group represents the "first generation" of RCC mixes, where the importance of the filler in the RCC mixes was not appreciated, and resulted in large permeability;
- **RCC-Current Practice** - It represents the RCC mixes with a large amount of fine material and results with permeability coefficient values - practically in the same range of CVC mixes values, for the same cementitious content.

The permeability of a concrete mass is largely dependent upon the entrapped air and porosity of the hydrated cement matrix and, therefore, is almost totally controlled by mixture proportioning, quality control and degree of compaction. When there are sufficient fines, controlled fine-particle distribution to minimize the air void system and full compaction, RCC will be relatively impervious. In general, an unjointed mass of RCC made from clean conventional aggregates with sufficient paste or very lean mixtures with controlled aggregate grading containing sufficient fines will have permeability values similar to the CVC concrete.

Figure 7.44 Permeability apparatus test at Capanda laboratory.

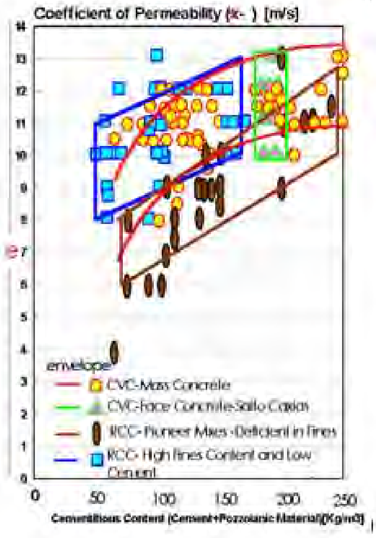


Figure 7.45 Permeability Coefficient values of RCC and CVC mixes, with and without fines and pozzolanic material.

The property that has caused a greatest concern to designers of RCC dam is the *in situ* permeability of RCC. Although the permeability of the parent (unjointed) material may be low, the joints between the layers are, as a matter of fact, the main cause of the difficulty. Nevertheless, it has been shown that it is possible to obtain an effectively monolithic and impermeable structure when RCC is placed in layers. The total seepage through an RCC dam is the sum of the water passing through the material itself (permeability) plus the one through any cracks or joints in the structure.

Some authors [7.58] suggest that the impermeability of RCC can be directly related to its cementitious content. This fact is especially applicable to RCC mixtures than conformable to the concrete approach where the paste exceeds the voids in the aggregate (see Chapter 6). Therefore, greater cementitious content produces a more watertight paste, which controls the permeability of the RCC material. For soils approach mixes, a greater impermeability can be achieved by a combination of increased cementitious content, greater compaction and sufficient fines and well-graded aggregate, all of them reducing voids in the material.

The improved RCC mixes with about the same permeability coefficient as CVC are more suitable for the construction of high gravity or arch/gravity dams. The use of a higher percentage of non-cement fines, or filler, or pozzolanic material, in an RCC mix contributes to its low permeability, without increasing the potential for thermal cracking.

The permeability coefficient of the tested construction joints ranged from $1x10^{-9}$ to $1x10^{-11}$ m/s, which is comparable to that of concrete.

As shown in Figure 7.45, the RCC permeability coefficient ranges from 10^{-6} m/s to 10^{-12} m/s with cementitious content from 60kg/m^3-250kg/m^3, as compared to 10^{-9} to 10^{-12}m/s for CVC, with similar cementitious content.

7.4.11 Durability

How does RCC compare with CVC as a material suitable for building high and large gravity dams of same durability and quality as in existing dams, which have performed well for several decades?

How does RCC compare with CVC as a material suitable for building pavements of same durability and quality as in existing pavements that have performed well for several decades?

A comparison of certain pertinent properties of RCC and CVC can be made to answer these questions. The durability of RCC is especially important if the material is exposed to weather or severe hydraulic forces. Both laboratory tests and field case studies have documented its durability.

7.4.11.1 Erosion or Abrasion Resistance

The erosion resistance of RCC is proportional to its compressive strength and the abrasion resistance of the aggregate used in the mix. RCC has shown good resistance to erosion and abrasion both in the laboratory and in the field. In conjunction with the design for Lost Creek, lean, large-aggregate RCC panels performed well when subjected to high velocity water jets at the Corps of Engineers test flume at Detroit Dam, Oregon [7.59]. Some mass sections of RCC were being submitted to high magnitude hydraulic forces, such as in a stilling basin or plunge pool.

The erosion resistance properties of RCC have been demonstrated in many projects. The most remarkable are Salto Caxias dam, the spillway rehabilitation at Tarbela Dam, the spillway for the North Fork of Toutle River debris retention dam and Kerrville dam.

From August/1997 to November/1997, the Salto Caxias dam was overtopped five times with a flow of 5500m^3/s (13,100m^3/s in total with 7,600m^3/s throughout the sluiceways), see Figure 8.01.

Pavements at heavy-duty facilities, such as log-storage yards and coal-storage areas have shown no appreciable wear from traffic and industrial abrasion under severe conditions.

7.4.11.2 Freeze-thaw Resistance

Experience has shown that RCC made with a substantial amount of clayey fines will check-weather and crack when subjected to alternate wet-dry cycles. RCC made with non-plastic fines or with no fines has shown no deterioration from wetting and drying.

Because proper air entrapment in RCC is generally not attainable with admixtures, freeze-thaw resistance must come from its strength and impermeability. If RCC mixes are designed for durability using freeze-thaw weight loss tests and criteria as developed for soil-cement, acceptable freeze-thaw durability can be expected. The amount of cement to produce a sufficiently durable RCC mix may be greater than that required achieving other properties, such as the compressive strength. Little or no pozzolan replacement for cement is advisable where horizontal RCC surfaces will be exposed to early freeze-thaw cycles while wet because high early strength is required under these conditions.

7.5 Comparison of Laboratory Test Specimens and Project Cores

Results obtained from the testing of cores from RCC dams are more indicative of actual properties of the material in the structure than results obtained from laboratory specimens.

Laboratory cylinders are used primarily to evaluate various mixtures and determine whether a given mixture can be expected to produce the strength required by the designer at a specific age. Cylinders prepared in the field at the time of construction have been used mainly for record keeping purposes rather than for construction control. This is mainly useful for rapid construction dams.

Figure 7.46 presents a comparison of the properties of laboratory cylinders and cores at various ages. For the tamping impact compaction methods of preparation, the cores had greater compressive strength than the cylinders at comparable ages with the exception of Willow Creek Dam. Most of the cylinders were prepared using a pneumatic pole tamper.

A standard deviation of 10.5% was found for 90 days compressive strength based on 55 tests at Bucca Weir, as compared to a standard deviation of 24.7% for the earlier Copperfield Dam cylinders.

Cores generally have had less average compressive strength than cylinders prepared by vibrating laboratory specimens.

From the results shown in Figure 7.46, there is a considerable difference in the compressive strength of cores and cylinders. There are many variables that can account for the strength differences, including material, temperature, curing and delay in compaction variations. Also, there are possible variations in cylinder manufacture, handling and shearing, as well as construction variations such as segregation at the bottom of the lifts. Still, the greatest variations in strength probably occur due to differences in moisture content and compactive effort between lab cylinders and the cores, resulting in density differences. It should also be noted that the mixture in the cylinders usually had a material greater than 38mm or 50mm screened out and, therefore, was not identical to the mixture sampled from the dam.

The difference in strength between lab-prepared cylinders and project cores, together with the variation in methods to prepare cylinders, indicate that standard methods for RCC cylinder preparation are needed.

Dam	Cylinders		Cores		Comparisson
	Age (days)	Compressive Strength (kgf/cm^2)	Age (days)	Compressive Strength (kgf/cm^2)	Grater values at (aproximatelly same age)
Lake Robertson	182	215	210	194	Cylinders
Capanda	180	111	from 128 to 223	127	Cores
Stacy Sppilway	90	218	90	182	Cylinders
Shimajigawa	91	145	91	195	Cores
Tamagawa	91	262	91	196	Cylinders
Mano	91	209	91	from 155 to 177	Cylinders
Pirika	91	161	91	136	Cylinders
Shiromizugawa	91	185	91	121	Cylinders
Asahi Ogawa	91	176	91	139	Cylinders
Upper Stillwater	365	435	365	365	Cylinders
Willow Creek	365	185	365	162	Cylinders
Middle Fork	28 and 90	90 and 116	42	142	Cores
Copperfield	28 and 90	47 and 73	56	99	Cores
Galesville	365	110	425	153	Cores
Castilblanco de los Arroyos	91	257	91	236	Cylinders
Stagecoach	365	88	365	135	Cores
Salto Caxias	180 and 365	from 115 to 132	from 180 to 365	from 100 to 129	Cylinders

Figure 7.46 Comparison data from laboratory specimens and cores.

Figure 7.47 RCC specimens cast and drilled cores.

7.6 References

7.01 HALL, D.J.; HOUGHTON, D. I."Roller Compacted Concrete Studies at Lost Creek Dam", in: U.S. Army Corps of Engineers. Portland, Oregon, June/1974.

7.02 U.S. Bureau of Reclamation: "Procedure for Casting No-Slump Concrete in: Cylinder Molds Using Vibratory Table", procedure 4906-86.

7.03 CANNON, R. W. "Concrete dam construction using earth compaction methods. economical construction of concrete dams", in: Conference Proceedings, American Society of Civil Engineers, 1972.

7.04 ANDRADE, Walton Pacelli de. "Water Content- DMA- Brazilian Method", 1997.

7.05 ANDRIOLO, F.R.; BETIOLI, I.; SCANDIUZZI, L. "Concreto Adensado com Rolo Vibratório", in: XIII Seminário Nacional de Grandes Barragens. Rio de Janeiro, Abril, 1980.

7.06 ANDRIOLO, F.R. "Contribuições para o Conhecimento e Desenvolvimento do Concreto Rolado". São Paulo, Brazil, 1989.

7.07 ANDRADE, W.P. et alli. "Estudo de Dosagens para Concreto Compactado a Rolo", in: XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, 1989.

7.08 ANDRADE, W.P. et alli. "Procedimento de Controle de Qualidade do Concreto Compactado a Rolo das Ensecadeiras Galgáveis para o Aproveitamento de São Felix", in: XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, 1989.

7.09 ANDRIOLO, F.R.; BRAGA, J.A.; GOTTARDO, G. "O Desenvolvimento e uso do Concreto Adensado com Rolo Vibratório, em Obras Hidráulicas em Países da América do Sul", in: Conferência Ibero-Americana sobre Aproveitamentos Hidráulicos. Lisboa, 1987.

7.10 ANDRIOLO, F.R.; BRAGA, J.A.; GOLICK, M.A.; ROSÁRIO, L.C.; ZANELLA, M.R.; "Concreto Rolado- Ensaios Especiais", in: XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, 1989.

7.11 ANDRIOLO, F.R.; GOLICK, M.ª; "Urugua-i (CCR)- Controle de Qualidade do Concreto Lançado no Tramo principal da Barragem", in: XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, 1989.

7.12 ANDRIOLO, F.R.; BRAGA, J.A.; ZALESKI, J.M.; ZANELLA, M.R. "Uso do Concreto Rolado - Projeto Capanda (ANGOLA) - Ensaios Especiais", in: XIX Seminário Nacional de Grandes Barragens. Aracaju, 1991.

7.13 CREVILARO, Celso Chineli; FERREIRA, Wilmar Souza; FERREIRA, Eustáquio. "Usina Hidrelétrica Salto Caxias - Programa de Ensaios- Concreto Compactado a Rolo", in: COPEL. Agosto, 1993.

7.14 Relatórios Trimestrais do Acompanhamento da Obra de Capanda- Angola, 1989-1993.

7.15 SCHRADER, E.K. "Willow Creek Dam - An Optimum Gravity RCC Dam With Vertical Upstream Face", in: CIRIA Conference, June/1981.

7.16 HIROSE, Toshio; YANAGIDA, Tsutomu. "Some Experiences Gained in Construction of Shimajigawa and Okawa Dams", in: CIRIA Conference, June/1981.

7.17 REEVES, Gary N.; YATES, Lewis B. "Simplified Design and Construction Control for Roller Compacted Concrete ", in: Roller Compacted Concrete- ASCE Symposium, May/1985.

7.18 PARENT, William F.; MOLER, William A.; SOUTHARD, Ronald W. "Construction of Middle Fork Dam", in: Roller Compacted Concrete- ASCE Symposium, May/1985.

7.19 YAMAUCHI, Takeshi; OKADA, Teruo; SHIMADA, Shoichi. "Construction of Tamagawa Dam by the RCD Method", in: XV ICOLD. Lausanne, 1985.

7.20 RICHARDSON, Alan T. "Upper Stillwater Dam Roller Compacted Concrete Design and Construction Concepts", in: XV ICOLD. Lausanne, 1985.

7.21 ELIAS, G.,C.; CAMPBELL, D.B.; SCHRADER E.K. "Monksville Dam - A Roller Compacted Concrete Water Suply Structure", in: XV ICOLD. Lausanne, 1985.

7.22 BENSON, Stephen A.; VERIGIN, William M.; CARNEY Michael J. "Cedar Falls Roller Compacted Concrete Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.23 SCHRADER, E.K. "Behavior of Completed RCC Dams", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.24 LOGIE, Charles V.; OLIVERSON, James E. "Roller Compacted Concrete Mix Design for Pamo Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.25 DRAHUSHAK, Roselle; DOLEN, Timothy P. "Evaluation of Cores from two RCC Gravity Dams", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.26 URLICH, Cecil M.; DEATHERAGE, J. David.; RAHE, John H.; DUNNE, Robert E. "Design and Construction of Lower Chase Creek Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.27 HOPMAN Dennis R.; CHAMBERS, Donald R."Construction of Elk Creek Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.28 DOLEN, Timoty P.; RICHARDSON, Alan T.; WHITE, William R. "Quality Control/Inspection- Upper Stillwater Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.29 DUNSTAN, M.H.R. "Whither Roller Compacted Concrete for Dam Construction?", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.30 BOUYGE, Bernard; LANGOIS, Andre P.; MARTIN, Jean-Pierre. "Quality of Works in RCC in France", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.31 FORBES, Brian A. "RCC in Dams in Australia", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.32 QUIN, Jin T.; REZENDE, Severino P.; SCHRADER, E.K. "Saco Dam- South America's First RCC Dam", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.33 HOLLINGWORTH, F.; DRUYTS, F.H.W.M.; MAARTENS, W.W. "Some South African Experiences in the Design and Construction of Rollcrete Dams", in: XVI ICOLD Congres. San Francisco, 1988.

7.34 FORBES, B.A. "The development and Testing of roller Compacted Concrete for Dams in Australia", in: XVI ICOLD Congres. San Francisco, 1988.

7.35 SCHRADER, E.K.; NAMIKAS, D. "Performance of Roller Compacted Concrete Dams", in: XVI ICOLD Congres. San Francisco, 1988.

7.36 GUZINA, B.J.; UZELAC, S.; SARIC, M. "Application of Roller Compacted Concrete at Appurtenant Hydraulic Structures of a Large Dam", in: XVI ICOLD Congres. San Francisco, 1988.

7.37 BAYAN, B.J. "Execution and Control of Castilblanco de los Arroyos Dam with Roller Compacted Concrete", in: XVI ICOLD Congres. San Francisco, 1988.

7.38 BOUYGE, B.; GARNIER, G.; JENSEN, A.; MARTIN, J.P.; STERENBERG, J. "Construction et Contrôle d'un Barrage en Béton Compacté au Rouleau (BCR): Un Travail D'Equipe", in: XVI ICOLD Congres. San Francisco: 1988.

7.39 BENCHEIKH, L.; TAYAE, M.; JAFRANE, S.; LAHLOU, K. "Barrage Ain Al Koreima en Béton Compacte au Rouleau, À Base D'Alluvions Naturelles - Conception et Composition du Béton", in: XVI ICOLD Congrès. San Francisco, 1988.

7.40 ARJOUAN, M.; CHRAIBI, A.F.; EJJAOUANI, H. "Utilisation du Béton Compacté au Rouleau Dans les Barrages de Faible Importance: Cas du Barrage de Rwedat", in: XVI ICOLD Congrès. San Francisco, 1988.

7.41 WONG, Noel C.; BISCHOFF, John A.; JOHNSON, David H. "Strengthening and Raising Gibraltar Dam With RCC", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.42 CASIAS, Theresa J.; GOLDSMITH, Vaughan D.; BENAVIDEZ, Abel A. "Soil Laboratory Compaction Methods Applied to RCC", in: Roller Compacted Concrete II- ASCE Conference, March/1988.

7.43 ANDRIOLO, F.R.; PACELLI, W.A..; SARKARIA, G.S. "Treatment and Performance of Construction Joints in Concrete Dams", in: International Water Power & Dam Construction, November/1993 .

7.44 ANDRIOLO, F.R.; SCANDIUZZI, L. "Concreto e seus Materiais - Propriedades e Ensaios". São Paulo, Brazil, 1986.

7.45 BOGS, Howard L.; RICHARDSON, Alan T. "USBR Design Considerations for Roller Compacted Concrete Dams", in: Roller Compacted Concrete- ASCE Symposium, May/1985.

7.46 HOLLINGWORTH, F.; DRUYTS, F.H.W.M. "Experimental Use of Rollcrete on Sections of a Concrete Gravity Dam", in: XV ICOLD. Lausanne, 1985.

7.47 ASTM-C 496. "Test Method for Splitting Tensile strength of Cylindrical Concrete Specimens", in: Annual Book of ASTM Standards, 1996.

7.48 ANDRIOLO, F. R. *Construções de Concreto - Manual de Praticas para Controle e Execução.* São Paulo, Brazil: Pini, 1984.

7.49 RAPHAEL, J. M. "Tensile strength of concrete", in: ACI journal title no. 81-71. USA, March-April 1984.

7.50 CARIC, D. M.; SARKARIA, G. S. et all. "The Itaipu hollow gravity dam", in: Water Power & Dam Construction, May 1982.

7.51 CRD-C-90. "Method of Test for Transverse Shear Strength Confined, Single Plane or Double Plane", in: Handbook for Concrete and Cement, 1973.

7.52 ASTM-C-39. "Test Method for Compressive Strength of Cylindrical Concrete Specimens", in: Annual Book of ASTM Standards, 1994.

7.53 PACELLI, W. A. "Concrete construction joints tests at ltumbiara dam". Rio de Janeiro, Brazil : Furnas Centrais Elétricas S.A., 1978.

7.54 SUNDQUIST, D. C.; KOLLGAARD, E. B. "Design and construction of Ross dam in successive stages", in: Q48, R2, 13th ICOLD Congress. New Delhi, India, 1979.

7.55 PACELLI, W. A. et all. "Desempenho do Concreto Compactado a Rolo (RCC) Através de Ensaios com Carotes da Usina Serra da Mesa". Furnas Centrais Eletricas S. A., 1990.

7.56 MCLEAN, Francis G.; PIERCE, James S. "Comparison of joint Shear Strengths for Conventional and Roller Compacted Concrete- Roller Compacted Concrete II, in: ASCE Conference, March/1988.

7.57 *Concretos-Massa, Estrutural, Projetado e Compactado com Rolo- Ensaios e Propriedades.* São Paulo: Pini, 1997.

7.58 DUNSTAN, M. R. H. *A Review of Design Criteria for High RCC Dams, Roller Compacted Concrete III.* ASCE, February 1992.

7.59 HOUGHTON, D.L.; BORGE, O E.; PAXTON, J. "Cavitation Resistance of Some Special Concretes", in: ACI Journal, December/1978.

8

Construction Planning, Construction and Details

8.1 General

In the development of RCC technology the construction of an RCC dam should be considered for any site which has a rock foundation suitable for a traditional CVC gravity or arched dam. This type of dam can be most economical especially if compared with an embankment dam which requires a separate spillway. The economic advantages can be even more attractive with an increasing scale of the dam and with few embedded facilities.

Approach differences do exist, however, steady progress is being made to establish a practical technology. In many countries, RCC has shown advantages over CVC mass concrete because the rate of equipment utilization is high as compared with labor requirements. Economic considerations in countries where labor costs are low and equipment has to be imported may indeed require a detailed analysis. Regardless of a lack of equipment and a surplus of manpower, there are other factors that make RCC preferable to either CVC dams or embankment dams, such as :

- Reduced environmental impact;
- Reduced cost of materials;
- Shortening of the construction period;
- Safer working conditions during construction;
- Proven technology of RCC as a concrete for dams;
- Improved condition to handle river flood with less risk.

This latter factor is based upon two premises. The first one is that diversion is simplified with RCC use in concrete dams as compared with other dams because diversion tunnels may often be replaced by conduits through the RCC mass, or in any case the distance through or around the dam is shorter and overtopping of the partially completed structure has been successfull and not catastrophic. The other one regards design that often allows for an overtopping spillway rather than a separate spillway structure.

It means that RCC dams provide cost advantages in river diversion during construction and reduce damages and risks associated with cofferdam overtopping. The diversion conduit will be shorter compared to embankment dams. With a shorter construction period, the probability of high water is lower and, thus, the size of the diversion conduit and the height of the cofferdam may be reduced compared to those required for both embankment and conventional concrete dams. These structures may be designed for one seasonal peak flow only rather than annual peak flows. With the high erosion resistance of RCC, the potential for a major failure would be minimal and the resulting damage would be less, even if overtopping of the cofferdam occurs.

Rapid construction techniques (compared to both concrete and embankment dams) and reduced material quantities (compared to embankment dams) account for major cost savings in RCC dams. Maximum placement rates of 4,000 to 9,000m^3 per day have been achieved. These production rates make dam construction feasible in one season even for large structures. When compared to embankment or conventional dams, construction time for large projects can be reduced by 1 to 2 years.

Figure 8.01 Overtopping at Salto Caxias Dam, in 1998, during construction.

Other benefits from fast construction include reduced administration costs, earlier project benefits and possible use of sites with short construction seasons. Basically, RCC construction offers economic advantages in all aspects related to time of dam construction.

RCC construction is an exciting technology which imposes some unique demands while using seasoned construction methods adopted from various disciplines. The essence of RCC construction is ***good planning*** and ***efficient resource handling*** during the intense period of placement. A successful construction, from all perspectives, relies on how the uniqueness and the intensity of RCC use are understood.

8.2 RCC Dams - Different Nominations - Evolution

During the last two decades, three main variations of RCC dams built so far were developed and the construction of each had its own peculiarities, or some authors' "trade mark" or country tendencies. They were grouped, as follows:

Low Cement Content	High Paste	RCD
Willow Creek	Upper Stillwater	Shimajigawa
Winchester	Santa Eugenia	Sakaigawa
Middle Fork	Platanovryssi	Pirika
Copperfield	New Victoria	Mano
Galesville and others	Puding and others	Tamagawa and others

Nowadays, there are two other main "classifications" of RCC dams built so far and they can be grouped as:

Gravity Dams	Arched Dams
Urayama	Saco de Nova Olinda
Pangue	Knellpoort
Capanda	Puding
Myagase, and others	Wolwedans, and others

From these experiences, important considerations and practices were worked out and established, as showed in next table.

Attention	Action	Dam
Aggregate	Use of a well graduated curve to proportion the aggregates so as to obtain a minimum voids content	Practically all
Segregation	Use of a reduced amount of the "coarser" fraction of the aggregates to reduce segregation	Practically all
Fine Portion	Use of a large amount of filler (finer than 0,075mm) material with pozzolanic activity; or	Upper Stillwater, Puding, Wolvedans;
	Use of a large amount of filler without pozzolanic activity (traditional filler only, as silt or non-siliceous dust material); or	Saco Nova Olinda, Canoas, Willow Creek
	Use of a large amount of filler with moderate pozzolanic activity (siliceous crushed powder filler), available near the job site on an economical basis	Urugua-i, Jordão, Capanda, Salto Caxias
Cement content	Reduction of the cement content to a minimum value that guarantees the required properties	Saco Nova Olinda; Urugua-i, Canoas

As a result of these approaches, several dams now under construction had their designs improved in different ways. Most of them have relatively low cement contents and have measures to control leakage at the horizontal joints. Some have also measures to carry seepage away before it emerges on the downstream slope. Experiences accumulated during the construction of these dams showed a cost saving when compared to the costs for a similar structure conventionally built.

The Japanese RCD approach is a cautious movement out from CVC mass to include RCC in their structures. In the Shin-Nakano dam – one of the first with RCC – 13,500m^3 were used in the spillway stilling basin while the total concrete to raise the old dam was of 276,360m^3. Later Japanese dams added a higher proportion of RCC but not to the full extent as used in other dams.

With regard to construction easiness, RCD concrete should be easy to transport in dump trucks, have a low material segregation, high workability and be easy to compact with vibratory rollers.

The Japanese RCD Construction Method uses not only RCC, but also CVC of different mix proportions to be used as exterior concrete, interior concrete, structural concrete and rock-contact concrete, according to functional requirements, as can be seen in Figure 8.02. Any concrete, except the one used as interior concrete, is a conventional "slumpable" concrete, although mix proportions vary from concrete to concrete.

RCD is a stiff and lean (zero slump) concrete transported and placed by dump trucks and compacted with vibratory rollers, with the following characteristics regarding mix proportioning:

a) As a stiff and lean concrete, RCD has unit water and unit cement contents lower than those of a slumpable dam concrete;

b) Its sand ratio, which ranges from 27% to 32%, is higher than that of CVC interior concrete;

c) In order to minimize bleeding and achieve high workability and watertightness, it is important to use a high percentage (7% to 15%) of fine grains (0.15mm or less) in fine aggregate and to also stabilize the surface moisture ratio of fine aggregate at a low level (3% to 4%).

In addition to properties, RCD concrete should have the following characteristics during construction:

a) Since RCD concrete is delivered in dump trucks, spread with bulldozers and compacted with vibratory rollers, it should have an appropriate consistency level (Vibrating Compaction – VC value: 20 ± 10s) so that heavy vehicles, such as dump trucks, may travel on the concrete spread with bulldozers, which in turn can be simultaneously compacted with vibratory rollers;

b) Segregation of aggregate during transportation, unloading and placement should be minimized;

c) After placement of concrete, joint cutters can be used to cut transverse contraction joints.

The Japanese dams are by all means as safe as the traditional dams. They even have transverse contraction or monolithic joints built in at 15m intervals. A series of layers are placed up to 50cm or 100cm before rolling. After rolling, the exposed surface is invariably treated with a thin bedding layes before the next lift is started.

American engineers at Willow Creek, taking a "calculated risk" [8.01] on seepage, built a unique structure which is a milestone in the history of dam construction. The cost savings were of the order of 50 percent. Many hard discussions has been held due to the fact that this structure seeps water between its horizontal lifts.

Benefiting from the Willow Creek experience, another unique American trial is the Upper Stillwater Dam with rich RCC mix. The dam did not leak through the construction joints, but leaked through the cracks that appeared due to thermal mass behavior and absence of contraction joints.

A third American experience started during the construction of Elk Creek dam, by the US Corps of Engineers, making a blend of Japanese and American experiences; however, the construction works stopped and the dam was not completed.

8.3 Sitting and Logistic Factors

8.3.1 General Considerations

In CVC dam block construction, traveling cableways, jib cranes or belt conveyors are necessary to transport concrete directly to the placement areas, often at different levels, and it is usual to ***think*** and plan the construction in a ***vertical*** way.

In RCC dam construction, handling equipment is greatly simplified because the concrete is placed over a wide horizontal area allowing transportation by trucks or a combination of belts and trucks; however, due to the high construction speed, it is necessary to ***think*** and plan the construction in both directions, ***vertical and horizontal.***

Design and construction are very interrelated in the successful completion of an RCC project. Equipment selection should consider quality, economics, schedule, risk and practicality. The designer should specify the mixing and delivery requirements necessary to the success of the design during construction and project operation as well. The contractor should understand that the equipment and construction procedures directly influence the achieved quality of RCC and that his options may be limited by design requirements.

One approach the designer can take to address this design interrelationship with construction is to just tell the contractor what the quality of the "in-place" material should be and give him a completion date. Some limits may be set up for the time allowed to mixing, delivery and compaction, but capability and type of mixing/delivery equipment, schedule and quality to be achieved are left to the contractor to decide. Consequently, the contractor determines a major part of the risk involving schedule and achievable quality.

Few contractors have enough first-hand experience with RCC to fully evaluate all the intricacies involved with the process, or to understand how dependent the design is on equipment selection. Even an experienced contractor may not realize that what was suitable or tolerated for a previous RCC project equipment may not be acceptable for the next project design and performance needs.

Thermal stresses due to hydration are an important design consideration in dams. CVC dams can pre-cool the mix with ice (or pre-cooled aggregate with cool water or air) and/or use cooling pipes to help control thermal stresses. These methods are not yet very useful in most RCC, but controlling the rate of placement is. The time of the year can be important, when placing is done and aggregates are produced. Sometimes, high internal thermal stresses can be avoided only when placing is done during very short time periods and at a certain production rate. However, the required mixing and placing capacity should consider shortcomings related to confined work areas, rain and obstacles, such as galleries.

The contractor should keep in mind that placing cannot be usually extended throughout the year by considering that the temperature at the time of placement is the only controlling factor. The length of time until peak temperatures are reached and when cooling begins, and the rate of cooling are as well critical factors.

Another important aspect regarding design is lift joint quality, for both structural stability and watertightness. Rate of construction, temperature and potential for contamination or damage to lift surfaces affect joint quality. If a joint with a good bond, friction and watertightness is needed, delivery methods that tend to damage the surface or cause unplanned delays or extend the exposure time of the surfaces should be evaluated or avoided.

Evaluation of weather and its effects on quality regarding the several methods and placement rates is another important factor to the designer.

Men and equipment selection and usage should be well planed in terms of availability, suitability and cost. Construction success depends upon a thorough project evaluation and factors affecting intensity and placement rate. The human factor is assessed by considering labor efficiency and an RCC learning curve [8.02].

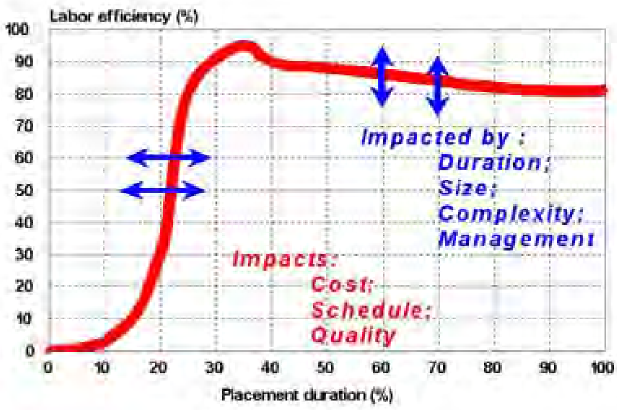


Figure 8.02 Labor efficiency and learning curve [8.02].

Since one recognizes that every project has a learning curve, what impact on cost, schedule and quality it has? The benefit derived from having an experienced team is clearly shown in projects with relatively short dam placement duration. Another element to be kept in mind is design constructibility; what considerations should be given or what questions should be made during the development of various design details and specifications?

While RCC construction includes similarities with other heavy civil construction in many respects, still it is unique. Construction schedule and material handling are the elements that generates its uniqueness and challenge.

Individual tasks performed during RCC dam construction are often found in several other projects. Foundation preparation, concrete production, concrete delivery, lift placement, drain installation and detail and mass concrete forming are not unique to RCC construction. Only by combining these and other elements during the dam placement itself, they will emerge to form a unique construction technology.

During the preparatory phase, which includes work such as mobilization, diversion, excavation, aggregate production, outlet works construction and grouting programs, several construction disciplines are represented. Until the dam placement begins, these disciplines are fairly separable and independent. Once placement begins, the coordination of men and equipment of the varying disciplines becomes the essential element to success. Following the placement, the work is again a typical one as remaining earthwork and structures are completed.

Successful RCC construction begins long before the equipment mobilization. Innovative, aggressive and talented people and the best equipment available are not enough to succeed if a project has been priced erroneously or a contract has significant inherent problems. Success begins with sound, thorough homework during the bidding or proposal stages.

Initial evaluation begins with the understanding of the project scope and establishing the technical capabilities required. Assuming that the equipment preliminarily selected is suitable, availability becomes a key point.

- How many superintendents are required?
- What other key labor is necessary?
- What is the skill and ambition level of the local work force?
- What rented or owned equipment is available?
- Further, is it ideally or just moderately suitable and what its impact on cost and production?

Market assessment is also part of the equation with regard to profitability and resources commitment.

It is essential that all materials, access, embedded parts, foundation and lift cleanup, etc, be planned and ***readied*** well ahead of time. It is also essential that communication between the involved teams (project engineer – contractor – inspection) be well established so that they can quickly solve problems of specification compliance that may significantly impact the progress of the work.

Since the design section of RCC built dams is mainly the same as for any CVC dam and the equipment used is similar to the one used on an embankment with a much larger cross section, the top of the concrete dam may become jammed, especially when the construction nears the crest. This aspect should be considered and very well detailed in the construction planning.

The options for river diversion for an RCC (gravity or arch) dam are similar to those for a CVC dam, except that others options can be adopted, such as the construction of a depressed area on the top of the RCC forming a weir, as it was done at Salto Caxias in Parana State–Brazil (see Figure 8.01). RCC dam is continuously placed in layers across its full length. Conduits can be built through the structure for river diversion. As with other CVC dams, RCC dams can be overtopped without serious damage. This characteristic influences the cofferdam and diversion requirements, as does the very short construction period which limits exposure to severe flooding.

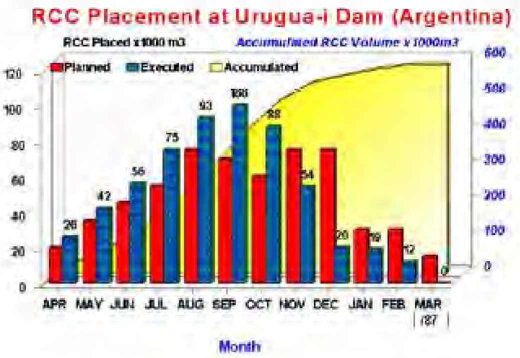
The use of RCC probably would be less suitable for structures with unusual structural complications, extensive inserts, or those which are heavily reinforced. Single reinforcement layers have been successfully used in RCC, as usually adopted in gallery roof.

Success is often determined by appropriate preliminary risk assessment. Frequently, specifications are written to shift contract unpredictable features into the contractor's responsibility. Failing to responsibly allow for these risks is proven to be disastrous.

Beyond the generic evaluation elements discussed so far, a contractor must understand the intensity of RCC construction. An accelerated project schedule often minimizes organization and planning time before dam placement begins. Also, a fast track schedule can shift work, such as aggregate production and auxiliary structures, along the scheduled dam placement, thereby intensifying the placement itself.

The significance of understanding the placement intensity is multifaceted and key to a successful evaluation, bidding and construction. **First**, it is difficult to maintain quality and optimize cost and production during long working hours in diverse tasks under congested conditions. **Second**, while adequate plant capacity is absolutely necessary to achieve satisfactory average placement rates, production is rarely determined by the plant. **Third**, appropriate project staffing is critical.

Figure 8.03 illustrates Urugua-i and Jordão dams monthly placement and a bar depicting the different types of production control results. While each project will exhibit some unique characteristics, typical production controllers include learning curve inefficiencies, gallery and other obstructions, conventional concrete production and delivery capabilities, safety, temperature and weather, mechanical breakdown, as well as RCC production and delivery.



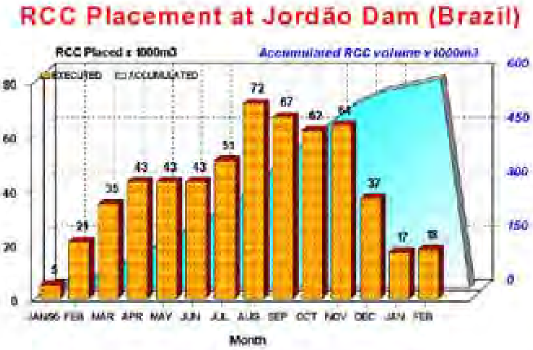


Figure 8.03 Monthly RCC placement at Urugua-i and Jordão dams [8.03].

8.3.2 Geology

The design and construction of concrete dam and many other structures are controlled mainly by foundation considerations. Failure of a concrete dam under sustained loading or flood conditions, as a result of initial failure in the concrete section above the base rock, is extremely rare. Historically, the failure mode for concrete dams has been by sliding or shear failure of the foundation rock.

8.3.3 Access

As previously mentioned, RCC dam is generally placed in continuous layers across its full length. In this way, it would be very simple to ***think*** and plan just one access from just one side of the valley. Unfortunately, this is not so simple or easy. The topography, plant location, cofferdams, river diversion phases and the characteristics of the structures themselves need to be understood in an overall way. From another point of view, as the RCC construction can go fast, a slight mistake during the initial phase can be catastrophic regarding milestones, quality and cost.

8.3.4 Environmental Condition

Placement rates will vary with climatic conditions and should be considered in construction scheduling. Conversely, during certain periods of the year, unrestricted placing rates may be permissible. In any case, lift scheduling should be precisely planned and controlled and be consistent with thermal requirements. Because the RCC overall production rate can be very high, controls limiting thermal cracking may restrict the time period when placement is permissible, as well as the placement rate.

In rainy zones, it is very important to consider not only the time lost during the rain period, but the time necessary to re-start the works, because of drainage of the area, cleaning and preparation, which in certain regions and under such conditions can be the worst factor.

The significant Pangue RCC dam in the Chilean mountains is well known [8.04]. The project zone has frequent and severe rains (4mm/hour and 4,000mm/year), difficult river diversion and other logistic problems. The control and handling of water running off the layer and the abutments make works very difficult to perform. The effects of rain not only depend on its maximum intensity but also on its duration.

8.4 Economical Feasibility of RCC Construction

RCC dam construction is a process of rationalization of concrete dam construction that includes reviewing both the design and construction process for CVC dams. The economy of RCC dam construction, described in Chapter 10, is of great importance and may be better understood through a comparative study with CVC dam construction. Economy is an important factor to take into consideration, but it should always be restrained by the need for adequate structural, quality, safety and durability properties.

8.4.1 Shortening Construction Period

The proper concrete placing schedule should be determined considering construction facilities, number of shifts, volume of dam, materials supply, main milestones, financial availability and site topography.

Project success ultimately depends upon the team assembled. Project size, schedule and intensity will not only determine the key positions but the number of qualified people required for an effective management. Equally, perhaps more unique to RCC than many other construction technologies, the management team should be more than technically skilled and experienced. Several factors combine to demand more not only from the general superintendent, but from his assistants and, to a degree, from the entire labor force.

During placement, two shifts, long working hours during 7 days a week and hard work create an atmosphere where quality and production are not necessarily everyone's highest priority, management included. Nevertheless, during placement, motivation and teamwork need to be at their peak because of the tremendous interdependence of activities. Therefore, the main management's task is to keep up their own stamina while planning ahead, ensuring quality, providing necessary materials and equipment, keeping up equipment and tools, and managing and motivating a tired, diverse work force.

Appropriate equipment selection and utilization are important elements to support success. Equipments are largely selected by their availability cost and task suitability. However, RCC is affected by production rates; perhaps the best way to focus it is to look at the plant capacity.

The concrete placement rate possible with roller compaction is so rapid that the dam can be completed in a considerably shortened construction period, which can not only reduce construction costs but also allow an earlier completion of the project. The cost savings achieved by shortening the construction period include decreased leasing charges for construction facilities, reduced costs for construction loans and reduced expenses, such as those for labor, electricity and so on.

The fast construction of a dam can be beneficial, especially in cases where concrete placement has to be interrupted during periods of adverse climatic condition, as it was done for RCC dams in some zones in Japan and Canada during the winter season.

The benefits obtained by the earlier completion of a project are many. Particularly, the shortened construction period reduces the probability of floods to occur during construction.

8.4.2 Rationalized Construction Period

RCC dam construction enables a wide use of conventional construction equipment, such as dump trucks, bulldozers and vibrating rollers. Properly used, these could adequate labor costs. The use of such construction equipment can increase the rate of transporting and placing the concrete and also adjust the number of skilled workers required.

The long, wide layers used in roller compacted concrete dam construction enable the improvement of concrete placement procedures. When the need for transverse contraction joints is foreseen, these may be cut in the concrete immediately after placement by different methods.

It has been thought for long that longitudinal joints can be minimized in RCC dams because a continuous construction reduces the possibility of longitudinal temperature cracks. However, the elimination of the transverse contraction joints must be carefully studied, considering the experience of transverse temperature cracks in some RCC dams as exemplified in Chapter 4. Embedded pipe cooling and, in many cases, joint grouting can also be eliminated in straight gravity dams but may be necessary in arched dams.

8.4.3 Materials saving

RCC construction requires no slump concrete to be transported by dump trucks and spread and compacted by crawler tractors and vibrating rollers to enable reduction in the cementitious content, consistent with the performance required by the design. The use of pozzolanic materials instead of part of the cement allows for further cost reduction.

A reduced cementitious content decreases temperature rise in concrete due to the heat of hydration, thus reducing the need for pre or post-cooling (if necessary, as for arch/gravity) of the mass when accompanied by a control of the lift thickness and the intervals of RCC placement.

8.4.4 Additional benefits

Project success depends on a cooperative interaction between the owner, the engineer and the contractor. Each party lends its own strength and character to the ongoing task of identifying and solving problems. While the contractor should evaluate and respect the design, its specifications and ultimate project goals, the engineer and the owner should recognize the contractor's task at hand.

What impact does constructibility have at the bid table? When construction competition is high, savings resulting from constructable design are often hidden at the bid table because of an aggressive competition and are disclosed only later when claims arise or not. However, when competition is lower, constructibility will produce real savings to the owner by lower construction costs and reduction of the pre-construction unknowns features and risk.

Although it is sometimes difficult to gather, an experienced team will endure the intensity and the effects of the learning curve, which will yield higher quality and better performance. While quality should not be compromised, the owner and the engineer ought to be aware of the elements impacting the contractor's costs and schedule. Such understanding will allow and encourage an atmosphere towards cooperation and teamwork.

RCC is placed in long and wide layers and the height difference along the layer is minimized (usually only one lift), improving safety conditions. The wide, horizontal working area allows a safe movement of workers, machinery and materials, as well as improves communication and instruction to the workers. The reduction of forms installation also reduces the risk connected with this hazardous work.

Dump trucks, bulldozers, vibrating rollers and tire rollers are the primary machines used in RCC dam construction and pavement. Easy availability of such equipment enables effective and flexible work by introducing the desired number of machines, according to the construction schedule.

The cableways usually used in CVC dam construction, on a narrow valley, require large excavations at both abutments of the dam. On the opposite, the absence of cableways in RCC dam construction minimizes the impact on the natural environment.

8.4.5 Safety

Dams should be conservatively designed and carefully built. Nevertheless, it is time for a study to find ways of reducing the cost of concrete dams with same safety. By comparison, earth embankments of all sizes have relative vulnerability due to the potential failures in overtopping and internal erosion of the fill material. In the meantime, even with a cost reduction in relation to concrete dams, embankments dams were and are more prone to failure. Following a number of different routes, researche carried out in the early 1960's and 1970's led to the development of RCC dam building.

8.5 Construction Planning

The layout, planning and logistics for construction with RCC are generally different from those for CVC mass concrete construction. Handling the rate of placement has been the essence of success in concrete construction. Considering the increased labor intensity, the learning curve of placement emphasizes such condition even further.

Figure 8.02 graphically shows the impact created when (a) working hours are increased to two shifts, 10 hours a day and seven days per week, and (b) the total labor force almost doubles. Additionally, a typical weekly paycheck during placement will be 150% of the one prior to placement. While this surge does not necessarily create a problem, it requires a well planned preparatory work, appropriate management structure and face the effects of the learning curve.

The learning curve defined as labor efficiency versus time may have a significant impact on cost, duration and quality. While larger projects exhibit similar characteristics, smaller or shorter duration projects are more adversely affected by new job assignments, new hires, training periods and employee turnover. Dam configuration, experienced supervisors and skilled labor also contribute to both learning and performing efficienty.

Placement begins with a fairly small lift, and unexperienced people. During the first few days, the engineer takes steps to assure the necessary labor-dependent quality standards regarding foundation cleanliness, bedding thickness, placement sequence, compaction timing, segregation control, etc. Meanwhile, the same labor force responds to demand for work efficiency, increasing production, task sequencing, as well as safety and awareness considerations. As mistakes diminish and the work force learns how to satisfy the supervision, the gallery is reached and enforces new parameters and tasks. When the gallery is finally cleared, the lifts are fairly long and still relatively wide, allowing smooth efficient placement. However, nearly two weeks after the last day off, the interest in keeping ***quality and production*** fades away. Within a few days more, the placement crew feels constrained as the lift width becomes difficult and the dam is now considerably higher.

Nearing the top, an internal spillway and/or vertical form transition reduces production and new methods and sequencing are adopted. Being aware that the placement is almost over, the tired labor force willingly adapts herself to the changes and finally the dam is completed. With a higher or larger dam, learning involves a smaller time percentage of the constructon period and much more can be done to maintain a motivated work force. Nevertheless, each project will have a cost impact and a labor efficiency curve dependent upon size, duration, complexity and management.

A tremendous benefit is being obtained as RCC technology takes hold and constructibility questions emerge as a natural consequence to the new development. Constructibility [8.02] could be understood as a design that ensures the desired performance and quality standards while maximizing construction efficiency and flexibility. Constructibility can and should be evaluated in terms of an overall project impact, including specific construction details or specifications as well. As to the design elements, evaluation should be thorough and methodical. During evaluation, one should remember that placement intensity and labor efficiency curve develop early. Equally, does the detail or specification require equipment, tools or people who otherwise may not be required? While many dams may exhibit similar design, each should be considered in the light of its overall project goals.

Few areas which frequently raise the issue of constructibility are mixing plant requirements, delivery requirements, backup equipment, aggregate gradation control, facing element design and sequencing, quality control versus quality assurance and seepage control measures. When primarily focused on final quality and performance, job methods (i.e.: equipment to be used) or both methods and performance show no consistency with the flexibility needed for maximum constructibility. A solid performance or an end product specification and corresponding control will produce the desired results and allow the owner to fully benefit from the contractor's own resources and innovation. For example, few projects have refused drum mix plants at the owner's potential expense when completed project performance would suggested this was unnecessary. As the finished project data base grows and confidence increases, more performance-based specifications will emerge.

Figure 8.04 Gallery at a low level in a large area, ready to receive RCC.

All unnecessary vehicles and personnel should be kept out of the placing areas and equipment paths.

When problems grow in the placing area, they should be quickly solved. Usually, there are no alternate monolith blocks in RCC construction where work can progress while the problem is studied. Raising a portion of the placing area ahead of the rest of the area has been done, but it can result in later placement difficulties and potential weakness planes at the perimeter of the low area.

It is essential that all materials, access, embedded parts, foundation excavation and preparation and similar work be planned and ready well ahead of time. It is also essential that communication between the project engineer and the contractor be well established so as to quickly solve problems and specification compliance issues that may impact the progress of the work. Interruptions and slowdowns generally reduces quality of joint and RCC, as well as increases costs. Direct communications and procedures for on-site problem resolution are essential, limiting excess of personnel, management or administration. This sounds basic and simple, but it is amazing how many jobs have suffered from insufficient authority, responsibility and responsiveness at the field – from both the contractor and engineers.

Construction contract arrangements, contractor selection and his qualifications are delicate issues lacking the attention they should deserve. These issues are seldom, if ever, openly discussed.

When a contractor is pre-qualified, it is important to assure that personnel and equipment supporting such pre-qualification are available and will be in the project. Some projects have selected contractors with RCC experience, but none of the experienced people were assigned to the project.

Contractors should be allowed to become pre-qualified by obtaining or contracting the services of personnel who have those capabilities. If they are good, their advice is used and they train additional people at the job site, all that is needed are several key employees. The owner should get assurance that these employees will be present to the full necessary extent and that they will participate in the project with appropriate authority and control. Qualification should include people for planning, equipment selection, scheduling, manpower assignments, layout, placing plans and other related management activities. However, the financial and technical success of RCC construction definitely rests on the individual workers who operate conveyors, drive trucks, clean lift surfaces and spread RCC.

Figure 8.05 Gallery at a high level in a restrict area to RCC placement.

Figure 8.06 If foundation irregularities (holes) have not occurred downstream the sluiceway, but in the area of the RCC dam, a delay in placing the first lifts can be expected.

8.6 General Layout

Layout and operations for construction of an RCC dam follow a considerably different pattern from those usual in placing conventional mass concrete. As previously mentioned, instead of a vertical CVC construction with nearly independent monolithic blocks, the placement follows a horizontal spread, stacking large expanses of thin horizontal lifts on the top of each other. When a problem arises on a given lift, it should be solved before any subsequent lift is placed. There are not so many options of an alternate monolithic block on which work can be done while a problem is studied. It is important that all related activities, such as foundation cleanup, access and providing materials and embedded parts be planned and scheduled ahead of time.

RCC (and CVC, if used) plants layout and location should minimize energy requirements whether RCC is transported by conveyor or hauled in vehicles or any other system. Overall hauling distances, vertical lift and exposure of the fresh concrete to sun and weather should be minimized. If vehicular haul is used, the plant should be on a raised area so that spillage and wash water drain away without creating mud. The plant can often be located in the future reservoir, just upstream of the dam above the cofferdam level, or on one of the abutments, reducing the environmental impact.

Fueling of equipment, construction of forms and installing embedded items should be planned and scheduled so that the majority of the work may be done off the dam or, if necessary, from the top of a lift during shift changes and downtime for the placing crew. As to safety, efficiency and minimal contamination, all unnecessary vehicles and personnel should be kept out of the placing areas and equipment paths.

Figure 8.07 RCC batching plant near the center-mass-point, at Capanda dam- Angola.

8.7 Aggregate Production

Aggregate plant and stockpiling (or aggregate plant capacity adjusted to the peak rate production) and the RCC plant location can be even more important than in CVC placing practice. Typically, very large stockpiles that could easily be half of the material needed for a placement period are required prior to the start of RCC work. Some of the reasons for the above are:

- **Small capacity of the aggregate processing plant –** Adopting in advance an aggregate stocking pile, it can be possible to reduce the capacity of the aggregate processing plant;
- **Technical design requirements** –Such as production of cold aggregates during winter so that they are stockpiled pre-cooled for later use; this climatic condition can be useful;
- **Schedule and cash flow –** It may be relatively easy to mobilize and have aggregate production in full operation while work, for the rest of the project, is just beginning;
- **Construction need –** The rate of aggregate usage during RCC placing may well exceed the aggregate production capacity.

The variability of aggregates during construction affects significantly the cementitious and water requirements, which in turn affect strength and yield. The maximum size of aggregates can have a very important effect on segregation. Generally, the smaller the maximum size the less will be the tendency to segregate. However, additional efforts required to produce aggregates with a smaller maximum size have to be balanced against the need to avoid segregation. The maximum size of aggregates used in completed RCC dams are shown in Figure 8.08.

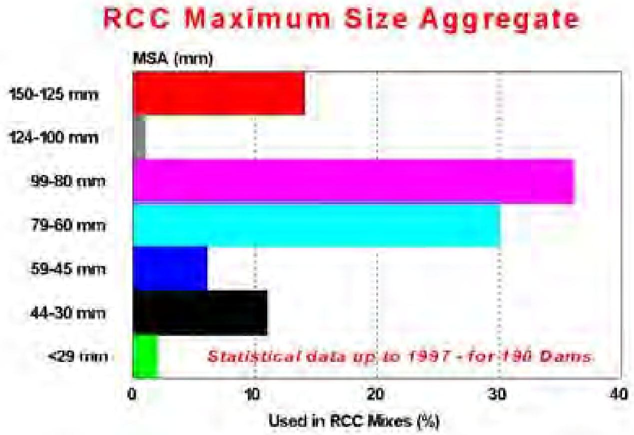


Figure 8.08 Maximum size of aggregates used in RCC dams. Data based on 128 of the 157 RCC dams that had been completed by the end of 1996.

The most popular maximum size is about 75mm to 80mm, although it now seems that there is a trend towards smaller sizes due to problem of segregation. The maximum size tends to be 50mm to 60mm for crushed aggregate and about 40mm to 50mm for natural gravel. The maximum size of aggregates is not related to layer thickness or compaction machinery.

Location, size and removal of aggregate from stockpiles should be coordinated with the RCC plant location and the feeding method to minimize segregation and variability. At very high production rates possible with RCC, several loaders or a conveyor system may be required to keep the feed bins full. The length of haul and size of turnarounds should be considered so that loading equipment will operate rapidly, efficiently and safely. Aggregate stockpiles and the concrete plant location can be even more important than with the production of CVC.

Although many RCC dams have been built with numerous aggregate size groups and stockpiles, many others have been very successfully built with just two-size groups. Usually, this is over 20mm and under 20mm. Some projects have used a single "all-in" size group. The great advantages of fewer size groups are obvious. Fewer size groups mean less required area for storage and less equipment for loading and transportation. There are fewer required aggregate bins and less complicated mix designs. An example of a major benefit often overlooked by designers has to do with the aggregate bin that fails. If a plant has 4 bins, each one being a separate material, production stops. If the same 4-bin plant is used but only with 2-size groups, at least one of the size groups would be fed by more than one bin. When a bin fails, production can proceed at a slower pace with the operating bins, while repairs are made in the bin that is out of order.

When RCC low cementitious content mixes are used, it is necessary to include non-plastic fines (finer than 75 microns) in order to compensate the otherwise low past content. When fines are included with a size group of under 20mm, the material is similar to a road base with a slight tendency to segregate, especially if it is damp. Also, the moisture content in the pile tends to stay quite uniform because the material is not free draining.

Because many RCC mixtures have benefited from having a high content of fines passing 0.075mm (Nº. 200) sieve in a range up to about 10% by weight, aggregate processing flow can be less restrictive than for CVC, reducing the waste material and hence, the environmental impact. Natural gravel may often be used with only the oversize cut off. Maximum size aggregates vary from job to job.

Where a quarry operation is necessary, aggregate processing may also be minimal, consisting of primary crushing with relatively little secondary crushing and no washing, as it was done at Willow Creek and Saco de Nova Olinda dams. There, the aggregate was crushed from a rock and part of the raw feed to the crusher was silt.

The production rates required by the mixers on large RCC jobs are unusual as compared to CVC production.

Figure 8.09 Aggregates processing plant and stockpiles near the RCC batching plant, at Jordão dam-Brazil.

Figure 8.10 Crushers to produce crushed sand and powder filler near the batching plant, at Capanda dam-Angola.

Figure 8.11 Aggregate system at Salto Caxias dam. The same aggregate fractions were used for CVC and RCC.

8.8 RCC Batching and Mixing

The RCC concept has completely changed the production-controlling elements of massive concrete placement, from the rate of placement to the output of the concrete plant. It is possible to increase production by using larger mixers or by adding mixers and batch plants. However a continuous mixing to offset the time lost in batching operations is desirable.

Mixers for RCC should provide sufficient capacity for the typically high placing rates and adequately blend the ingredients. The mixer should operate with little or no downtime and scheduled maintenance and repairs should be accomplished rapidly. RCC mixtures can be very harsh. The drums or mixing chambers should be designed or coated to resist buildup that tends to result from the high fines content of some RCC mixtures. Even with these precautions, experience has shown that substantial buildup can develop in drum mixers. If buildup is not removed, the result is a loss in mixer effectiveness.

Figure 8.12 RCC batching plant near the center-mass-point, at Rialb dam-Spain.

The concrete plant layout and location should be selected to minimize energy requirements and be appropriate for the terrain in case RCC is transported by conveyor or haul vehicle. It should minimize overall hauling distances, vertical lift and the exposure of fresh mixture to sun and weather (see Figures 8.07 and 8.12). In case a vehicular haul is used, the plant should be located on a raised area so that spillage and wash water are drained away, without creating a muddy area. The plant location for dams will generally be above the cofferdam level or on one of the abutments. The plant should have a by-pass or belt discharge that allows for wasting out of RCC specification, without delivering it first onto the dam. This capability may also be used for sampling, delivery to trial sections and for other construction uses of RCC.Both continuous mixers and batch mixers have been used to produce RCC, continuous pug-mill mixers being the most common. Continuous mixers generally provide a higher output capacity than batch type plants. Continuous pug-mill mix plants, specifically intended for RCC and properly operated/routinely maintained, achieve good production rates and uniformity. This applies to plants operating with volumetric control, as well as those operating with weight control.

The types of mixers that have been used for the production of RCC are shown in Figure 8.13. It can be seen that the great majority of mixers are of the batch type (75%) while the remaining ones are continuous mixers. It can also be seen that more than 35% of the mixers is of the twin shaft batch type.

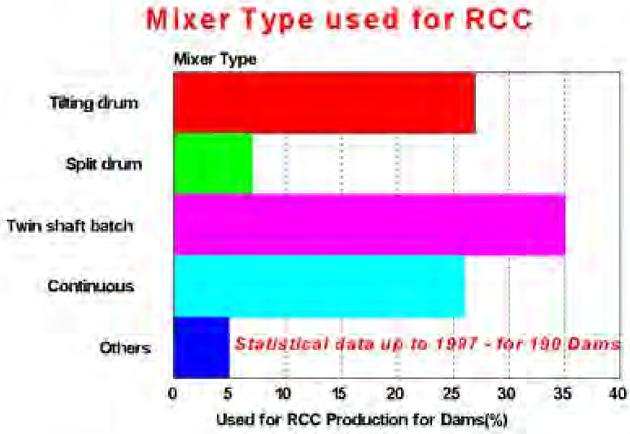


Figure 8.13 Mixers used for RCC production. Data based on 103 out of the 157 RCC dams that had been completed by the end of 1996.

Figure 8.14 Continuous mixers used for RCC production, in Capanda dam-Angola.

Figure 8.15 Batching tilting mixer used for RCC production, in Capanda dam-Angola.

Figure 8.16 Batching twin shaft with two-axis paddle mixer used for RCC production, in the Japanese dams mainly.

Figure 8.17 Batching ribbon mixer type for RCC production, for pavements mainly.

Rapid and continuous delivery of RCC is important to mass applications. The theoretical or rated peak capacity of the plant should be well above the desired average production. As a general guide, the sustained average placing rate usually does not exceed 65% of the peak or rated plant capacity when haul vehicles are used for delivery on the dam, and 75% when a whole conveyor delivery system is used. These values tend to be lower in smaller projects and higher in uncomplicated larger projects. Mixers for RCC and CVC should fulfill two basic functions:

- Capacity and
- Blend of all ingredients

Scheduled maintenance should not be neglected and repairs should be accomplished rapidly.

Variations in free moisture content of the aggregates can be particularly troublesome when the plant starts up. Some plant operators make the error of over-estimating free moisture and provide too little water in the initial mixtures. This is particularly undesirable because most initial mixtures will be used to cover construction joints or foundation areas, where RCC should be slightly on the wet side for improved bond. It is better to start on the high side of the moisture and then reduce it to the desired consistency than to start with a mixture that is too dry. Mixture uniformity should be maintained at all production rates to be used.

Properly designed pug-mills have handled 75mm and larger MSA; however, experience has shown that the amount of material larger than 50mm should not exceed about 8% and the maximum size should not exceed 100 mm. Continuous drum mixers have been used successfully with over 150mm MSA. Twin shaft mixers have been used successfully with over 150mm MSA for both RCC and CVC types, mainly in the Japanese RCC dams.

Accurate introduction of the correct quantities of materials into a mixer is only one part of the mixing process. A uniform distribution and a thorough blending throughout the mixture and then the discharge in a continuous and uniform way is the other part of the process; therefore, it can be more troublesome with some RCC mixtures than with CVC mixtures.

Accuracy of the concrete plant and methods to control the mixture during production should be studied as to its cost effectiveness. If an exact quality control and a low variability are necessary, they can be provided for RCC mixtures but at an increased cost and reduced placing rates.

Proper ribboning of the aggregates and cementitious material as they are fed into the mixer is very important to minimize mixing time and buildup. The exact timing of adding water to the mixture and the angle of its introduction have also been critical. Each plant and RCC mixture design seems to have its own peculiar requirements that can only be determined by trial and error.

Different mixing plants have been successfully used in the production of RCC. Both continuous and batch mixers are acceptable for RCC production.

Important technical requirements include providing sufficient capacity for the typically high placing rates and blending the ingredients into a uniform mixture. From a practical standpoint, the mixer should operate for extended periods with little or no downtime. Repairs should be made rapidly. Since RCC mixtures are relatively harsh, drums and mixing chambers should be designed to resist concrete buildup in recessed corners due to the dry mixture.

Continuous and forced (twin shaft and ribbon types) batching mixers often provide higher output capability than batching-tilting type plants. Computerized continuous plants, with load cells, may now provide the same degree of control found in batching operations. Continuous

Dam	Country	Mixer Type	Number and Mixer Capacity (m^3)
Shimajigawa	Japan	Twin shaft forced	2* 1.5
Pirika	Japan	Twin shaft forced	2 * 2.5
Sakaigawa	Japan	Tilting drum	4 * 2.25
Tamagawa	Japan	Tilting drum	6 * 3.0
Mano	Japan	Tilting drum	3 * 1.5
Asari	Japan	Tilting drum	2 * 3.0
Miyagase	Japan	Twin shaft forced	2 * 3.0
Willow Creek	USA	Tilting drum	2 * 4
Middle Fork	USA	Tilting drum	
Upper Stillwater	USA	Tilting drum & Ribbon type	(2 * 6) + (2 * 3)
Monksville	USA	Continuous "pug-mill"	
Elk Creek	USA	Twin shaft forced	4 * 4.5
Cenza	Spain	Tilting drum	2 * 7.0
Santa Eugenia	Spain	Tilting drum	3 * 3.0
Maroño	Spain	Tilting drum	3 * 3.0
Tongjiezi	China	Twin shaft forced	4 * 1.5
Shuikou	China	Twin shaft forced	
Puding	China	Tilting drum	6 * 1.5
New Victoria	Australia	Continuous "pug-mill"	
Molonglo	Australia	Continuous "pug-mill"	
Copperfield	Australia	Continuous "pug-mill"	
Craigbourne	Australia	Continuous "pug-mill"	
Bucca	Australia	Continuous "pug-mill"	
Concepción	Honduras	Continuous "pug-mill"	
Saco de Nova Olinda	Brazil	Continuous "pug-mill"	
Jordão	Brazil	Continuous "pug-mill"	
Salto Caxias	Brazil	Continuous "pug-mill"	
Capanda	Angola	Continuous "pug-mill"+ tilting drum	
Knellpoort	South Africa	Split drum	1 * 4.5
Wolwedans	South Africa	Split drum	1 * 5.5
Urugua-i	Argentina	Continuous "pug-mill"	

Figure 8.18 RCC dams and mixers-plant type used.

mixers of the pug-mill type have been successfully used with RCC. Many pug-mills suitable for asphalt and road-base materials have not been able to provide reliable and continuously adequate mixing of RCC for dams, whereas specially designed pug-mills have had a very good performance.

Continuous and twin shaft mixers generally have much higher power requirements. Batch-type drum mixers capable of handling large aggregate for CVC concrete can also be used for large aggregate RCC, but mixture "bulking" may reduce the capacity of the mixer drum by 10% to 15%.

Truck mixers have been used successfully for small aggregate RCC with a MSA of 25mm and for trial placements when other equipment was not available. However, the result is a severe segregation and a poor mixing due to the use of aggregates over 38mm size.

The desirable accuracy of the concrete plant equipment and the degree of control of the mixture during production are matters to be taken into consideration when job and equipment are specified. The same plant accuracy, testing degree and mixture proportioning standards used in CVC operations may be provided for RCC, as seen in Figure 8.18. There are cases when, for a specific application, additional economy and simplicity can be achieved.

Another design concern dependent on equipment is mix variability. An "overdesign" factor is used to account for variability. The designer should address how much variability is expected. Because mixing and delivery systems are major factors contributing to variability, the contractor should define and compare several mixing and delivery options and then adopt the equipment consistent with the design criteria.

Figure 8.19 Segregation in the batching plant, during handling.

Figure 8.20 Segregation at an RCC Batching Plant.

The mixer is one of the equipments responsible for variability, but only a part of the system. Quality and variability at the placement are the issue, not just variability at the mixer. Testing should be done on material after it has been placed and spread. If the mixer does a good blending job of all the ingredients with low variability, but segregation and differential drying occur in trucks at transfer points on a poorly designed conveyor, or while spreading, the end product can present an unacceptable variability.

Before mixing methods are selected, consideration should be given to aggregate size, shape, gradation, moisture content, hardness and number of size groups; feeding methods for the mixer; available space; handling requirements; other plant uses for this and other subsequent projects; availability of spare parts; cement and pozzolanic material contents; mix "wetness" and variability. Equipment that can handle RCC paving mixes with small aggregate may not be able to handle larger dam aggregates. Mixers suitable for a cement-treated base do not necessarily have an adequate performance with RCC. It is a mistake to presume that expensive drum mixers with a good performance in paving and/or mass concrete projects with CVC are suitable equipment for RCC. It is a mistake as well to presume that pug-mills which are good for asphalt can provide similar uniformity and productivity with RCC. A further mistake is to assume that the more complicated and expensive a plant is, with more electronic controls, the better the performance will be.

There are several examples of efficient and reliable RCC mix plants where equipment especially designed to handle RCC was used. Plants of this type with a proven experience record are economically available and easy to ship and instal.

The number of aggregate size groups that should be fed into and blended by the mixer is a major factor. Fewer size groups result in an easier mixing, still limiting the adjustment degree that could be made later to mix proportions. Many RCC projects have used two-size groups and some have used a whole single one in stockpile. Others have made use of a number of stockpiles which are typical of conventional concrete. Each size group means that the mixer should meter, feed and blend one material more. It also means more coordination, more space for storage, greater distance to transport materials to the mixer. Therefore, many other things can go wrong.

The number of size groups and their proportions should be compatible with the mixer capacity. With only one size group, only one feeder or bin should be supplied, calibrated, monitored and maintained. If a plant has multiple bins but just one or two-size groups, production can still be carried on at a limited capacity if one of the bins becomes plugged. If each bin has a different aggregate and one of them becomes plugged, the whole production stops. If multiple size groups are needed, it is to add a standby bin and a feeder. In order to minimize this advisable concern, more coarse aggregate should be included in the stockpile containing the fine aggregate.

It is expected that the same moisture variation problems experienced with CVC sands occur with RCC gradings using clean sands which are stockpiled wet or subjected to rain. In contrast, gradings including fines tend to keep a uniform moisture throughout the pile. The moisture can be near as much the total water required in the mix. They also tend to have less segregation. It means that the mixer has less water to add and less mixing to do.

Whether or not pozzolanic material is used in RCC, the quantity involved is a decision based on a variety of factors. Each situation should be evaluated separately. A consideration to make is whether cost, space, additional mix designs and extra work involving handling pozzolanic material are necessary. It is one more thing to order, deliver, store, meter, and mix. On a small project the simplicity of using a plant that does not handle pozzolan outweighes the benefit of pozzolanic material even if good quality fly-ash was readily available. The quantity involved can be so small that cement savings do not offset the cost of an extra storage silo and a feeder and there is no technical need to use it. Still, if it is technically necessary to use a pozzolanic material, a pozzolanic cement can be a solution.

Retention time in continuous mix plants may only be 5 to 10 seconds. If additional mixing is needed, some paddles can be reversed to let the material throw back against the flow path, paddles angle can be changed, an end baffle can be added so that the volume of the mix chamber is increased, or a longer chamber may be needed. In general, pug-mills have a better performance when they operate at/or near their capacity. Slowing down flow rate decreases the volume of material in the chamber and the degree of agitation.

Water requirements in most RCC mixes are lower than CVC mixes. It may be necessary to have smaller water pipes, recirculating piping or restrictors, if the mixer was designed to handle larger flows and cannot accurately meter low flows. A common way to introduce water into the mixer is with two or three longitudinal pipes above the mixing chamber, with small holes for the water to run out. It drops onto the material being mixed. If the holes are large and/or the addition of water is very small, the water may only run out of one pipe, on one side of the chamber. The use of smaller holes and the turning of the pipes so they are transverse to the axis of the mixing chamber were of good help in this situation.

Minor moisture adjustments desired during placement can be made immediately at the plant on request by the placing foreman or inspector without adjusting other batch weights for yield. The theoretical yield adjustment associated with production changes in moisture will be within the practical accuracy of the operation.

During the first runs of a newly established RCC plant, higher water demands should be anticipated until the whole equipment is saturated and the planned production rate achieved. As the plant operation stabilizes, the placing foreman or inspector may then call for a water reduction consistent with placing conditions at that time.

Cement and pozzolanic material feeders require special attention at low cement content mixes or low production rates, as well as at high cement contents or high production rates. High production and cementitious contents use cement at an unusually fast rate. If on-site storage consists of only one silo, trucks should fill it continuously without interruption. Adequate space and careful truck scheduling are essential. The flow of cement from the silo into the cement feeder should be the same with both a full silo and a nearly empty silo, however, the fluid flow of cement may act differently when the silo reaches a certain level. Pressurizing the silo and providing an automatic plant shutdown below the level at which inaccurate feeding begins may be necessary.

Low cement contents can be troublesome unless a feeder intended for this purpose is provided. It is important to recognize that calibration tests of the feeder may show that the correct amount of cement is being added per cubic meter, but within each cubic meter the cement content may be higher for a portion of the mix and lower for the next portion.

8.9 RCC Transporting and Placing

The entire process of mixing, transporting and placing RCC should be accomplished as quickly as possible and with minimal re-handling. Local conditions at job sites will affect the time limits for these operations, but it is recommended that dumping should be accomplished within 15min of initial mixing, spreading within 15min of dumping and compacting within 15min of spreading.

Local environmental and placing conditions at different job sites will affect the reasonable time range for these operations. The time between the start of mixing and the completion of compaction should be less than the initial set time of the mixture under the same conditions. A general recommendation to follow with non-retarded mixtures is to accomplish placing, spreading and compacting within 45min of mixing. The entire system of mixing, transporting, placing, spreading and compacting should be accomplished as rapidly as possible and with as little re-handling as possible. It can be extended for colder (and night) weather and should be reduced in warmer weather (and sunlight). It can also be extended for mixtures that are proven to have effectively extended set times because of high pozzolanic material contents, slags or effective admixtures with wet RCC consistencies.

8.9.1 Equipment Selection

The volume of material to be placed, access to the placement area, available equipment and capital cost for new equipment and design parameters are in general the controlling factors for the selection of equipment and procedures to be used to transport RCC from the mixing location to the placing area.

Essentially and theoretically, there are two methods for transporting RCC:

I. by batch,
II. continuously, or

combination of both. Typically using continuous conveyor feed to a hopper on the dam from which vehicles take batches for final delivery to the spreading area. This would practically be the third method.

To some extent, selection may be influenced by the type of mixing equipment used. However, with proper controls and accessories, such as holding hoppers designed to control segregation, continuous mixers could be used with batch transportation and batch mixers could be used with continuous flow transportation equipment.

Equipment and procedures currently available are capable of mixing, delivering and placing RCC at sustained rates in excess of 750 m^3/hr in large projects. This rate is significantly greater than the one achievable in the past with CVC. It can be similar to the one shown in Figure 8.22, which is actually being used.

The two prime methods to transport RCC are hauling vehicles and conveyor belt. As to a conveyor system which is not designed to reach and place RCC continuously over the entire lift surface, a temporary holding hopper, or "gob hopper", for the mixed RCC may be necessary at the end of the main conveyor. It allows the mixers to operate and discharge continuously without interruption, while waiting for a hauling vehicle. With this system, a conveyor delivers RCC to the gob hopper, which is on the lift surface of the dam and moves up as the dam is built. Hauling vehicles remain on the dam and load from the hopper. The hopper ensures that hauling vehicles will always have a fresh load of RCC available and avoids start-stop operations, highly undesirable with continuous mixing plants. It also precludes vehicles tracking contamination onto the dam. A minimum gob hopper size is approximately twice the capacity of the largest hauling vehicles to be used. Material should not be retained in the storage hopper more than 5min to 10min, although occasional exceptions may be permitted if the material has not begun to dry out and if it is subsequently placed, spread and rolled expeditiously.

There are different ways to support and arrange all conveyor delivery systems, as shown in Figures 8.22 to 8.32. Cuchillo Negro Dam (USA) is an example. Vertical posts were embedded in the dam and raised with the dam to support and raise the conveyors. From the posts, conveyors reached the whole dam surface.

Figure 8.21 A modern system used for CVC placement at Huites (CVC mass concrete) dam-Mexico, at a monthly rate larger than 250,000m^3.

Figure 8.22 Belt conveyor used for RCC transportation and placement at Elk Creek dam (Courtesy: Rotec Industries).

Figure 8.23 Belt conveyor used for RCC transportation and placement at Cuchillo Negro dam (Courtesy: Rotec Industries).

Seigrist and Spring Hollow dams (USA) are examples of a conveyor being supported by smaller pipe posts anchored to the upstream face of the dam, with a long conveyor extending the full length of the upstream face of the dam and raising with the dam. This conveyor fed a tripper that ran along the main belt, at the upstream face, to feed a crawler mounted mobil conveyor placer on the lift surface. The crawler placer can drive on the surface, extend or retract its conveyor, lift it, or swing similarly to the boom on a hydraulic crane. It allows the operator to deposit the RCC in a layer at its final place. Smoothing of the layer with a bulldozer and compaction can follow immediately after the RCC has been deposited from the conveyor. The crawler placer, with a different setup for conveyors that fed it, was used at Concepcion dam (Honduras) and at Pangue (Chile) and other RCC dams as well.

At Echo Lake and Big Haynes dams (USA), wheel mounted conveyor placers, or "creter cranes", reached the lift surface from outside the dam and deposited the RCC in layers.

Conveyors should operate at high speed in order to reduce exposure time and the amount of material actually on the belt. They should have covers to protect the RCC from rain, wind and sun. They should have scrapers that thoroughly wipe the return side of the belt so that no paste is

Figure 8.24 Belt conveyor used for RCC transportation and placement at Seigrist dam (Courtesy: Rotec Industries).

lost from the mix and nothing drops off onto the lift surfaces. Even with these precautions it is also advisable to provide a cleanable "diaper" under those portions of the belt, over RCC lift surfaces. Deflector plates or baffles should be provided at the end of each conveyor section to remix the RCC as it drops onto the next belt. Each transfer point should also be designed and/or maintained in such way that buildup or plugging is not allowed. Belts should have enough power and an adequate design to ensure the operation at the steep-up-and-down slopes usually necessary for portions of dams. They should have the capacity to be started and stopped while loaded. Typical RCC belts can operate slopes of 10°-15°, 15%-20% down and 20°-30°, 40%-45% up.

Two basic approaches have been used with the whole conveyor system. They each use a series of semi-permanently fixed feed belts from the mixer to the area near the dam. The conveyor segments going onto the dam are raised with the dam. For one approach, continuation of belts is used on the dam to feed a mobil placer similar to the crawler mounted equipment shown in Figure 8.26. This equipment can be driven and turned while the conveyor extends, retracts, rotates around the crawler chassis and booms up or down – all controlled by one operator while delivering RCC continuously to any location.

Figure 8.25 Belt conveyor used for RCC transportation and placement at Spring Hollow dam (Courtesy: Rotec Industries).

As with CVC mass concrete conveyor systems, special attention should be given to belt widths, speed, protection, maintenance, inclined angles, backup systems and spare parts. Belt scrapers should be provided to clean the return belt. Typically, these require frequent attention for adjustment and wear. Properly designed charge and discharge hoppers are essential to prevent segregation at transfer points.

Continuous belt conveying from the mixer to the final placement area can substantially increase placing rates and reduce significantly other equipment needs with their related labor requirements. The use of a continuous high speed conveyor belt directly to the placing point is an effective transporting method.

Exposure time on conveyors should be as short as practical. Belt speeds should be of about 2m/s to 5m/s. To protect mixture from drying and from rain, covering the conveyor should be required for all long sections and, preferably, for the entire system.

Urugua-i (Argentina) and Capanda (Angola) dams are examples of a conveyor being used with dump rear trucks that remain on the dam and load from a hopper.

Several delivery and handling methods have been used or attempted with RCC. They include dozing, front end loaders, bottom-and-end dump trucks, highway and off-highway equipment, scrapers, travelling hoppers, chutes, inclined gravity pipes, "elephant" trunks, several conveyor belt systems and combinations of these methods. Haul vehicles can be end-dump or bottom-dump trucks or wheel tractor scrapers or large front-end loaders. Because of the high RCC density, weight rather than volumetric capacity of the vehicle will probably control the amount of material hauled per trip, even considering the bulking effect.

Figure 8.26 Belt conveyor used for RCC transportation and placement at Concepcion dam (Courtesy: Rotec Industries).

Figure 8.27 Belt conveyor used for RCC transportation and placement at Pangue dam (Courtesy: Rotec Industries).

Figure 8.28 Belt conveyor used for RCC transportation and placement at Hicho dam (Courtesy: Rotec Industries).

Figure 8.29 Belt conveyor used with a hauling vehicle for RCC transportation and placement at Urugua-i dam-Argentina.

Figure 8.30 Belt conveyor used with a hauling vehicle for RCC transportation and placement at Capanda dam-Angola.

Figure 8.31 Belt conveyor used with a hauling vehicle for RCC transportation and placement at Val dam-Spain (Courtesy: Rotec Industries).

Figure 8.32 Belt conveyor used in conjunction with a "crawler-placer" vehicle for RCC transportation and placement at Rialb dam-Spain.

Trucks can be highway or off-highway and bottom or end dumps. They may be used to deliver RCC from the mixer to the dam and then over the lift surface. Damage caused by truck tires and contamination from spillage are minor problems that can be corrected during the joint construction surface prepair for the next placement.Segregation may occur when dump trucks are filled and coarse aggregate rolls down the sides of the pile. During the drop onto the lift surface, coarse aggregate tends to roll out first, often under the rest of the pile where it is view-hidden, and may result in a poor quality joint interface. By dumping the mix onto the uncompacted material of the lift being advanced instead of onto the previously compacted layer, the dozer may provide remixing as it pushes the RCC forward. End-dumps may also be used, if needed, for inaccessible areas and to level off a rough bedrock foundation.

Bottom dump trucks afford advantages to some spreading action while dumping. They are not effective in dam construction because they lack maneuvrability, but can be useful in long narrow areas, including the top of dams, where the truck can be driven onto one end and off the other without turning. Bottom dumps minimize segregation, spreading and the drop distance.

Dozers should not be used as a primary method of delivery. RCC should only be pushed in relatively short distances by a bulldozer. The practical distance to achieve without drying or segregation depends on the properties of the mix, the quality required "in-place", the skill of the operator and the speed of production. Due to damage caused by its tracks, dozers should only operate on RCC that has not yet been compacted. Specifications typically require that compaction be accomplished within 30-45 minutes right after the RCC was mixed.

Figure 8.33 Segregation occurred during RCC drop onto the lift surface.

Figure 8.34 RCC dumped onto the uncompacted material.

Front end loader is useful for reaching isolated areas that are not accessible by truck or any other system, but should not be used as a primary method of delivery. An exception might be a low dam that has a small volume, short haul distance, adequate room and minimal requirements for joint quality. In extremely rough areas and where the initial foundation area has deep holes, a front end wheel loader can be used to reach placement site and deposit material. It results in a slow operation, but may be the only practical solution for initial placements at some locations or for a relatively small scale operation.

Despite their size, scrapers are a remarkable maneuvrable equipment and can be backed into tight areas by a skilled operator. They carry large volumes, deposit and spread a thickness of a lift. Their tires tend to cause less damage than truck tires, but likewise trucks they cause surface damage and contamination by spillage. Wheel tractor scrapers are even better because they force-feed while discharging and spreading the mix into a relatively uniform layer. Scrapers also offer the advantage of an improved mobility over standard bottom dumps of the highway type, and they are less stressed under the tires.

Figure 8.35 Damage caused by heavy dozer tracks on the RCC surface.

Figure 8.36 System used for handling RCC, at some Japanese dams.

Figure 8.37 Scraper used for placing RCC, at Willow Creek dam-USA.

Figure 8.38 Hopper used to transport RCC, at Sakaigawa dam-Japan.

Delivery bins or hoppers travelling on rails from the plant to the lift surface can minimize some of the problems discussed for haul vehicles between the mixer and the dam, depending on the size of the structure, time constraints, terrain and cost.

Chutes and gravity pipes can be useful for RCC transportation, as used at Capanda dam. A very well designed method for concrete transportation was used in the Capanda Project (see Figure 8.39), which consisted of the use of belt conveyor feeding a (practically) vertical discharge tube that fed dump rear trucks inside the dam body. A similar system was adopted at Platnovryssi dam (Greece) and Jiangya dam (China).

At Jiangya dam, the RCC-CVC batching plant was on the left abutment, above crest level. RCC was delivered to the placement level by "vacuum chutes" consisting of a half-round steel chute with a diameter of 0.6m, covered by a 5mm to 7mm thick rubber sleeve. The slope of the chutes was 47% and each chute could deliver 170m^3/h of mix, 100 meters below the batching plant, without segregation.

Elephant trunks (vertically suspended rubber hoses) have been used to drop RCC mixes. If the trunk is operated at a low capacity, segregation and loss of coarse aggregate will probably occur at the discharge end.

A procedure, combining the solutions of conveyors and the maneuvrability of trucks as well as reducing its serious problems, is to deliver the mix to a "conveyor placer" located off on the dam.

A well designed conveyor system can also be capable of handling CVC to be used concurrently with RCC (see Figure 8.22). However, a well planned operation is necessary as to not complicate the placing, unless separate parallel conveyors for RCC and conventional concrete are provided.

Figure 8.39 Gravity pipe used at Capanda dam-Angola and Jiangya dam-China, for RCC transportation.

8.9.2 RCC Placement

The preferred technique of placing RCC is to push an advancing face or front of each layer, progressing from one abutment toward the other. An exception to this procedure is where special materials are used, that is, at the upstream or downstream face of a dam.

Haul roads should smoothly transition towards dam working area and keep large curvature radius with the aim to prevent tire damage to the top of the lift. If a right angle turn is necessary for roads entering the dam perpendicularly to the face, significant scuffing and damage follow as a consequence. Hauling units should turn slowly, using the largest turning radius possible. To the extent possible, a road should be built with clean, free draining rock or gravel. The last portions of the roads entering the dam should be paved with a material that allows clean tires of the haul units, hence preventing contamination of the RCC surface. A tire washing apparatus may be installed at this point, as developed at Sakaigawa dam. Extra RCC extending to the road is not sufficient to keep the lift surface clean. The cleanliness of the lift surface is of such importance that RCC haul roads and yards in lateritic soil areas, for instance, should be completely paved.

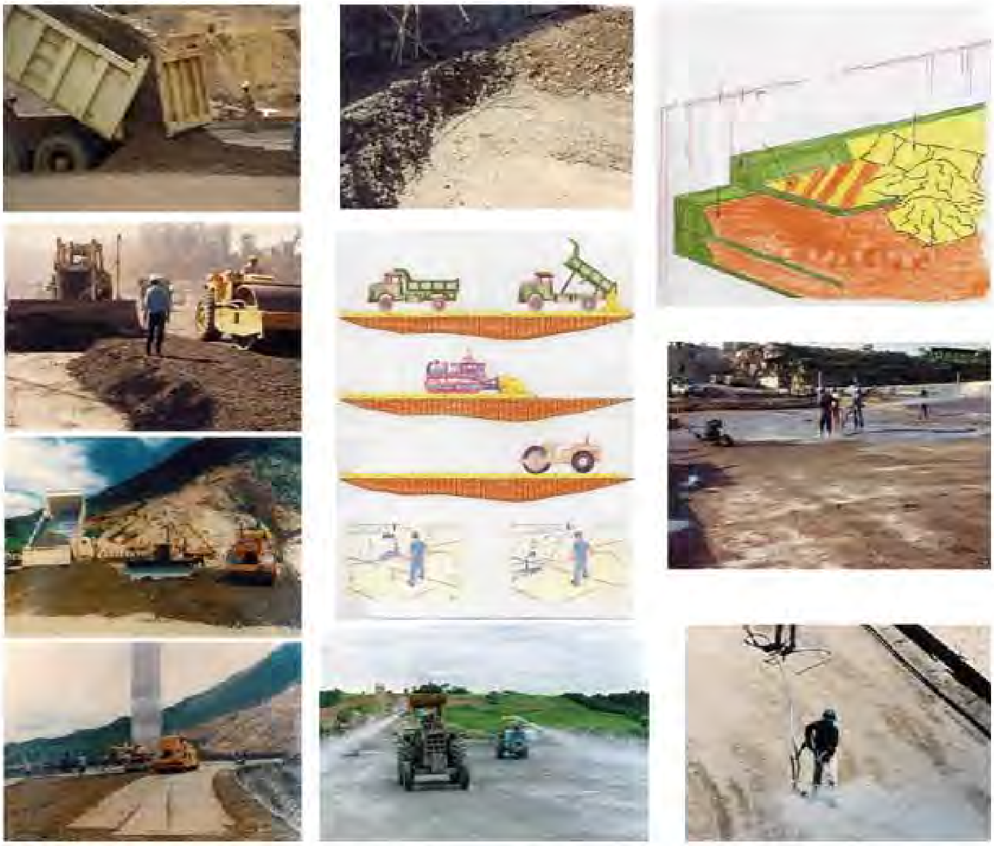


Figure 8.40 Schematic procedure usually used fo RCC placement.

Figure 8.41 Tire washing equipment used at Sakaigawa dam-Japan.

8.9.3 Segregation

The type of transporting equipment used to move RCC from the mixing plant to the placement area will be influenced by the largest aggregate size in the mixture. Experience indicates that mixtures with large 75mm MSA aggregate tend to segregate more when they are dumped from this type of equipment on hard surfaces, however, with care and proper procedures these mixtures have been hauled and dumped successfully. Segregation problems occurring during transportation and placing of 150mm MSA mixtures have been severe. This situation is a basic condition to recommend the use of limited amounts of the total coarse fraction of the coarse aggregate.

Recent Japanese practice has used mixtures with limited amounts (not more than about 25% of the total coarse aggregate) of 76mm, even 150mm, MSA aggregate and a larger percentage of fine aggregate. This approach agrees with the gradations discussed in Chapter 7 and has produced RCC mixtures with less tendency to segregate.

8.9.4 Spreading

A tracked dozer in the range of 10ton (85HP) to 20ton (200HP), has proven to be the best for spreading RCC. It is fast, sufficiently accurate and contributes to uniformly compact RCC. By careful spreading, a bulldozer may remix RCC and minimize the segregation that may occur during dumping.

The dozer should operate on fresh RCC not yet compacted. All turning and crabbing should be done on uncompacted material. Operating the dozer on a compacted surface will damage it. When it is necessary to drive the dozer on compacted RCC, the operator should limit the movement to a straight back-and-forth travel. Track marks made prior to the mixture reaching initial setting can be recompacted by the vibratory roller without significant loss of joint quality.

Figure 8.42 Damage caused on the RCC surface due to the dozer (heavier than necessary).

Figure 8.43 CVC mixture being placed in advance with RCC immediately spread against and on top of the sloping unformed face of the CVC, at Capanda Dam-Angola.

Spreading equipment should leave a flat or plane surface with an adequate thickness before the roller compacts the lift. Typical tolerances for lift thickness are more or less 50 mm.

Where special mixtures are specified, at the upstream or downstream face for example, special procedures can be required. If CVC is used against a formed face with a dry consistency RCC mass behind it, CVC mixture should be placed first with RCC immediately spread against and on top of the sloping unformed face of the CVC. CVC mixture should be designed to lose slump rapidly but not set rapidly. This is a slow operation, however, it may be the only practical solution for some locations.Graders can be used on RCC projects, but they generally are not necessary and can actually become a problem. They are difficult to maneuver in small areas and at abutments. The tires and blade can damage otherwise good compacted surfaces. There is also a tendency to overwork and rework the surface as if it were soil instead of concrete with a limited working time.

Regardless of the method of transportation, RCC should generally be deposited as near its final location in the lift, as possible. Scrapers and bottom dumps have the advantage of depositing material in the lift to be spread, as they are moving. When rear dumps are used, the material should be dumped on the top of the new lift being placed, not the one to be covered. It allows reworking of slightly segregated dumped material as it is bulldozed forward. Because of the typically dry consistency of RCC, segregation may become serious if the material is dumped in large piles. Otherwise, the larger aggregate will roll to the bottom edges of the pile. Careful spreading by bulldozer can remix much of the segregation that might occur even with small piles. However, it will be quite impossible to avoid coarse aggregate segregation when it occurs ahead the advancing layer. When placing on the top of a new layer, blending can be accomplished as the material is pushed forward.

Figure 8.44 Material being dumped on top of the new lift being placed, allowing rework of slightly segregated dumped material.

Figure 8.45 Dozer tracks provided with street pads to minimize damage to the compacted surface.

Each 15ton (150HP) dozer spreads RCC at the rate of over $100m^3$/hr. Dozer tracks may be provided with street pads so that damage to the compacted surface is minimized. Whenever possible, the dozer should operate on fresh RCC that has not yet been rolled. All turning and crabbing should be done on uncompacted material. When it is necessary to drive the dozer on compacted RCC, the operator should limit the movement to straight back-and-forth travel. Track marks made prior to the mixture reaching initial setting may be recompacted by the vibratory roller.

RCC damaged after the mixture has started setting may be recompacted, however, the disturbed area will have little or no strength. This material can be easily removed by blowing an air jet even after many hours.

The spreading equipment should leave a flat surface before the roller compacts the lift. Depending on the workability of the mixture, ridges or steps between adjacent passes of the dozer blade may result in an uneven distribution of compactive effort and variable quality of the RCC.

Where special mixture designs are specified for limited areas, at the upstream or downstream face for example, special procedures are required. If the special mixture is CVC for a formed face, CVC is placed first and RCC is dozed against it. CVC is consolidated with immersion-type vibrators while the adjacent RCC is rolled. When the special mixture is RCC, it is practical to leave the area uncovered to receive the special mixture while the interior mixture advances forward. To tie the interior and special mixtures together, the edge of the advancing RCC should not be rolled prior to placement of the adjacent mixture. Then, the special mixture area is filled and rolled along with the previously placed interior RCC.

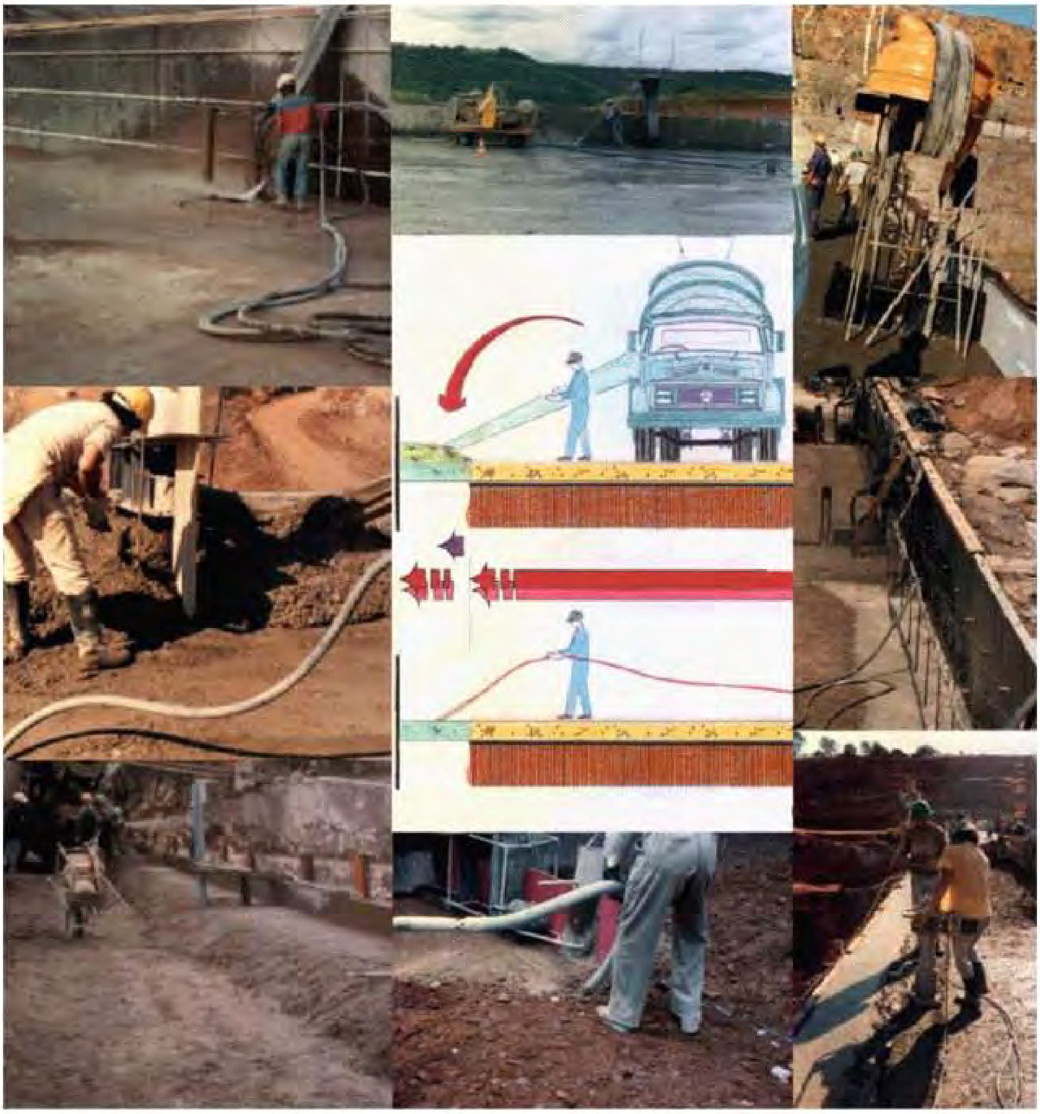


Figure 8.46 Schematic procedure - CVC being consolidated with immersion-type vibrators while adjacent RCC is rolled.

In extremely rough foundation areas and where the foundation has deep holes, a small front-end loader or small excavator bucket may be used to reach the placement site to deposit material. This is a slow operation and may be the only practical solution for some locations. When the lift surface is established, it is desirable to start each lift from the same general area and to begin in a non-critical area, such as the downstream rather than the upstream slope.

A front-end loader may be needed to safely spread the mixture to the external edge of an unformed downstream slope. The blade can be set so that it extends ahead, over the wheel tracks to either side so the equipment and the operator are not at the edge of the lift at the downstream slope. These machines are also useful where a narrow zone of higher quality RCC is specified to protect the downstream slope. Hauling equipment will not be able to dump the mixture in this narrow area, but the grader may spread the dumped material into its designated offset.

As can be seen in Figure 8.45, bulldozers are usually equipped with lugless tracks (street pads) which leave a flat lift surface either horizontal or on the design inclination, though tracks with lugs may produce better compaction. Inclination may be used for surface drainage, from the order of 20 (H) (horizontal) to 1(V) (vertical) to as flat as 50(H) to 1(V) have been used in some cases. About 15(H) to 1(V) is considered the maximum practical grade for RCC placement, where vibratory rollers are used for compaction. The roller should compact the lift only after it has been properly spread. Ridges or steps between adjacent passes of the bulldozer blade may result in an uneven compaction. As a general rule, having a flat surface ready to be rolled in the shortest time is more important to high quality work than having an exact grade but delaying rolling. An approximately 330mm lift spread by a bulldozer will usually result in a net 300mm compacted lift.

Spreading with wheeled equipment, such as a front-end loader or motor grader, has several disadvantages. This equipment is generally slower than the dozer, requires more room, tears RCC by spinning tires when attempting to push too much material, and precompacts the material under the tires. Such precompacted areas are then filled with additional material during the spreading operation. There is a concern that the roller may ride on these precompacted zones and partially bridge over the material between them. It seems that this problem is less severe when tracked or heavy rubbertired vehicles are used. However, and as a general rule, if the material has sufficient "workability" for lateral movement under vibration, bridging will not occur in unsegregated material.

8.9.5 Lift thickness

The most common compacted lift thickness can be seen in Chapter 4, Figure 4.56. In Japan, many thicker sections of about 450mm to 1000mm have been compacted in one lift after being spread by dozers in several layers. Within a range of about 150mm to 450mm, the large dual drum vibratory rollers used for compaction may reach about the same consolidation with only 4 to 7 passes. A compacted thickness of 200mm to 400mm can be easily placed and compacted with the use of most equipment and mixture designs.

A 300-mm-350-mm thickness is convenient to work with in the field. This is also about the maximum thickness that can be easily deposited by scrapers and bottom-dump trucks. However, the trend is to use the thickest lifts compatible with the spreading and compaction equipment.

Each project should be studied aiming at optimizing the benefits of thicker or thinner lifts. Thicker lifts mean fewer lift joints and fewer potential seepage paths, but thinner lifts allow the joints to be covered sooner with better bond potential. Thinner lifts generally suit better smaller jobs and thicker lifts suit better larger jobs. Thicker lifts may cause hardship to compaction.

8.10 Compaction

Compaction is the mechanical means by which consolidation is achieved, providing a reduced porosity. Consolidation is the term applied to CVC, but RCC is densified by compaction. Several different parameters influence compaction:

- maximum size aggregate;
- quantity and type of binding material;
- moisture;
- thickness of layers;
- equipment used, translation speed, etc.

Adequate compaction is an essential factor in order to guarantee a good behavior of the material. RCC is tamped or rolled into a dense mass by external equipment energy rather than by being internally (or externally) vibrated and densified by settlement under its own weight. Compaction should be performed as soon as possible after the no-slump concrete is spread.

8.10.1 Roller selection

Maneuvrability, compactive effort, drum size, frequency, amplitude, operating speed and required maintenance are all parameters to take into account when selecting a roller. Compactive output in volume of concrete per hour obviously increases with the physical size and speed of the roller, but larger size rollers do not necessarily give the same or better density and compactive effort provided by smaller rollers with a greater dynamic force per unit of drum width. Job size, workability, lift depth, consolidation extent due to dozer action and space limitations will usually dictate roller selection. Large rollers cannot operate closer than about 250 mm to vertical formwork or obstacles, so smaller hand-guided compaction equipment is usually needed to compact RCC in these areas. If a slipformed or precast facing system, with an internal face sloping away from the RCC is used, the large rollers may operate all the way to the facing.

The dynamic force per unit of drum width or per area of impact on tampers is the primary factor that establishes effectiveness of the compaction equipment. Experience has also shown that rollers with higher frequency and lower amplitude compact RCC are better than rollers with high amplitude and lower frequency, although suitable results have been achieved in some projects which have used rollers with both high frequency and amplitude. A typical compactor is a 10ton double or single drum roller with a dynamic force of at least 8kgf/mm of drum width. These rollers are typically used for asphalt and roadway compaction. Larger 15ton and 20ton rollers with more mass and size, typically used in rockfill construction, have been used with RCC but they usually have larger amplitudes, lower frequency and suit less the aggregate gradings used in RCC. It is more difficult to achieve density and a good lift joint interface with these larger rollers.

The present RCC technology depends upon compaction by vibratory roller. Vibratory rollers within the following standard data have proven to be effective, in most cases, in the compaction of RCC mixtures typically used in dam construction. The Japanese have generally used 7ton machines. The trend in the industry is toward heavier vibratory rollers and RCC technology is expected to benefit from the 13ton and 15ton machines now being manufactured.

The standard data for the machines commonly used are as follows:

Equipment	Single Drum Roller	Single Drum Roller	Single Drum Roller	Tandem Rollers	Tandem Rollers	Tandem Rollers	Light Single Roller	Light Double Drum Roller
Drum Width (mm)	1600-1700	2000-2100	2000-2200	1400-1600	1500-1700	1700-2200	500-600	600-800
Static Weight (ton)	6 – 8	34646	10 – 15	6 – 8	9 – 11	10 – 16	0,15– 0,20	1,2 – 2,5
Power (kW)	55 – 65	80 - 90	85 – 110	55 – 65	80 – 90	90 – 120	2,5 – 4,0	5,0 – 25
Frequency (Hz)	30 – 40	30 - 40	30 – 40	40 – 50	40 – 50	40 – 50	70 – 80	40 – 70
Normal use-layer depth up to (mm)	200 -250	250 -350	300 - 400	200 - 250	250 – 350	300 – 400	150 - 300	200 - 400

Figure 8.47 Most common roller characteristics

Figure 8.48 Equipment used for RCC compaction.

In tight areas, such as the ones adjacent to forms and next to rock outcrops, tamping foot-type compactors may be useful. They are mobile and may provide high impact energy to produce good density. However, they usually do not leave a smooth surface and may sink when tamping RCC placed over an excessive thickness of wet bedding mixture, when tamping RCC with excess water or if tamping next to a conventional concrete mixture that has not lost its slump. One-man vibrating plate compactors intended for sands are not very effective, however, the recently more massive plate compactors intended for deep gravel lifts are effective. They may require multiple passes. Four to six passes of this type roller on fresh RCC, not deeper than 300mm, usually result in suitable compaction for tight areas with densities about 98% of that achieved with the large roller. This reduced density is often considered acceptable, except for special areas identified as critical and truly in need of greater compaction.

A single vibrating pass is a length, not a circuit, lap or round trip. Rolling without vibration should not be considered as a pass. One pass with a double drum roller is equal to two passes with a single drum roller. In Japanese practice, the 45cm to 100cm lifts are compacted with as many as 12 passes of a 7ton vibratory roller followed by 6 passes of 25ton rubbertired roller. Within the range of 150mm to 460mm, the 10ton double drum vibratory rollers are used in others countries. The 10ton to 15ton double drum vibratory rollers may develop suitable compaction of 150mm to 400 mm layers.

In the development of RCC technology, other rolling equipment and compaction methods have been used and tested with varying degrees of success. For vibratory rollers, the dynamic force is apparently the most critical factor. Care should be taken to ensure the uniformity of compaction throughout the layer thickness.

8.10.2 Minimum Passes and Lift Thickness

The minimum number of passes for a given vibrating roller to achieve specified compaction depends primarily on RCC mixture and lift thickness. Experience shows that the maximum lift thickness will be governed more by how fresh the mixture is at the time of compaction, gradation and effectiveness of the dozer, while spreading, than by the number of roller passes. Tests should be performed in test fills prior to or during the early stages of construction to determine the minimum number of passes required for full compaction based on the design mixture and the planned lift thickness. As a general rule, the compacted thickness of any RCC lift should be at least three times the MSA diameter.

The required number of roller passes may be determined or verified in the test section. Some compaction specifications require the first pass to be in the static mode for wetter consistency mixtures. This may compress the surface and prevent the roller from bogging down. Drier mixtures may begin with the vibrating mode. Additional passes should be in the vibrating mode. Frequency and amplitude settings may have to be adjusted depending on the workability of the mixture. The most effective compaction typically occurs with a high frequency of 1,800vib/min-3,200 vib/min and a low amplitude of about 0.4 to 0.8mm. The transient loading and vibration result in consolidation of wetter consistency mixtures with a measurable VeBe time. The same frequency and amplitude ranges have also been very effective with "compaction" of drier consistency mixtures.

Typically, 4 to 6 passes of a double drum 10ton vibratory roller will achieve the desired density for RCC lifts in the range of 150mm to 450mm of thickness. Overcompaction or excessive rolling should be avoided. A density reduction has often been observed in the upper portion of the lift. The technique of compacting thick lifts but spread in several thinner layers, has been used in Japan. It requires effective compaction by the dozer during spreading and may require more roller passes on the top layer of the lift. Special attention is needed so that higher numbers of roller passes do not overcompact the top of the lift, while a deeper part is under-compacted

The fresh surface should be smoothly spread so that the roller drum produces a uniform compactive force under the entire width of the drum. If the uncompacted lift surface is not reasonably smooth, the drum may over-compact high spots and under-compact low spots. Rollers should not be used to "flatten" ridges or high spots that remain from spreading. The drum will otherwise over-compact the ridge and under-compact between ridges.

Figure 8.49 Tests being performed in test fills prior to early construction stages to determine the minimum number of passes required for full compaction, based on design mixture and topographic survey.

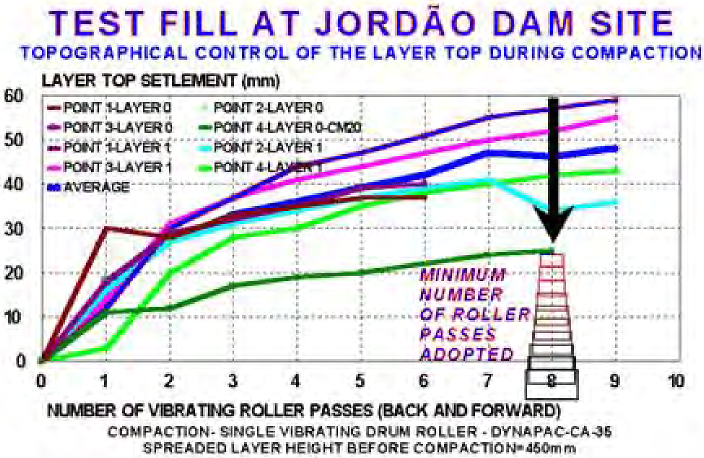


Figure 8.50 Vertical RCC settlement (compaction effort) due to roller passes.

Figure 8.51 Over-compaction promotes a lamination on the RCC surface and may lead to lower densities and, thus, should be avoided. The top of a lift may become less dense while the bottom becomes denser.

Over-compaction can lead to lower densities and should be avoided. This may occur locally and may be difficult to detect; the top of a lift may become less dense while the bottom becomes more dense. Driving over a previously compacted lift with the drum vibrating should be avoided because it may disrupt the microstructure which begins to obtain initial set as the cement hydrates, but still has little strength.

Minor damage from scuff marks, unavoidable dozer tread tears or other defects in the surface of a freshly compacted lift should be immediately rolled down with the drum in a static mode. If the concrete is sufficiently fresh, moist and re-rolled, the damage will be suitably rehabilitated. If the concrete is too old or severely damaged, the re-rolled material will only be seemingly acceptable. In this case, it can be easily blown off by compressed air used for cleanup of loose debris on the lift.

Each RCC mixture will have its own characteristic behavior for compaction, depending on temperature, moisture, wind, plasticity of the aggregate fines, overall gradation and maximum size aggregate. Generally, RCC mixtures should compact to obtain a close textured and relatively smooth surface. The material should not be picked up to the roller drum, nor should show free moisture or excess water pumped from the mixture. These conditions may well be observed by trained workmen and adjustments should be made in the water content in case they occur. However, if superficial material is lifted by the roller drum and recompacted prior to initial set, an acceptable condition may be obtained. Optimum moisture content will depend primarily on the compactive effort. Other aspects to consider are temperature, moisture, plasticity of the aggregate fines, overall grading and maximum size aggregate. Cementitious content has little effect on the moisture needed for compaction. Generally, RCC mixtures should compact to obtain a close textured and relatively smooth surface, as can be seen in Figure 8.53.

Figure 8.52 Poor texture of RCC surface (opened texture), due to low fines content.

Figure 8.53 A very well closed RCC surface texture.

8.10.3 Timing and Procedures

Visual observations can be of help to moisture control. The material should not be "picked up" by the roller drum, nor should there be free surface moisture or excess water pumping from the mixture.

The appearance of a fully compacted RCC depends on mixture proportions. Mixtures of wetter consistency usually exhibit a discernible pressure wave in front of the roller. If the paste content is equal to or less to the volume needed to fill all the aggregate voids, rock-to-rock aggregate contact occurs and a pressure wave may not be observed. This can also occur if the mixture is simply too dry to develop internal pore pressure under the dynamic effect of the roller. Mixtures with more paste than necessary to fill aggregate voids and a wetter consistency will result in a visible paste on the surface that may be picked by the roller drum, depending on the paste constituents and plasticity.

RCC compaction should be accomplished as soon as possible after it is spread, especially in hot weather. Tests have shown [8.08] substantial reductions in compressive, tensile and modulus values if material is compacted when it is more than about 30min to 40min old and mixture temperature is about 20C°. These times may be increased for RCC mixtures with extended set times due to pozzolanic materials, admixtures or colder temperatures.

Rubbertired rollers have been effective in sealing, smoothing and tightening the surface of mixtures that are susceptible to damage and exhibit surface checking after final drum rolling. Adequate use of fines content on set retarder admixture reduces the use of the rubbertired roller.

Exposed edges of RCC layers, which will not be extended with additional material, should be rolled down at the steepest possible angle within 30min approximately after placing. The roller should be driven normally, back and forth to the edge without turning. Later on, adjacent material may be placed and compacted against the already compacted edge while exercising consistent care following bonding requirements.

Figure 8.54 Wet RCC mixture giving wave aspect in front of the roller during compaction.

8.10.4 Roller Travelling Speed

The Japanese [8.09] developed several studies concerning compaction methods and respective results.

In RCC placement, it is important to know the vibration energy required to obtain a specified density ratio. This could be understood considering the vibratory roller to be used, vibration conditions, such as frequency and vibration amplitude during placement, rolling speed and number of passes.

According to the results on a test section performed [8.09] with five different vibratory roller models with RCC mix proportions, compaction thickness, number of passes and compaction speed, a correlation was done. The expression below shows that the roller traveling speed has a great influence on compaction.

E= [(2a*L*n*N)*(W+F/2)]/(V*B*L) where

E	= Vibration Energy	(kg.cm/cm2)
a	= Amplitude	(cm)
W	= Axial Load	(kg)
F	= Centrifugal Force	(kg)
V	= Travel Speed	(cm/min)
L	= Contact Length between Drum and Concrete Surface	(cm)
n	= Frequency	(cpm)
N	= Passes of Roller	(times)

During the construction of the Jordão Dam, it was observed [8.10] that, with the roller speed of approximately 2km/hour, about 50% of the passes were necessary as for a travelling speed of 4km/hour.

8.11 Curing and Protection

After RCC has been placed and compacted, the lift surface should be cured and protected just as for concrete placed by conventional methods. The surface should be kept in a moist condition, or at least as to avoid moisture loss. This is done by fog spraying or covering. Also, the surface should be protected from freezing or from contamination agent by insulating it with plastic sheets until it aquires sufficient maturity. It should be protected from temperature extremes as well, until it exhibits sufficient strength.

Immediately after an RCC lift has been compacted, it is essentially impermeable and will not be damaged by light to moderate rain if there is no hauling or traffic on the surface. After a rain, hauling on the lift may resume only after the surface has begun to naturally dry back to a saturated dry surface (SDS) condition. A slightly sloped surface will aid in draining free water and speed the restarting of placing operations.

At the completion of rolling, lift surfaces should be moistened and kept damp at all times, until the next lift is placed or until the required curing period has ended. It is quite hard to achieve this requirement since contractors have tended towards using water trucks with coarse sprays to wet the lift surface. This should not be permitted since good fog spray nozzles providing an extremely fine spray are readily available. If coarse sprays are used, paste and fine aggregates sometimes erode away from the surface. The operators of a water truck, in the attempt to cover all parts of the surface, often make tight turns and repeated passes over the same areas. It also should not be permitted because tire action mechanically damages the surface. Even though a properly proportioned RCC mixture will not develop laitance, improper use of a water truck may produce a surface scum much alike laitance due to overwetting, erosion and tire action. Piping use and hand-operated hoses with fogging nozzles should be considered. Still better it would be to place RCC fast enough so as to cover each lift surface before it dries out or, instead, place RCC during cool and humid periods so that little additional wetting would be required. However, the need for fogging the surface will seldom be entirely eliminated.

Cure during construction has been accomplished with modified water trucks or tractors on larger projects, and with hand-held hoses for all size projects. Trucks should be equipped with fog nozzles to overspread a fine mist that does not wash or erode the surface. They may be intensified with hand-held hoses for areas inaccessible to water truck. Provision should be made to maintain the damp surface while the trucks are fueled, maintained and water refilled. Care should be taken so that trucks do a minimum amount of turning and disruption to the surface.

The final RCC lift should be cured during an appropriate period of time, over 14 days. Curing compound is unsuitable because it is difficult to achieve a 100 percent coverage on the relatively rough surface and there may be a probable damage to it from construction activity, a low initial moisture in the mixture and the loss of a beneficial surface temperature control associated with moist curing.

During construction, the compacted surfaces of RCC layers should be maintained in a damp condition but with no ponded water. This is accomplished in a most convenient way with water trucks remaining on the placement during 24 hours a day, 7 days a week. Where labor is inexpensive and/or the area is too congested for an effective use of trucks, sprinkler systems and hand-held hoses may be more efficient. The trucks should overspread a fine mist that does not wash or erode or puddle the surface, and should be augmented with hand-held hoses to reach areas inaccessible to truck. Provision should be made to keep the surface damp while the trucks are fueled, maintained and water refilled. Care should be taken so that trucks do a minimum amount of turning and disruption to the surface.

During RCC placing, a light rain may be tolerated providing that the equipment does not track mud onto the RCC or begins to drive moisture into the surface, thus damaging the compacted material. Damage is evident when the roller begins to pick up material on the drum; placing should then be stopped. When conveyors are used for delivery and little or no vehicular traffic is necessary on RCC, construction may continue in damp weather but may require a gradual decrease in the amount of mixing water used due to the higher humidity. The point at which damage first occurs, when operating under too wet conditions, is obvious and usually sudden.

An effective cure may be done by an agricultural fog spraying, as shown in Figure 8.55.

Advantages may be obtained by placing thicker lifts in warm climates to reduce the total number of potential cold joints. In cooler climates or climates subjected to wide temperature range, fast placement of thinner lifts may help to protect hardened lower lifts while plastic upper lifts "absorb" the thermal shock.

In cold weather, attention should be given to potential problems caused by sudden cooling of the large exposed RCC surface, especially during night time temperatures, while awaiting the next lift. The placing cycle may be adjusted to overcome such irregular cooling conditions by night time placing. In other times, insulation in the form of plastic blankets may be used to prevent sudden heat loss and possible thermal cracking of the mass.

Figure 8.55 Fog spray during RCC placement and curing at Salto Caxias dam.

Figure 8.56 Fog spray equipment that may be useful for RCC protection during placement and curing.

Figure 8.58 Deep holes in the rock foundation at Jordão dam.

Figure 8.59 Foundation preparation at Capanda dam-Angola.

A thin layer of CVC is usually applied to the rock surface to fill the existing cavities and allow an accessible surface to be used by the RCC placing equipment.

To remove the loose material existing in the cavities, a backhoe-excavator dozer (see Figure 8.60) and a mobile crane are commonly used and may be complemented by manual work due to the size and imperfections of the job, such as:

- Removal of blocks and loose rock fragments;
- Removal of gravel, sand and slurry;
- Pressurized water-blast cleaning of the remaining rock surface;
- Concrete placement.

When RCC and the rock are in contact at the abutments and at the dam foundation, a CVC bedding should be used. This CVC should have an MSA of 19mm 38 mm at the most and should have a slump between 50mm and 10mm. At the abutments, this mixture and the RCC mixture should be intermixed, as previously described for upstream facing concrete. Bedding thickness should be sufficient to allow this intermingling. The bedding thickness on the foundation will be governed by the roughness of the foundation, but should be no thicker than necessary to fill the voids at the RCC foundation interface.

The following productivity parameters were observed during these operations [8.11] at the Jordão dam construction:

- Team Production = $3,29m^2/h$
- Sand (for sand-blast) Consumption = $0,02m^3/m^2$
- Workman Labor = $0,46\ Hh/m^2$

The criteria adopted to define CVC thickness near the foundation rock was based on the surface slope [8.11], as follows:

- Slope greater than 15° - average thickness up to 10cm;
- Slope equal to or less than 15° - thickness of approximately 30cm;
- The rock surface is kept under the SDS up to the concrete placing.

Figure 8.60 Equipment used for rock surface preparation.

8.12.2 Construction Joint Surface

For sliding stability, joint tension and/or watertightness, the design usually requires clean and relatively fresh joint surfaces with good bond. Another consideration is the permeability of the untreated construction joint, which is likely to be much higher than that of the concrete. Several are the undesirable consequences of a highly permeable construction joint:

- Increase in uplift pressure;
- Opening of the joint and loss of bond;
- Leaching out of lime and other cementing compounds;
- Risky increase of a deleterious alkali-aggregate or alkali-silica reaction; and
- Penetration by cold water starting or extending cracks.

One of the most important design considerations for RCC dams is the control of seepage. Excessive seepage is undesirable from the structural stability aspect, possible long-term adverse effects on durability, adverse appearance of water seepage on the downstream slope and the economic value associated with lost water. Properly proportioned, mixed, placed, and compacted, RCC should make a structure as watertight as does a conventional concrete. The joints between RCC lifts are the major pathways for potential seepage through an RCC dam. Seepage can be controlled by incorporating appropriate design and construction procedures as the use of bedding mortar over the full area of each lift joint, contraction joints with waterstops, draining and collecting seepage water. Collected water can be channeled to a gallery or to the toe of the dam. Collection methods include vertical drains with waterstops at the upstream face and vertical drain holes drilled from within the gallery, near the upstream or downstream face. It should be emphasized that any RCC dam, regardless its intended use or structural or environmental conditions, should be designed and built to prevent seepage as a matter of good engineering, as well as produce a high quality structure at little or no extra cost.

Typical specifications or requirements for the clean-up of construction joints being prepared for placement of a new concrete require the removal of all loose, flaky, unsound fragments of concrete, sand, oily or organic materials, scaling compounds, deleterious coatings and other foreign or defective materials. Immediately prior to placement of concrete, the surface of the construction joint should be clean and damp.

The ACI Manual of Concrete Practice (Sec 4.3.2)[8.12] provides the following general guidelines:

"Efficient and best preparation of horizontal joint surfaces begins with the activities of topping out the lift. The surface should be left free from protruding rock, deep footprints, vibrator holes and other surface irregularities.

In general, the surface should be relatively even with a gentle slope for drainage. This slope makes the clean-up easier. As late as is feasible, but prior to placement of the next lift, surface film and contamination should be removed to expose a fresh, clean mortar and aggregate surface. Overcutting to deeply expose aggregate is unnecessary and wasteful of good material.

Strength of bond is accomplished by cement grain, not by protruding coarse aggregate. Usually, removal of only about 2mm of inferior material will reveal a satisfactory surface."

While removal of all objectionable material implies satisfactory cleanliness of the joint surface, specifications rarely include standards for judging its roughness, resulting in disputes about the adequacy of joint preparation or treatment methods.

Sometimes, there is also a confusion about how to define objectionable and deleterious materials, such as a fine film of crystalline calcium carbonate which strongly adheres to the concrete surface. Any material which is compatible with Portland Cement and its cementation and setting process, or does not impair the strength, permeability or durability of the concrete, does not need to be removed.

In an ideal situation, a well treated construction joint should have essentially the same strength properties as the monolithic concrete. Thus, when responding to loads imposed upon the structure, the elastic response of the joint should be indistinguishable from that of the concrete above and bellow it. In other words, in bond, tension, shear and bending, the same safety margins should be available at the joint as in the concrete. Also, the treated joint should be as impervious as the concrete.

The following questions always arise when design, specifications and quality control procedures for a concrete dam are prepared:

➢ How does the actual performance of construction joints treated by various methods compares with the desired objective?

➢ How should the adequacy or acceptability of the various types of construction joint treatment be evaluated?

To find realistic and representative answers to such questions, a larger number of investigations involving tests on samples cored out of test fills or existing dams, at different concrete ages, have been carried out by organizations throughout the world. Results of *in situ* tests to determine bond and shear strength between new concrete placed on the roughened surface of a several years old concrete are also indicative of the efficacy of joint treatment.

Joint development

Horizontal construction joints may be either of a planned or unplanned variety. When an RCC lift is not covered with additional RCC before it reaches initial set, it becomes a cold joint to some degree.

Horizontal joints are inevitable in mass RCC because of its layered or lift method of construction. Each layer is the thickness of material spread. Layers may be compacted as individual lifts, or several layers may be spread before compacting them as one lift prior to initial set of RCC

Cold joints result from temperature, time of exposure, wind, sunlight and are also sensitive to the quantity and characteristics of the cementitous material and the effectiveness (if any) of set-retarding admixtures. If the set time of the mixture is retarded through cold temperatures, for example, a high percentage of pozzolanic material, an effective retarder and wetter consistency, or slag, the length of time prior to a cold joint can be extended.

Large projects and others, where joint shear strength is critical to stability and safety, should confirm design assumptions for joint shear strength with full scale bi-axial shear tests of RCC to be used, conditions to be encountered, and construction controls that will be enforced. Initial design assumptions can be based on extrapolation from substantial tests, evaluations and successful design assumptions from previous projects.

Designers generally have found it prudent to require the bedding mixture after a lift has been exposed for about 1 to 2 days. Other designers have found it prudent to use bedding in a systematic way for a portion of all layers, regardless of the surface maturity. Shear strength, as it relates to design, can be checked by a test fill.

Joint Surface Treatment

The bond between layers is produced by two mechanisms:

- Binding and penetration of the aggregates;
- In the capacity of bonding and, therefore, in the formation of one or other type of joint, multiple parameters are influential: mix, humidity, type of binding material, setting time, consistency, spreading (segregation), compaction system and equipment, curing, etc.

Treatment of RCC horizontal lift or construction joints differs from that of conventionally placed mass concrete; in that there is no surface water gain during set of the concrete. Thus, there is no weak laitance film at the surface. Bleeding does not occur in properly proportioned RCC. However, it is not uncommon for full consolidation of RCC to bring paste to the surface. If the joint surface has been contaminated by dirt, mud or other external element, it should be removed.

Lift joints should be kept protected continuously, 24 hours per day, from drying or freezing prior to placing the next lift. If the surface is more than about 2 days old and it has become sufficiently hard, water washing may be necessary if humid-air blowing alone does not adequately clean off damage, contamination, and general laitance that may be present. Water washing can only be used after the surface has hardened. Water-blasting or sand-blasting is generally not advisable or necessary.

RCC mixtures generally do not bleed or develop laitance at the surface. An exception is very wet mixtures and some cases of dry mixtures after days of moist cure. If there is no weak laitance or other contamination on the surface, lift joint cleaning typically required with CVC is not necessary. Although there is some debate, minor intermittent laitance that may occur in some situations is generally not removed.

Figure 8.61 Schematic routine for joint surface cleaning and treatment.

The required lift surface preparation prior to placement of the overlying lift of RCC depends to some extent on the construction procedures and sequence a few hours old, still relatively green and damp, could be ready for placement without any preparation, except for a removal of any construction debris. However, if the surface is several days old and has been allowed to dry, then the use of a high pressure water jet may be necessary to remove dried, partially bonded sand, silt and other debris which have been caused by construction traffic. Of course, in as much as possible, dirt and debris, as well as construction traffic should be kept off the joint surface at all times.

The practice of arbitrarily requiring a thin layer of high-slump mortar as a bedding over all lift joints is routine in Japan. Others have found it to be expensive, time consuming, not always necessary, and difficult to control, and so have used a reduced zone to require the bedding between lift joints. The RCC layer is spread over the bedding while the bedding still retains its slump or workability, and the RCC is then compacted into the bedding.

Many RCC projects have used a highly sanded CVC mixture for bedding with good results. The mixture should have at least a 150mm slump and be substantially retarded by admixtures. A 9.5 to 25mm MSA is desirable and has been used. The bedding thickness should average the same dimension as the largest aggregate particle in the mixture. Cores have consistently shown that this procedure thoroughly bonds the RCC layers. The bedding mixture should blend into the fresh RCC, so that it does not leave a layer or thin lens of mortar or bedding at the joint.

Each project and mixture should be evaluated individually for bedding mixture types and requirements. Where bedding has been used over the entire surface of every RCC layer, it has basically been a management decision made to simplify inspection and cost estimating, achieve better cores and joint interfaces throughout the dam, guarantee tensile capacity at the lifts and provide added lift joint seepage protection. Other projects have used a bedding mixture only when and where it is actually needed to achieve the required factors of safety. Typically, these designs dictate a width of bedding near the upstream face as percentage of the hydraulic head, at the normal operating reservoir level for lifts that are cold joints.

Figure 8.62 RCC core specimen showing the bedding mix (previously placed on the surface joint) interpenetrating in the next RCC layer.

The RCC layer is spread over the bedding while the bedding still retains its slump or workability and the RCC is then compacted into the bedding.

The Japanese RCD invariably make use of a cement-enriched mortar 15mm bedding mix between rolled lifts as well as next to the foundation rock. They also call for green cutting and a clean-up procedure on every lift, thus assuring themselves that they have the same degree of watertightness and shear strength as in a conventional concrete dam. It is important to carry such leakage control along the abutments, as well as along the upstream face of the dam.

Figure 8.63 Mortar bedding layer being applied on construction joint surface.

Bedding layers and joint treatment are important consideration when the structure has been designed using high cohesion value.

The design of RCC structures, where watertightness and bonding are required between lifts, should require the application of a bedding mortar over the entire surface area between all lift placements. Other surface treatments need not be specified as long as the surfaces are kept clean and moist, zones of segregation or large rock pockets are avoided and lift surfaces are not damaged by construction activities. Contract specifications should include provisions for high pressure washing if placement intervals between lifts exceed 72 hours. A bedding mortar is a high-slump, high-cement-content material used to increase bond between RCC lifts and to improve watertightness by filling in any voids that may occur at the bottom of an RCC lift during placement and compaction. The thickness of bedding mortar must be sufficient to fill any voids at the bottom of the overlying lift. Retarders should always be used to extend the setting time of the bedding mortar.

Because of the high slump and high water content, the cementitious content should be high to provide adequate strength. The bedding mortar application preceded placement of the RCC, usually by 10 to 15 minutes, and in an approximately 3m to 5m wide zone in front of where the RCC was being spread. During hot or wet conditions, the interval between spreading of the bedding mortar and placement of RCC had to be shortened. The bedding mortar was distributed from the chutes of ready-mix trucks and then spread with a serrated rubber squeegee mounted on the front of a small four-wheel farm tractor. Haul trucks and other equipment were allowed to track over the bedding mortar. This was not believed to be damaging in any way and might have been beneficial since it forced the bedding mortar into depressions and voids at the lift surface, incorporating into the bedding mortar any remaining silts, sands and gravels not removed during lift-joint clean-up operations. This method has been an efficient non-labor-intensive way to spread a bedding mortar and at the same time provide the necessary bonding and watertightness along the lift joints.

The treatment of the different types of horizontal joints in which the joint does not require cleaning but it does indeed require a bonding agent for its correct treatment. Different solutions can be adopted:

- Spreading a layer of mortar only in the upstream zone;
- Spreading mortar over all the layer;
- Placing the following layer of a concrete rich in paste.

Figure 8.64 Mortar bedding layer being applied on the upstream zone of a construction joint surface, at Capanda dam-Angola.

A bedding mortar over the full area of each lift joint is recommended as mandatory for providing watertightness for any dam that will impound water for extended periods. It is also necessary for dams where appreciable bond strength between lifts is necessary (such as those built in earthquake zones where more tensile strength across the lift joints is required than is available without bedding mortar). Tests show that the use of a bedding mortar can approximately double the tensile strength and shear strength at the joints. It is desirable to provide bedding mortar over the full area of each lift joint even if watertightness or tensile strength is not a concern. At Elk Creek dam, the cost of full-area bedding mortar was found to be 33 US$ cents/m^2 of lift joint surface area. A bedding mortar for other structures such as massive foundations, dam facings, sills and cofferdams, should be considered during the design stage based on the need for bond or watertightness, or both.

Another type of bedding mixture application has been used in some of the dams built by other commercial or governmental agencies in the United States. It involves the spreading of concrete mixtures having up to 19mm MSA to a thickness of 20mm to 50mm in a zone along the upstream face of the dam. The width of application ranges from several feet to approximately one-third of the width of the dam. This type of mixture has been used only to provide watertightness at the upstream face. Spreading of this type of bedding mixture is usually by manual labor. The effectiveness of this treatment is not considered to be equal to the full-area bedding mortar described above and this treatment should not be used except when especifically approved by the designers.

8.13 Detailed Construction Method

8.13.1 Facing Systems

Large surface areas that are not horizontal can be shaped to almost any desired slope or configuration, but special consideration must be given to anchorages, appearance and technique. A wide range of options exists.

The height of overhanging sloping forms restricts areas accessible to the vibratory rollers. These forms should, therefore, be limited in height or hinged at mid-height to reduce the volume of concrete that should be placed under the overhang by conventional methods. Conventional jump-form anchors may not have adequate embedment depth for form support when anchored in low-strength RCC and special anchors may be required.

Handling and raising conventional form-work may become the restrain factor during RCC mass production. Near the crest of the dam, where the volume of RCC per lift is low and the form area for upstream and downstream faces is relatively large. It can easily take more time to set and move the forms than it takes to place RCC.

Small rollers can be operated til 25mm of vertical formwork; however, large rollers usually cannot get closer than about 200mm. Good compaction can be achieved at vertical surfaces with MSA of 38mm and smaller and careful attention to details as layer thickness and size of roller. After compaction, there is always a small projection of uncompacted RCC above the surface that the roller cannot reach. If this is kept raked away from the form, layer lines will not stand out after removal of forms and surfaces comparable with conventionally placed mass concrete are possible.

8.13.1.1 Upstream

Upstream faces are, generally, nearly vertical, built usually with conventional concrete casting formwork, prefabricated panels with or without impermeable membrane, curbs being executed *in situ* with a sliding formwork curbing machine, etc.

On occasions and aiming to simplify construction, it is carried out as roller compacted concrete with a higher fines content than that of the core.

Formed Upstream Face: Conventional forming can be used at the upstream or downstream slope with RCC placed directly against it. The resulting surface may have relatively poor quality, unless particular attention is given to the placement and type of mixture used next to the formwork.

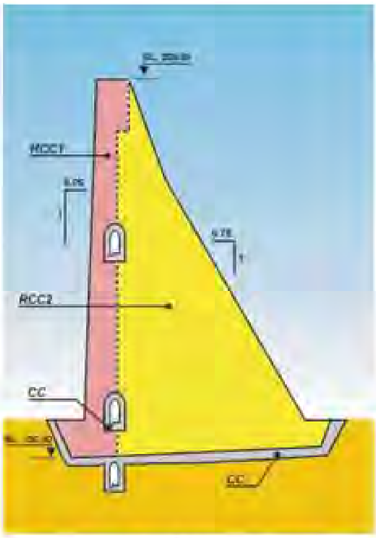


Figure 8.65 RCC poured directly against form on upstream slope.

Formed CVC Face: If better appearance, watertightness and surface quality are desired, conventional forming can be used at the upstream or downstream slope with CVC placed directly against it, just ahead of RCC placement. Another approach is to precede RCC placement with the construction of a CVC wall. In either case, the wall can be provided with waterstopped contraction joints.

When cast-in-place CVC is placed on the upstream face of a dam built of RCC, or when CVC is placed against rock abutments, care must be taken to ensure that the interface between CVC and RCC is thoroughly consolidated and intermixed. So, CVC also provides a medium for installing contraction joints with waterstops and drains, as well as for installation of thermal or seismic reinforcement, form-tie anchors, or instrumentation that cannot practically be installed in RCC. Consolidation should take place in a sequence so that the entire interface area is intermixed and becomes monolithic without segregation or voids, in either material or at the interface itself. The recommended sequence is one in which CVC is placed against the rigid forms or abutment rock followed by placement of RCC in thin layers against the CVC. Each layer of RCC should be vigorously tracked into the CVC by the dozer until the full liff thickness is achieved. The two concrete types should be extended across the dam at as close a placing time interval as can be accomplished with the available equipment. Before initial set occurs in either type of concrete, it is essential that the interface between the two should be vibrated using heavy-duty internal concrete vibrators inserted at close intervals along the interface. A retarder, used both in RCC and CVC, provides benefit in attaining a good joint by extending the time of initial setting and workability of both materials at the interface. The consolidation of this interface has at times been a difficult quality control problem. To be successfully consolidated, the interface requires intensive use of closely spaced heavy vibrators and care in removing segregated coarse aggregate particles.

Figure 8.66 CVC being placed against form on the upstream slope, just ahead of the RCC placemen.t

Precast Concrete Form: Vertical and very steep slopes can also be controlled with precast concrete panels or blocks. Precast concrete panels consist of relatively thin high-quality concrete slabs with integral and/or external supports for handling. Slopes can also be controlled with precast concrete panels or blocks. These panels act as insulation themselves or can incorporate added insulation to protect the interior concrete in extremely cold regions. They also can include a heavy-duty flexible impervious membrane attached to the rear of the panel to provide watertightness. With dry consistency RCC, the rate of rise of RCC is controled only by the rate at which the panels can be placed. When a wetter consistency mix is used, especially if it is cold and/ or otherwise retarded, the rate of rise will be limited by the set time of RCC, unless additional anchorage or panel support is provided. This technique, with field splices made in the membrane at panel joints, was used successfully at Winchester, Urugua-i and Capanda Dams.

This procedure has been 100 % effective in providing a watertight barrier. High density polyethylene also can be used as liner.

Curb Forming : One means of forming upstream and downstream slopes is using powered curbing machines to slipform conventional concrete curbs or facing elements against which the RCC placement can be made within about 8 hours. This method is more suitable on wide valleys and large projects where the rate of rise of RCC does not exceed the rate of slipforming. At Upper Stillwater, it was possible to maintain an average production rate of 0.6m of vertical rise (two RCC lifts) per day, and the curbs had enough time to develop the necessary strength.

Figure 8.67 Precast element with PVC membrane at Urugua-i dam-Argentina.

Figure 8.68 Element being cast with the PVC membrane as a (internal) face.

Figure 8.69 Precast element being installed at Urugua-i dam-Argentina.

Figure 8.70 PVC membrane being spliced at Urugua-i dam-Argentina.

Figure 8.71 Dam face being cast by a powered curbing machine at Upper Stillwater dam-USA.

At Upper Stillwater Dam, Utah, the US Bureau of Reclamation (USBR) used slip-formed facing conventional cast-in-place air-entrained concrete elements to form both the upstream and downstream slopes of the RCC dam. The slip forms moved across the dam extruding curb-facing elements. Grade and alignment were maintained using laser control. After each lift of the facing elements (curbs) on each side of the dam had achieved sufficient strength, RCC was placed in 0.3m lifts across the width of the dam between the facing elements before the next lift of curbing was placed. With this procedure there is no intermixing of the conventional concrete and RCC; however, this system provided a straight, aesthetically pleasing facing, both upstream and downstream. A concern regarding this system is the condition of the interface between RCC and the extruded curbing. At the interface there may not be any bond, thus creating a plane of weakness between the facing and RCC. Also, there may be segregation and rock pockets in RCC at the interface. When 0.3m lifts were used at Upper Stillwater, extruding of the curbing often restrained the rate of RCC placement. Greater lift thicknesses might create an additional scheduling problem.

8.13.1.2 Downstream

The downstream slopes are performed in a stepped way with stiffened panels or prefabricated elements, or without formwork leaving an extra width as sacrificial concrete. In some cases they are built in conventional concrete with formwork or curbing.

Uncompacted Slope: If no attempt is made to compact the edges of an RCC placement, the slopes will rest at the natural angle of repose of about 50 degrees with crushed aggregate and 45 degrees with rounded aggregate. This presumes reasonable care with spreading and compacting. Any means of containing loose concrete at the edge, for example by board forms, the height of the lift and supported by pins driven temporarily into RCC, results in steeper slopes.

At some dams, the downstream slopes are not formed, except where the upper portions are nearly vertical, but are placed by pulling back each following lift to make an average 0.8(H) to 1(V) or 0.75(H) to 1.0(V) batter, as required. The finished slope has a horizontally corrugated appearance and is expected to ravel away the loose outside material. It is overbuilt to permit "sacrifice" of the material on the slope due to the poor quality of the non-compacted zone. This type of construction, and other construction as well, may require personnel safety measures during construction in the form of temporary fences or barriers to be closed immediately after the lift placement.

Figure 8.72 RCC poured directly, without form, on downstream slope.

Stepped Slope: On some others dams CVC was used (placed against form, or with curb machine, or precast panel) or RCC (poured directly against form or compacted with a machine) giving a stepped appearance which is aesthetically pleasing.

Figure 8.73 RCC poured directly against the form at a stepped downstream slope - Jordão dam-Brazil.

Figure 8.74 CVC poured against the form at a stepped dowstream slope - Salto Caxias dam-Brazil.

Figure 8.75 CVC casted in a stepped appearance with a pleasing aspect at Arriaran dam-Spain.

Figure 8.76 RCC in a downstream slope compacted by a special machine.

8.13.2 Spillway

Spillways for RCC dams can be directly incorporated into the main structure. A typical layout allows discharging flows over the dam crest and down the downstream slope. In contrast, the spillway for an embankment dam is usually built in an abutment at one end of the dam or in a nearby natural saddle. Generally, the embankment dam spillway is more costly. For projects that require a multiple-level intake for water quality control or for reservoir sedimentation, the intake structure can be readily anchored to the upstream portion of the dam. For an embankment dam the same type of intake tower would be a freestanding tower in the reservoir or a structure built on the abutment. The cost for an RCC dam intake is considerably lower, especially in highly seismic areas. The shorter base dimension of an RCC dam compared to an embankment dam reduces the required size and length of the conduit and penstock for outlet and hydropower works.

The spillways over RCC dams are similar to those of CVC dams, being classified according to the form of the spilling face and the material with which they are built:

I. Flat face and CVC spillway as in the Jordão, Salto Caxias, Capanda, Urugua-i, Santa Eugenia dams or the Japanese dams;

II. Stepped slope and conventional concrete spillway, as in the Rio do Peixe, Caraíbas, Jucazinho and Upper Stillwater dams;

III. Stepped slope and RCC spillway, like Willow Creek.

The stilling basin can also be of CVC or RCC.

Most of the RCC dams built or currently under design have overtopping spillways and stilling basins at the downstream toe. An important example is the Salto Caxias dam-Brazil, where a large length of the right RCC dam was overtopped many times during the year of 1997, reaching about 7000m^3/s in the section (plus 7000m^3/s through the sluiceway).

Figure 8.77 CVC smoothed spillway face at Urugua-i dam-Argentina, Jordão and Salto Caxias Dams - Brazil.

Figure 8.78 CVC smoothed spillway slab being cast over RCC dam body (and sluiceways) at Salto Caxias dam-Brazil.

Figure 8.79 CVC stepped spillway at Jucazinho and Rio do Peixe Dams - Brazil.

8.13.3 Diversion, Galleries and Internal Drainage

The structural and hydraulic conception of RCC dams is identical to that of those built with CVC and, therefore, all the determining factors of safety and control of the fabric and the foundation are the same.

The economic considerations of roller compacted concrete tend to greatly simplify the constructive methods and to reduce or eliminate the obstacles which face the works. That is why the generalized tendency observed is to reduce the number of galleries and to simplify their shape and execution. In many cases only a perimeter gallery is built which is embedded in the rock encased with CVC.

8.13.3.1 Diversion Conduits

Diversion on all of the RCC dams built or planned up to date has been accomplished by using embedded conduits through the base of the dam (for small flows) or sluiceway. In some cases, diversion facilities are combined with low level outlets, as would be expected. All of the usual diversion schemes for concrete gravity dams are available.

Figure 8.80 Diversion sluiceway built on CVC slipformed at Jordão dam-Brazil.

Figure 8.81 Diversion sluiceway built on CVC slipformed at Salto Caxias dam-Brazil.

8.13.3.2 Galleries

There are several different approaches to building galleries in the dam mass. One method is by conventional forming and another is by placing gravel or fine aggregate in that part of the RCC lift where the required gallery will be and later mining out this material to open the gallery. The internal surface resulted from the latter allows inspection of the RCC, after all loose material is removed, but roughness from the fill material remains and some of it will adhere to the RCC. A method to overcome this is to use wood separators between the RCC and fill as each layer is placed. Another method that has been effective is to place the RCC to the top of the gallery, and then remove it with an excavator before it gains much strength. Slipformed curbs were used as gallery walls at Upper Stillwater. Precast concrete sections installed as permanent gallery linings have also been used. The design aspects of galleries are discussed in references.

Figure 8.82 Gallery cast with RCC against conventional forms.

Figure 8.83 Pre-cast concrete pieces for the shaping of the gallery.

Figure 8.84 Shaping of the gallery with granular material against wooden or metal forms.

Figure 8.85 Molding of gallery with granular material acting as a filling.

Figure 8.86 Pre-cast concrete piece for the ceilling of the gallery.

Figure 8.87 Containers with granular material for casting the gallery.

8.13.3.3 Drains

Gravel drains, porous concrete and porous drain tubes have all been used to collect seepage and relieve pressure. In some cases, these techniques can be used in lieu of a gallery. Drain holes have also been drilled from planned RCC construction joints to galleries and from galleries into the RCC. This drilling can start soon after the RCC is compacted and is usually done with percussion equipment.

Several recent dams have internal draining holes near the upstream face that exit in the gallery. These holes vary in diameter from 73mm (NX size) to 102mm and are usually drilled vertically from the surface of a lift into the gallery.

8.14 Contraction Joints

As is the case of most non-reinforced concrete structures, cracks do occur in RCC structures, and, if it is a dam or other water retention structure, leakage will also occur. Cracking may occur despite measures taken to prevent it. The possibility of unplanned cracking should be anticipated in design by providing for drainage conduits and sumps where necessary to remove water from the structure. Cracking that has occurred at various projects has not diminished the stability of these structures, but has caused some operational problems, although repairs were successfully undertaken.

One of the roles of contraction joint spacing is to mitigate the effects of foundation restraint and to control cracking in the dam. The main functions of contraction joint spacing are to control the effects of foundation and abutment restraint, to prevent relative displacements due to some relevant topography variation and to allow contraction of the concrete without cracking in the dam.

Placing vertical transverse contraction joints in dams built with RCC and installing waterstops in these joints near the upstream face should be considered for crack control. The number and placement of these formed construction joints should be determined by a thermal study, construction considerations, and by examination of the foundation profile parallel to the dam axis. Joints should be considered where changes occur in the foundation profile which may cause a concentration of stresses. In RCC dams, transverse contraction joints can be installed with no impact to RCC placement operations.

Thermal stresses can be the controlling criteria in RCC dams and they deserve proper attention. However, thermal issues sometimes receive excessive attention in design and not enough attention to options available in construction. RCC offers options that should not be overlooked just because they are not practical with CVC concrete. In addition to the obvious concern for peak internal temperature, thermal stress is related to foundation restraint, material properties and the rate of cooling.

Reducing the cementitious content in the central portion of the dam where tensile and compressive stresses are very low, will reduce the peak temperature, with no major influence on the controlling criteria of shear or sliding stability.

The amount of stress that develops due to cooling from a peak internal temperature is much greater near the foundation contact or abutment than it is at some distance away from the foundation or abutment.

One economic advantage of RCC is that formed transverse walls along the inner faces of monolithic blocks are eliminated. However, other measures to prevent temperature cracks are required. These joints are perpendicular to the dam faces and are used to prevent cracking consistent with CVC dam construction. The vertical joint at the upstream face contains waterstop embedded in the facing concrete to control seepage.

As it has been mentioned in Chapter 4 in the Japanese concept-method the spacing between transverse joints is of the order of 15 meters (as in CVC dams), extending the concrete in a continuous way and proceeding afterwards with the execution of the joint by a groove using a vibratory cutter, within which are inserted galvanized steel or PVC sheets which act as joint initiators. In other countries the spacing between joints is perceptibly larger and even in some (nowadays so few) cases their establishment is not considered. It can be done by especially developed joint-cutting machines as is done in Japanese RCD dams. These machines are very effective and have little or no detrimental effect on the rate of construction. The reduction or elimination of formwork is also an important factor for economical construction and is time saving.

Another method successfully used in dams like Urugua-i, Capanda and Brazilian ones (Jordão and Salto Caxias) employes a steel thin plate covered by a plastic sheet to form the contraction joint, as shown in Figures 8.90 to 8.92.

A further example is the placing method of joint inducers like the one which was created and used in South African dams.

If transverse contraction joints are used, standard waterstops should be installed in an internal zone of conventional concrete at the joint near the upstream face. This zone would be monolithic with a CVC facing. Waterstops and joint drains are installed in the same way as in conventional concrete dams.

Figure 8.88 Back-hoe joint cutter machine used at Sakaigawa dam-Japan.

Figure 8.89 Joint cutter machine used at Japanese and Chinese dams.

Figure 8.90 Schematic procedures for contraction joint casting.

Figure 8.91 Procedure for contraction joint casting at Jordão dam-Brazil.

Figure 8.92 Contraction joint cast at Urugua-i (Argentina) and Capanda (Angola) dams.

8.15 References

8.01 *Willow Creek Design Memorandum, Supplement to GDM 2 - Phase 2, Main Dam, Spillway, and Outlet Works.* U.S. Army Engineer District, Walla Walla, Washington, December 1981.

8.02 MOLER, W.A. and JACKSON, H.E. "How high RCC?", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

8.03 PIMENTA, Gilson Viviani; ANDRIOLO, Francisco Rodrigues. "Importância do Planejamento nas Obras em CCR", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March/1996.

8.04 PINILLA, L. "Pangue dam construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

8.05 ANDRADE, Walton Pacelli de (ed.)."Concretos- Massa, Estrutural, Projetado e Compactado com Rolo-Ensaios e Propriedades". Equipe de FURNAS - Laboratório de Concreto, 1997.

8.06 Spanish Dams 1996 - IECA & Comite Nacional Español de Grandes Presas. Spain, 1996.

8.07 "Current Activities on Large Dams in Japan", in: Japanese National Committee on Large Dams, 1997.

8.08 BRAGA, J.A.; ROSARIO, L.C.; ANDRIOLO, F.R. "Efeito da Revibração nos Concretos Massa e Rolado", in: Proceedings of the XIX Seminário Nacional de Grandes de Barragens. Aracaju, Brazil, March/1991.

8.09 HIROSHE, T.; YANAGIDA, T. "Construction of Dams with Roller Compacted Concrete in Japan", in: Symposium on Roller Compacted Concrete – ACI 207. Los Angeles, California, March 1983.

8.10 Board Meeting XVI Report- COPEL. Paraná, Brazil, November/1995.

8.11 KREMPEL, A.F.; LEVIS, P. and ANDRIOLO, F.R. "Jordão River derivation dam. Foundation conditions for placing the RCC", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

8.12 ACI - Committee 207 - "Mass Concrete for Dams and Other Massive Structures". Detroit: American Concrete Institute, 1980.

9

Inspection, Quality Control and Assurance

9.1 General Points, Philosophy and Guidelines

9.1.1 The Need for Quality Assurance

Who does not want assurance that the concrete job in which he is involved will achieve the quality necessary to give good performance and great appearance throughout its intended life? Probably, no one.

The designer wants it; his reputation and professional satisfaction depend on it.

The builder wants it for much the same reason, but sometimes there are adverse influences such as time and money problems.

The owner wants it; his money is in the project and he has to live with what he gets. Any governmental agency responsible for public welfare and caring of its reputation wants it.

✓ Why then, if all responsible parties want quality, it is not automatically achieved?

✓ What it is necessary to consider aiming to assure quality?

✓ Perhaps the answer lies in the inadvertencies, not uncommon in construction activities.

✓ Perhaps it lies in the loss of pride in craft.

✓ Perhaps it is inherent in human nature and culture. More than many centuries ago in 79 AD, Frontinius, the operations and maintenance superintendent for the famous Roman aqueduct, noted, possibly with a touch of exasperation, after describing the procedure necessary for making secure repairs, that these were things "which all the workmen know, but few observe."

✓ Perhaps, because people are no different today, we need to do something special to insure quality in concrete construction.

It is very common in manufacturing and service industries today to maintain a rigorous program of inspection and testing, reporting independently to top management and with authority to say **"No"** and reject substandard performance. It can be noted that large companies are increasingly emphasizing their efforts to better serve customers in their advertisements.

Quality control and resulting assurance is no different on concrete construction work. Basically this is inspection and the related testing of materials and concrete. It is however, more than making a few slump (CVC construction) or consistency tests (RCC construction) and cylinders for strength tests. The full scope of duties and responsibilities of the inspection and testing staff are only effective if it includes everyone interacting with them.

This means recognition by management of the worth of this wider concept, and accordingly, adoption of a policy that is in full support of it. For instance, it will require that engineers and other professionals firmly support their own specifications. Capable inspectors struggling to see that there is substantial compliance and not making concessions in disregard of specification requirements, which presumably were the basis on which bids for the work were taken, should be taken into account.

It also includes proper study and designation of available materials to make concrete with properties best suited to the purpose. But this is a separate subject of its own.

Quality assurance includes specifications which clearly spell out requirements, limits, standards, and where necessary, equipment and methods. "Performance-type" specifications for CVC or RCC work are totally unrealistic. They merely reflect a complete unawareness that they can produce inferior results despite apparently acceptable performance or appearance, unless each step, which will be covered by the next step, is inspected as the work proceeds. Few constructions can be accepted only on the basis of final performance or appearance trusting that all is as it should be. If quality is to be assured throughout, it must be definitely recognized, confirmed, and recorded with adequate consistency during the entire performance of the concrete work, so that whenever it is not as it should be, prompt and effective action can be taken for its correction.

Owner surveillance, acceptance inspection and testing are necessary, starting during aggregate production and continuing through the mixing, placing, and curing of RCC. For the surveillance to be effective, surveillance and inspection personnel must be trained before the beginning of construction. This can be done by seeking instruction from other personnel who have had experience with RCC and by the use of available training aids in the form of slides and videotapes.

9.1.2 The Need for Inspection

The purpose of inspection is to assure that the requirements and intentions of the contract documents are faithfully accomplished.

The term *inspection* as used in concrete construction includes not only visual observation and field measurements, but also laboratory testing and the assembly and evaluation of test data.

One important responsibility for the concrete inspector is the quality of the materials used in the concrete. Often low quality raw materials, particularly aggregate materials, can be used to produce concrete of satisfactory quality if they are suitably processed or prepared. However, the final materials entering the concrete mixture must be of specified quality. It is difficult and usually impossible to produce specified concrete from nonconforming materials.

On the other hand, a principal ingredient needed for specified concrete construction is good ***quality workmanship*** in all operations and processes. It has been said that most good concrete is made from tested and certified cement; sound, durable, well graded, and properly tested aggregates; suitable admixtures; and clean, pure water-and most nonconforming concrete is made from the same good materials.

Manual skills, technical knowledge, motivation, and pride of workmanship -all contribute to good workmanship which is the real key to quality concrete construction. Workers in concrete jobs may have been exposed to some technical training but seldom adequately. Many workers have pride in their work and do make an attempt to attain satisfactory quality. However, the need to stay within cost limits often requires an emphasis on production rate. If this consideration is uppermost, quality may receive inadequate attention. Ironically, cost may suffer also: unsophisticated pursuit of fast production may increase the cost and slow the schedule. Techniques that speed concrete placement may add material cost or require extra finishing or repair, or lengthen the curing process.

9.1.3 Costs of Quality Construction

Properly organized, a quality control program increases a contractor's profits by reducing the amount of money needed to correct poor workmanship or replace substandard materials.

It can be estimated that business spends as much as 15% to 20% of gross income to correct or rework products to an acceptable level of quality.

Whether it has a quality control program or not, every project has a quality cost component. Every contractor has a choice as to when he will pay that cost. He can pay the controlled cost of quality control during construction, or he can pay the uncontrolled cost of correcting defective workmanship and materials later.

The benefits far outweigh the costs of quality control. Building the job right the first time can increase a contractor's profits-and future business.

Quality builds future business. Some contractors feel that low prices generate more business than high quality. But it is a rare buyer who accepts poor quality because it was a bargain. Those that build it right the first time are more often favored with a seat at the planning table in future projects.

In broad terms, the cost of quality includes:

I. Failure prevention cost

· Running your company's program to improve workmanship and eliminate substandard materials

· Solving quality problems as they arise and adjusting the Quality Control plan for future savings

· Management audits to make sure the system functions

· Quality control measurement equipment

· Training programs for workers and supervisors

II. Appraisal cost

· These are the costs to measure the degree of conformance to quality requirements.

· Testing incoming materials, vendor inspection, the costs of test personnel, supervision and clerical support

· Cost to verify tolerances, concrete strengths, the placement of joints, inserts, blockouts, and reinforcing steel

· Any field test procedures

III. Failure or rework costs

· Costs of replacing work, materials, and rejected products
· Troubleshooting on nonconforming materials and products
· Complaint costs, including meetings and price adjustments
· Correcting surface imperfections
· Replacing unacceptable work including demolition and disposition of rejected products, trucking new materials to the site- hauling rejected materials away
· Equipment and labor costs while awaiting decisions on repairs or corrections
· Backcharges by others for tolerance problems in your work

The total cost of quality is the sum of these three costs. The potential profit for the company is the money difference between the modest cost of quality control and the substantial savings possible as defects are eliminated or reduced. Quality does create profits.

Quality is marketing strategy that builds future business. Contractors with a reputation for ***"building it right the first time"*** have an edge over those whose poor workmanship usually causes delays and problems.

9.1.4 Specification Inclusions

The task of inspection will be easier and thus more effective, and job results will be better, if the specifications include as many requirements as possible to insure accomplishment of the intended result with relatively little inspection.

This broader concept for quality construction with CVC or RCC will also include any pre-testing of materials, mixes, and concrete properties needed to insure that they will be suitable for the work.

During construction they will be regularly tested for compliance and performance, and results will be recorded. Specifications will state that sampling, testing, and evaluation of results for acceptance will be based on statistics patterns, not on a single test. Basically, this will mean that when 4 out of 5 consecutive tests for each specified property of materials or concrete meet specified values, it will be considered to comply with that requirement. The principal of 100 percent compliance is now widely discredited and recognized as not only unrealistic but also expensive. Concessions made under it, though probably reasonable in some aspects, tend to weaken firm requirement of compliance with non-material, performance aspects of the specifications.

A good specification is that which only requires things that need to be done to make the concrete suitable for its purpose. It contains no requirements that can be ignored or slighted and omits no requirements that must be met. It is not possible to write such a specification; it is only possible to try to do so.

With a "**good specification**" neither the contractor nor the inspector has any doubt as to what must be done. With such a specification, any part of the work that is not in accordance with the requirements must be changed so that it does comply. The question of whether it is **"good enough,"** even though not as good as required by the contract, will not arise.

The vast majority of concrete satisfactorily serves the purposes for which it was produced. Few examples of concrete are the best that they could have been. Most are better than they need to be and hence cost more than they needed to cost. A few do not satisfactorily serve the purposes for which they were made and receive most of the attention.

The few jobs that do not satisfactorily serve their purposes do so, in nearly every case, for several reasons rather than a single reason. Some of these reasons are:

(a) Failure of the owner to understand what he needed;

(b) Failure of the engineer to understand the owner's needs and to translate these needs into proper quality levels of relevant properties and into correct specification requirements for the work;

(c) Failure of all concerned with establishment of specifications to include only what was needed and exclude what was not needed;

(d) Failure to require uniform compliance by the contractor with all requirements of the contract;

(e) Failure by the contractor to comply with all requirements of the contract.

9.1.5 Desired Performance

Quality Control (QC) and Quality Assurance (QA) can maximize the probability of obtaining the level of performance that will result if the construction meets the specified requirements. There are an infinite number of quality levels that can be set. Sometimes the levels are set too low and the product, even if it meets the established requirements, fails to give satisfactory service. Often the levels are set too high, and the work is made more costly than necessary. Procedures using such tools as electronic data processing should associate all the relevant properties that a structure must have to give the desired service -in the environment in which it is to serve- to the properties of available materials and combinations of materials, construction systems, methods, practices, and schedules. An infinite number of alternatives are then considered, and the single, most economical, satisfactory solution selected. Thus the proper levels of quality will be established, which, if met, will insure construction that will give the desired service at a lowest cost.

Everybody wants concrete with levels of relevant properties it should have to serve its purpose, but no one wants to pay extra for higher property levels that are not necessary. Therefore, the best concrete for any given purpose is the one that does the job adequately at the lowest cost, considering both maintenance and repair. A concrete job that costs more than it should is a poor job, regardless of being structurally stronger or having a better appearance.

Individuals and organizations involved with inspection must recognize that needs and requirements will vary and must be tailored to each individual project. The actual level of inspection used depends on the type and complexity of the project, special features involved, specific legal requirements, and the purpose of the inspection program. These may demand more or less detailed inspection requirements.

Inspection is not an end in itself. It is simply a subsystem of the quality assurance system and of a contractor or producer's quality control system. Inspection and testing by themselves do not add quality to the product or process being inspected. Inspection and testing only confirm whether the product or process meets the criteria established. The information derived from the inspection and testing process, however, when properly evaluated and with conclusions and decisions implemented, will result in improvement of the quality of the product or process. It also must be recognized that quality is achieved only by implementation of an adequate quality assurance program from planning through design and construction to acceptance by the owner.

Quality during the construction phase is achieved almost entirely by the contractor or producer's quality control program. This quality control program involves everyone from management to field supervisors to the workmen themselves. Quality control must have the strong active support of top management, and the active concern and participation of everyone involved in the construction process. Again, inspection and testing are only a part, although a very important part, of both quality assurance and quality control programs.

Different standards and criteria are applicable to different constructions as these constructions have different purposes. The fitness of concrete to do a job is similar to the fitness of a person to do a job. For some purposes a concrete-or a person- needs a much greater degree of any of many capabilities than is needed for other purposes. Such capabilities include the ability to carry load without undue strain or cracking, the ability to endure adverse environmental conditions, physical attractiveness, or the ability to remain relatively unchanged in dimensions with changes in ambient temperature or moisture conditions.

How should proper levels of quality be established? To be specific, how should appropriate levels of quality be established to insure that the concrete to be used in a particular part of a particular structure will give satisfactory performance by adequately resisting the deteriorative forces of its environment of service?

(a) We should do concrete work as well as needed;

(b) We should do concrete work the best we know how;

(c) We should provide the best concrete work we can afford;

(d) If we deliberately do less than the best, we should know why we did it and what to expect as a result;

(e) We should not waste money doing better work than is justified.

9.1.6 Traditional Quality Assurance

Many specifications for concrete used in the past (and still being used) are recipes or prescription-type specifications rather than end-product specifications. Some also spell out in detail the operations of the contractor and the equipment to be used in the production of concrete. Such specifications were developed because adequate quality definitions and test methods, and their evaluation, related to the quality of the end product were lacking. Attempts to define required end-product quality and the values used were usually based on experience and judgment rather than any rational concept. These specifications, combined with the skills of experienced designers and the cooperation of experienced contractors with skilled workers, have produced good concrete structures. However, sometimes the resulting structures have been of less than desired quality.

Under the above procedure, usually a random, supposedly representative, sample is taken. This sample is tested and the result compared with the specified value of the particular characteristic. If the test result is within the specified tolerances, the material passes and is accepted. If not, the material *fails* to pass. Engineering judgment must then be applied and a decision made as to whether the material may be said to *substantially comply*, and thus be accepted, or whether the material truly fails and must be rejected, or whether the material should be re-tested. *Substantial compliance* is not defined, and thus can vary from person to person and job to job, creating confusion and disputes. Actual research has shown that as much as 30 percent of some construction controlled by traditional methods has been outside the stated limits when closely examined by statistical methods using random sampling, even though it was considered completely acceptable under the control practices used.

When a failing test is encountered, re-testing, without upgrading the material being tested, is not an appropriate action (unless the original test has been improperly performed, in which case the entire test should be voided). Even if the results of the two tests (original test and retest) are averaged, there is a built-in bias because the second test is taken only if the first test fails, not if it passes.

9.1.7 Turnkey Type Operation

In the case of the turnkey type of construction, the design and construction are done within the same organization, which usually has an engineering group and a construction group. The engineering group is usually charged with inspection for acceptance and the construction group operates as the contractor in a conventional construction operation.

The contractor is responsible for the management, control, and documentation of activities that are necessary for compliance with all contract requirements. The Owner Quality Assurance (OQA) program is responsible for establishing performance periods and quality control requirements and for ensuring that the Contractor Quality Control (CQC) program is functioning as required.

For RCC production, several areas of the CQC program are important. The first is to maintain a well-managed and trained CQC staff. This is partly affected by the geographical market area from which quality CQC personnel can be drawn. In many areas qualified personnel with experience and training are not available.

Another concern is that CQC organizations often do not respond to or modify, in a timely manner, operations that prove to be in disagreement with specifications. Certain activities such as making aggregate moisture or grading adjustments must be addressed immediately to prevent permanent deficiencies. A project program should emphasize monitoring and correcting those features that must be responded to immediately. There are also parts of the specifications that the contractor might not view to be as significant as the government does. As an example, a contractor may try to make the case that an aggregate grading that is slightly out of specification will not alter the product quality and surely does not warrant stopping RCC production. For such issues, it is best to develop a clear understanding at a high level (government resident engineer and contractor project engineer) of what appropriate actions should be taken to prevent problems from occurring and when they do occur, how to prevent a similar event in the future. In the example given, it is possible that most of the aggregate has already been produced and there is no practical way to bring the aggregate back into grading. It may be more prudent to analyze the consequences of using the aggregate as is, or adjusting the mixture proportions to a new grading curve. Quality-control problems associated with specific monitoring or testing can be well defined and are, therefore, usually easier to control.

9.1.8 Credibility

When the personnel is employed by the owner or engineer their efforts to achieve quality construction are never questioned. Unfortunately, there is a trend in some agencies, supported by some engineers, to place these activities in the hands of the contractor. This is the case of turnkey projects. It may be suggested that the credibility of such inspection can be affected by a conflict of interest.

Such doubts could be largely reduced or eliminated altogether if the owner or engineer had at least one qualified person working with the contractor's inspection forces. This person could not only make confirmatory observations but make confirmatory random tests as well, to insure that the record being produced by the contractor was accurate. On turnkey work where the owner has no staff on the job, the contractor can establish the credibility of his testing and inspection records only by convincing evidence that his quality forces are entirely free agents, responsible only to his top management. As one advertisement said about its quality managers:

· Their job is to help make sure that you get what you pay for.
· Their only allegiance is to quality.
· If they say ***"no"*** due to nonconformance, then ***"no"*** it is. And no one reverses their decision.

Careful inspection should be enforced in all of the operations relating to:

· the selection of the materials;
· the design of the mixtures;
· mixing, transporting, placing, consolidating, and finishing;
· protection and curing.

9.1.9 Statistical Concepts In Quality Assurance

The science of statistics is a versatile tool. Its use permits decisions to be made with an established degree of confidence.

Contract documents can be written using statistical concepts to express quality requirements as target values for contractors, and to express compliance requirements as plus or minus tolerances. Tolerances for the target value, prescribed by design needs, can be based on statistical analyses of the variations in materials, processes, sampling, and testing existing in traditional construction practices. Tolerances derived in this manner can be both realistic and enforceable. They take into account all the normal causes of variation and allow for the expected distribution of test results around the average. Provisions can be made both for control to the stated level and for control of the variation from this level.

In addition to indicating the acceptable and non-acceptable material in construction, it is also common in highway construction to use statistical methods to indicate "gray area" whenever the test results show that the material is not completely in compliance with the requirements but can be accepted if and when permitted by the contract documents.

Contract documents based on statistical concepts are widely used and becoming more common. Public agencies, particularly the various state highway departments have emphasized their use basically because statistical concepts are particularly appropriate, and valuable, for use on projects involving high rates of production and large volumes of concrete or other materials, such as highway paving projects, large dams, and airfield paving. Use of statistical concepts has proved not only feasible but also very effective and efficient where properly applied.

Statistical procedures for quality assurance are based on the laws of probability; consequently, these laws must be allowed to function. One of the *most important* requirements for proper functioning is that the data be selected by *random* sampling. A true random sample is one for which all parts of the whole have an equal chance of being chosen for the sample. Without true random samples, statistical procedures give false results.

Random selection is obtained only by positive action; it is not merely a haphazard selection, nor one declared to be without bias. Selection by the proper use of a standard table of random numbers is acceptable. It is possible and feasible to adapt the use of random numbers to the laboratory, to the field, and to the factory. Mechanical randomizing devices (dice, spinning wheel, etc.) are sometimes used, but no device is acceptable as random in the absence of passing certain statistical tests.

The difficulties in attaining randomness are greater than generally known. A discussion of the preparation of sampling plans is presented in ASTM E 105 [9.01].

9.1.10 Records

Assurance of quality in construction is not a reality without records that give that assurance. These records must be systematically and presentably kept. They must be accurate, consistent, and believable. But they need not be excessive in coverage and should not be redundant.

If faithfully kept records show compliance with specification requirements and the general appearance of the concrete work is good, there should be no question of acceptance of the work regardless of its size, complexity, or importance, or for what owner or agency it is built. It is emphasized that further records of other tests or observations are not necessary and they will not improve the assurance that can be taken from the fully adequate record herein advocated. In fact, any further testing and inspection, such as recording all batch weights, slump tests on most truck loads, or routine sampling at the end of pump lines, is likely to detract from the quality of the work through its many interruptions, and certainly will increase its cost unnecessarily.

Written records and reports of inspections and tests are required by contract documents, codes, and regulatory agencies. The contract documents should consider the needs of the project and regulatory requirements when defining the specific reports and records that must be developed. Many reports must be maintained for the life of the project and therefore should be legible, complete, and reliable. They provide a record of as-built conditions, including verification of construction performed in accordance with the contract documents, and include any noncompliance and corrective action taken. Many times, they are used to settle disputes and as a basis for future modifications to the structure. When public safety is involved, particular attention must be applied to include all of the attributes required to satisfy code and jurisdictional authority requirements.

The records and reports mentioned in this Chapter are illustrative of those that could be used when required by project conditions or contract documents. Obviously, the detailed needs for inspection (and, therefore, the records and reports to verify it) are affected by many factors. Some of these factors, but by no means all, are the legal requirements of the jurisdiction in the project's local, contract requirements, size of project, location of project, criticality of the concrete being placed, amount of concrete being placed, etc. Just as in preparing contract documents to fit the needs of each particular project, so the inspection requirements are determined for each project, and the records and reports required for verification.

9.2 Quality Plan

An overall Quality Plan or System for a construction can describe in general terms the Quality Control System used for the a project with emphasis on:

· The quality objectives to be attained;
· The specific allocation of responsibilities and authority during the different phases of the project;
· The specific procedures, methods and work instructions to be applied;
· Suitable testing, inspection and examination at appropriate stages;
· A method for changes and modifications in a quality plan as the project proceeds;
· Other measures necessary to meet objectives.

The main objective of each quality plan is to give the project manager the overall tool assuring that the work in the different phases is executed in a controlled manner. Personnel performing activities affecting quality must be appropriately trained and records will be kept of executed training. Records of training and a list of persons authorized to perform certain tasks must be kept and maintained by the respective members of the team.

Procedures need to be established, maintained and documented in order to perform, verify and report that the service meets the specified requirements. The reliability, availability and maintainability of the operation need to be monitored and reported.

The Quality Control System tries to increase the quality and productivity of the works and reduce costs. It must be designed to prevent and eliminate or reduce mistakes during the construction works, and provide repairs, if and when mistakes occur. The design of a structure should be accomplished considering what measures will be required to insure that the required quality is achieved. It is obvious that the design of projects where little quality control is anticipated should be more conservative than the design of a project where a very effective quality control program is anticipated. For most projects the quality control requirements are specified in the contract documents, or by separate agreement with a quality control organization. The preparation of those documents should be coordinated with project designers so that the design requirements are suitable.

While quality control is usually considered to be an activity performed during RCC placement, it is also important that quality control issues be considered during design, planning, and the initial phases of construction of an RCC project.

A viable Quality Control System should consider the numerous construction operations basic not only to RCC but also to the CVC, and how they are performed. Preparation and advance planning are the key to success and quality construction. Pre-construction meetings, pre-construction testing, and pre-construction evaluations such as test sections are critical parts of the quality program. Once the concrete (RCC and CVC) placement is underway, the more traditional concepts of quality control become evident, but advance planning and preparation continue to be important.

Evaluation and acceptance procedures that quickly deal with inevitable quality variations during construction are also critical to quality control.

Before any purchasing deal is closed, offers must undergo a technical and commercial analysis to ensure that specifications are fulfilled. Whenever necessary, a quality certificate can be requested from the supplier. Acceptance inspection can be made by a trained and specialized team using specific procedures for each kind of material or product. This inspection can take place either at the supplier, before shipment, or at the job site, depending on the situation. The Overall Quality Plan must be adjusted to the local conditions taking in count the workman labor performance, equipment and technical knowledge.

The control can be based on the following main items:

· A qualified team;
· Adequate and modern technology;
· Adequate equipment and facilities;
· Elimination of mistakes and defects;
· Monitoring of the process;
· Standardizing

The objective of Quality Control is to ensure that the characteristics of received or produced materials and equipment are preserved. Adequate care and methods will be employed in the handling of materials and equipment. Whenever necessary, specific arrangements will be made for the handling of sensitive equipment.

All data and information relative to the Quality Control System must be collected in a standardized routine and accurate manner, to give evidence of the required quality for materials and equipment. Records will include the following features:

· Quality assurance as used herein refers to all functions involved in obtaining quality materials to provide satisfactory services;

· Periodical reports based on statistical analyses must be made for all items in the project;

· Before concrete production starts, all materials will be analyzed according to their properties and only those in conformity with the standards will be chosen.

RCC placing rates can be extremely high when compared to conventional concrete. Placing rates in excess of $400m^3/hr$ have been achieved on some large projects (see Chapter 8). Small structures have been constructed in only a few days or weeks. With such rapid placement rates or short-term construction periods, problems must be evaluated and solutions implemented in a short period of time. Any problem that delays RCC placing essentially delays the whole production. Good communication among the owner, engineer, inspection personnel, and contractor personnel is essential. The most common placement delays are usually due to problems caused by:

1. Insufficient materials
2. Foundation preparation and cleanup
3. Joint cleanup
4. Equipment breakdown
5. Weather condition (hot or cold ; wet or dry; rain)

After the selection of the materials (cement, pozzolanic materials, aggregates, water and admixtures) available for use according to the standards and specifications, concrete mixes must be designed by the laboratory, in compliance with an adopted **"Recommended Practice"** or Standard. Materials inspected for acceptance before being shipped to the job site can have their status checked for damage during shipment and storage.

It must be assured that all personnel are correctly selected, trained, qualified and motivated so that the results anticipated by the company will be attained and even surpassed. A key element in resolving potential problems in advance is to assure that all participants understand the project requirements, and that necessary procedures are clearly understood. Basic issues that must be considered in advance are:

✓ **Staffing** - Sufficient laboratory and inspection personnel should be trained and available for the anticipated production operations. Shift overlaps and transitions require advance planning. All staff members must know what is acceptable and unacceptable, and they must consistently apply acceptability criteria. Whenever necessary, the work will keep proof on file showing that executive and quality personnel are qualified and/or certified by an agency of recognized competence.

✓ **Facilities and equipment** - Appropriate testing facilities and equipment for the size and volume of tests that may become necessary must be available in advance of RCC related work. Technicians should be trained in the proper use of the equipment and in the proper implementation of the test methods.

✓ **Communications** - The project staff should meet with the contractor to review and discuss requirements and procedures for RCC material production, placement, testing, inspection, and job site safety. Adequate radio communication at the job site among key personnel of the contractor, inspection/quality control organization, and field design personnel has been responsible for avoiding work stoppages and unnecessary removal of questionable material.

Based on what was described above, it can be suggested that before the works start a "Quality Control Plan" and a "Manual for Quality Control" should be adopted. This "Manual" proposes measures which include the following basic points:

- Be aware of possible problems;
- Anticipate possible corrections;
- Guarantee quality;
- Seek modifications and improvements;
- Be objective, dynamic and compatible with the pace of construction;
- Controls must include materials and concretes (RCC and CVC);

For an overall view of the scheme that can be adopted Figure 9.01 shows a flow chart of actions with the following points:

Action A - Pre-qualification and knowledge -This corresponds to the stage of initial studies, knowledge and selection of materials and suppliers.

Action B– Information on handling.

ActionC - Control of arrival (delivered) of material - This action seeks to guarantee quality and uniformity of the material and products, based on pre-qualification data. These tests are proven by certificates, and will be performed by each supplier.

Action D - Control during production - This action is to evaluate the points or procedures that could be vulnerable during production.

Action E - Control of application- This point consists of disciplinary actions during production.

Action F - Inspection during execution- This action will have the function of evaluating the best procedures for executing the works.

Action G - Structure commissioning- This will have the function of formal commissioning of each stage of structures or services.

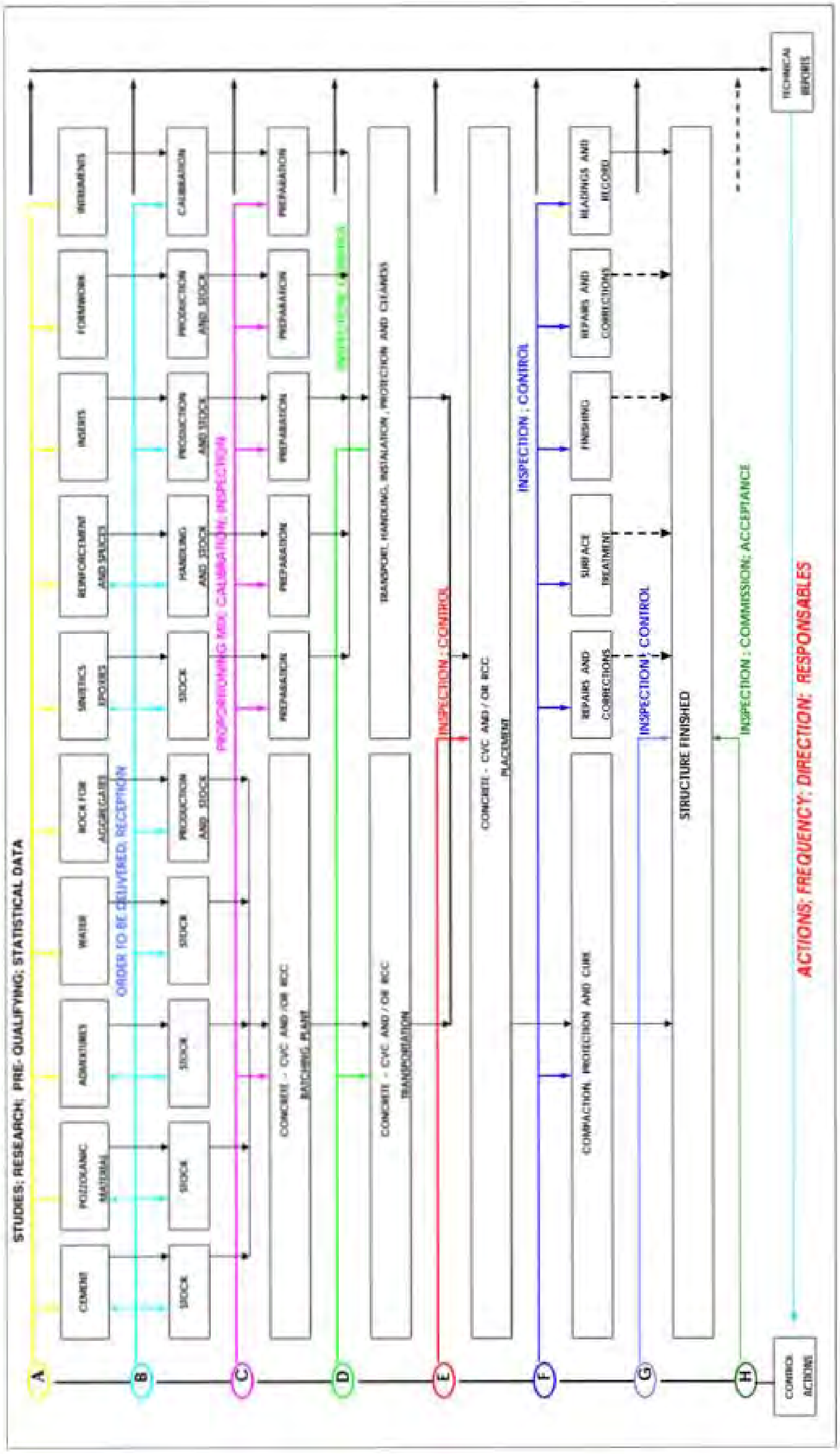


Figure 9.01 Quality Control Actions.

MATERIAL OR SYSTEM	SAMPLE POINT	STANDARD REFFERED	TYPE OR INTENTION	FREQUENCY	LABORATORY	TESTS OR EVALUATION
REINFORCING STEEL	STOCKS	ABNT-NBR-7480	RECEPTION	EACH TRUCK (30t)	JOB SITE	WEIGHT LINEAR; YELD STRENGTH RUPTURE STRENGTH; ELONGATION AT RUPTURE; BENDING
REINFORCING SPLICES	STRUCTURES	ABNT-NBR-7480	CONTROL	2 % FROM TOTAL SPLICES	JOB SITE	RUPTURE STRENGTH
WATER	BATCH PLANT	LCAP - 1 - 10	CONTROL	WEEKLY	JOB SITE	SOLIDS, pH, O2, SO4, Cl
ADMIXTURES	BATCH PLANT	LCAP - 2 - 1	CONTROL	ONE / 1000Kg	JOB SITE	SOLIDS, pH, SPECIFIC GRAVITY
WATER STOPS	SUPLIER	LCAP - 5 - 1	DELIVERY	ONE / 200m	ITAIPU BINACIONAL BRAZIL-PARAGUAY	ALCALIES, HARDNESS,RUPTURE STRENGTH ELONGATION AT RUPTURE
CEMENT	SUPLIER	BS - 4550	DELIVERY	ONE / 2 HOURS OR ONE / 100t	CEMENT FACTORY	FREE LIME; SPECIFIC SURFACE BLAINE TIME OF SETTING; LOSS ON IGNITION
			CONTROL	ONE / DAILY/ ONE / 500t	CEMENT FACTORY	SiO2; Fe2O3; Al2O3; SO3; CaO;MgO; FREE LIME LOSS ON IGNITION; ISOLUBLE RESIDUE SETTING TIME; RESIDUE ON #200 AND #300 SPECIFIC GRAVITY; AUTOCLAVE EXPANSION "LE CHATELIER" EXPANSION COMPRESSIVE STRENGTH
	CONTAINERS	ABNT - NBR - 5781	RECEPTION	ONE / 100t	JOB SITE	
	BATCH PLANT		CONTROL	ONE / WEEKLY	JOB SITE	
			INTER-LABORATORY	ONE / 5000t	OFFICIAL LABORATORY AND ITAIPU	
AGGREGATES	CRUSHER SYSTEM	LCAP - 10 - 2	PRODUCTION	ONE / WEEKLY	JOB SITE	GRAIN SIZE; APPARENT AND ABSOLUTE DENSITIES ABSORPTION; FLATNESS
	BATCH PLANT	ABNT - NBR - 7218	CONTROL	ONE / SHIFT	BATCH PLANT	HUMIDITY; MIXES ADJUSTMENTS
				ONE / SHIFT	JOB SITE	GRAIN SIZE; APPARENT AND ABSOLUTE DENSITIES ABSORPTION; FLATNESS
CONCRETES	BATCH PLANT	LCAP - 4 - 1	CONTROL	ONE / 200m2	JOB SITE	SLUMP; AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH
CVC				ONE / 2000m3	JOB SITE	SLUMP; AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH; MODULUS; TENSILE SPLITTING
RCC	BATCH PLANT	LCAP - 7 - 1	CONTROL	ONE / SHIFT	BATCH PLANT	GRAIN SIZE;CEMENT CONTENT;CONSISTENCY (VeBe) COMPRESSIVE STRENGTH; SPECIFIC GRAVITY
	DAM	LCAP - 10 - 3	CONTROL	ONE / 100m3	DAM SITE	SPECIFUC GRAVITY; COMPACTION RATIO; HUMIDITY
DRILLED CORES	DAM	LCAP - 11 - 5	CONTROL	ONE / 10000m3	JOB SITE	SPECIFIC GRAVITY; MODULUS ; PERMEABILITY COMPRESSIVE STRTENGTH
CRUSHER PLANT		LCAP - 10 - 1	INSPECTION	DAILY	SYSTEM	CHECK LIST
BATCH PLANT		LCAP - 10 - 7	INSPECTION	DAILY	SYSTEM	CHECK LIST

Figure 9.02 Test plan and frequency adopted for the Capanda Dam- Angola [9.02].

In addition to inspection activities, a comprehensive RCC quality control program should monitor the aggregate properties, RCC mixture proportions, fresh concrete properties, hardened concrete properties, and in-place compaction. An example of possible tests and test frequencies are given in Figure 9.02, that was successfully adopted during Capanda RCC Dam construction in Angola [9.02]. The frequency and extent of testing should be adjusted according to the size of the project, the sensitivity of the design to variations in quality, and the rate of RCC production.

Quality control of the material and concrete used for the Capanda project, was the Constructor's responsibility. To perform these activities, a "Quality Control Plan" was devised, in order to comply with design and specifications requirements. Logistic conditions for construction of the development were also considered such as, purchase of basic materials, distance from site to production centers, quantity and quality of labor available, schedules, and assurance of quality parameters compatible with the magnitude of the works. Figure 9.02 shows, in schematic form, the Quality Control Plan established.

The "goal" of quality control is to identify problems before they occur or sufficiently early in the process so they can be corrected. Monitoring and reacting to the trend in performance is preferable to reacting to specific test results. The trend, identified by a series of tests, is more important than data provided by a single test. By continuously tracking trends it is possible to identify detrimental changes in material performance and initiate corrective actions. Further, it is possible to modify the frequency of testing based on trend performance. For example, it is common to specify a high testing frequency during the beginning of aggregate production and to later reduce the testing frequency as production stabilizes and the trend in grading stabilizes.

Tests must be performed rapidly. The rapid placing rates and typical 20 or 24 hour per day construction timetables require careful attention and interaction between Quality Control testing, inspection personnel, and production personnel. If Quality Control System activities cause significant delays to any stage of RCC production such as mixing, placing, compacting, or foundation cleanup, all construction may be affected and possibly stopped.

Fresh RCC properties may vary with daily, weekly, or monthly fluctuations in ambient weather conditions. This, in turn, affects water requirements, compaction characteristics during construction, and the quality of the concrete. Normally, construction activities continue throughout a variety of warm, cold, wet or dry ambient conditions. Quality Control System personnel should assure that continuous adjustments in moisture and, if appropriate, other mixture proportions are made to adapt to these conditions. All personnel must communicate between shifts about these adjustments in order to achieve continuity of the product.

Even more than in CVC, the use of compressive strengths test on concrete specimens as a method of control in RCC construction has a major disadvantage in the time required obtaining results. Because of the rapid rate of placement in RCC construction, and the fact that layers of material can be covered with new lifts within hours, test cylinders serve as record data for quality assurance and are not an effective method of day-to-day quality control.

Emphasis on thorough control of materials (gradation, cementitious content, and moisture content) and conditions during placement is essential to proper RCC. If the aggregates are as specified with regard to source and quality, the cementitious materials are pre-tested from pre-qualified sources, the technique and timing of mixing, spreading, and compacting are within the designated guidelines, and an appropriate method of curing is followed, the end product will be acceptable.

An advantage of RCC and the above approach is that unacceptable material is identified early and can be removed at relatively low cost. For example, a zone of low-density material can be identified by nuclear density gauge testing within a short time of placing and then can be re-compacted or removed prior to achieving final strength.

It is important that qualified personnel be in close contact with the mixing plant at all times to maintain water contents at the optimum level for compaction. The control measures that should be instituted in RCC construction are essentially material dependent. If the mixture was designed for strength and consistency requirements, measurements of consistency should be performed to maintain consistency within the desired range and to expand the judgment based on observations of the inspector and placing foreman. Adjustments in batch water can be made prior to placement when consistencies approach control limits.

9.3 Training and Communication

Quality is best assured when the inspection and testing force is well trained and skillfully supervised. This includes seeing that the inspectors know at least what they need to know and that they have the correct attitude of firm but pleasantly detached authority, although endeavoring to be helpful wherever they properly can. For these important reasons of supervision and training, it is usually better to include these functions in the owner's or engineer's organization than to assign this great responsibility to an outside organization over which supervision and control is difficult at best. This condition is more important in RCC than in CVC construction due to the rapid rate of concrete placed. The cost of quality concrete work will be least when all concerned really want it and work harmoniously together to see that they get it.

An important early move in this direction is to hold pre-bid and pre-construction meetings attended by responsible representatives of the owner and builder, engineer, inspection and testing people, and materials suppliers. Thus mutual understanding of specifications and potential problems is promoted, and acquaintance and communication is established. Such meetings can also be helpful during construction.

As part of the quality assurance and control program, orientation and training sessions should be held for supervisors, inspectors, and workmen. The differences in technique between CVC and RCC as well as granular embankments should be discussed and understood by all. Key issues should be explained, such as time limitations for mixing, spreading, and compacting, and concerns about segregation, joint integrity, and curing. It should be emphasized that although RCC looks and behaves like granular fill in its early stage, it is concrete and should be treated as carefully as conventionally placed concrete. This includes cure, protection, and care of compacted concrete surfaces.

During construction of an RCC structure, both the designer and inspection personnel should be aware that, as with other construction methods, undesirable material will be placed occasionally. Field personnel should not overreact to isolated cases of placement of "rejectable" material that does not jeopardize the overall function of the structure and where remedial action would create a worse condition than leaving the material in place. Critical operations should be identified and given more attention during construction and inspection to prevent placement of marginal material.

The tendency is to treat lift surfaces as compacted embankment rather than as fresh concrete.

It is very important to take in account that in RCC construction, due to its speed, the construction planning and the quality control system must be considered in advance, and very welladjusted.

9.4 Materials

What inspection and testing then is necessary to provide the quality desired?

This may be divided into material-acceptance testing, concrete production inspection and testing, and inspection of concrete placement and other aspects of construction. Together with these go sufficient record keeping showing what was done and what was obtained. The extent to which each is carried out may vary somewhat in accordance with the size and importance of the job, but always bearing in mind that each is an element in getting quality, regardless of size of job.

Concrete materials other than aggregates can be accepted on certification of the producer but it should be required that these certifications be accompanied by a copy of his test results showing that the cement, pozzolanic materials, or admixture does in fact meet specification requirements. Random samples of delivered materials can be taken, possibly at one month intervals more or less as experience may indicate advisable, and tested for conformance with certification tests.

All RCC materials should meet the project specification requirements prior to placing. The test frequency (Figure 9.02) should be established based on the size of the structure, the rate of RCC production, and the degree to which it is necessary in the design requirements. For small structures, certain materials may be accepted based on the supplier certification. Larger structures may require testing at the point of manufacture in order to keep up with the high output necessary to maintain production.

9.4.1 Cement and Pozzolanic Material

Cement and pozzolanic material (if used) should conform to the adopted standard quality requirements. Cement can be accepted on manufacture certification, or the suppliers may be required to be "pre-qualified" (see **Action A** - Figure 9.01). Tests may also be performed on grab samples during construction of large projects under their quality assurance program. Non-prequalified sources should be tested before construction begins, and subjected to check tests during construction.

On the Capanda Development the only brand of cement used was Cimangola, Ordinary Portland type, supplied in bulk. According to the supply contract, the manufacturer himself was responsible for quality control and for the dispatch of his product. To this end, the procedure established was that the samples were delivered every 2 hours or 100ton produced, to determine Free Lime, Blaine Fineness, Setting Time and Loss on Ignition. Supplementary "Factory Control" samples were taken daily every 500ton, for complete physical-chemical tests. Manufacturer's tests were made to British Standard BS 4550. On site, the Quality Control Plan established that Control and Reception samples be taken. Reception (on arrival) samples were taken from each batch received on site, at the rate of 1 sample for every 100ton or fraction thereof. Control samples were taken weekly from each concrete batch plant, characterizing the cement immediately on application to concretes. Eventually, a sampling at every 5,000ton was also established for inter-laboratory testing, allowing checking of the procedures used by the Laboratories involved. Figure 9.03 shows all data obtained through control made (with samples taken at the concrete batch plants) as well as the requirements as specified, based on methods of ABNT-NBR 7215 (Brazilian Method of Test).

9.4.2 Admixtures

Admixtures (if used) should conform to the adopted standard quality requirements. Admixtures can be accepted on manufactures certification, or the suppliers may be required to be "pre-qualified", also (see **Action A** - (9-01). Admixtures can be added with equipment and procedures similar to those used for CVC concrete in both batch and continuous mix plants. This typically involves introducing the admixtures with the water, and often requires that the admixture dosage be interlocked with the RCC production rate to assure the proper dosage.

REQUIREMENT	UNITY	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
% RETAINED ON # 200	%	371	5,7	23,9	
% RETAINED ON # 325	%	318	20,6	21,9	*< 30*
SPECIFIC SURFACE BLAINE	cm^2/g	392	3430	12,5	*> 3200*
APPARENT SPECIFIC GRAVITY	g/cm^3	187	1,1	2,7	
ABSOLUT SPECIFIC GRAVITY	g/cm^3	349	3,12	0,6	
TIME OF SETTING - INITIAL	h : min	600	02:07	23,2	*> 1,0 h*
- FINAL	h : min	567	03:23	22,3	
LE CHATELIER - EXPANSION	mm	252	1	18	*< 5,0*
AUTOCLAVE - EXPANSION	%	167	0,5	258	*< 0,8*
COMPRESSIVE 3 DAYS	kgf/cm^2	154	177	23,6	*> 100*
STRENGTH 7 DAYS	kgf/cm^2	155	267	18,1	*> 200*
(AGE) 28 DAYS	kgf/cm^2	193	349	14,5	*> 320*
HEAT OF 7 DAYS	cal / g	23	78,1	7,7	
HYDRATION (AGE) 28 DAYS	cal / g	23	88,3	5,9	
LOSS ON IGNITION	%	212	1,13	32,7	
INSOLUBLE RESIDUE	%	214	0,53	39,6	
SiO2	%	214	20,5	3,4	
Fe2O3	%	202	3,58	13,3	
Al2O3	%	202	6,31	10,8	
CaO	%	214	64,3	1,4	
MgO	%	214	0,89	38,2	*< 3,5*
SO3	%	600	1,99	19,6	*< 3,0*
FREE LIME	%	601	1,51	39,7	*< 2,0*
C3S	%	202	44,9	14,2	
C2S	%	202	24,2	22,6	
C3A	%	202	8,96	19,6	*< 9,0*
C4AF	%	202	11,5	11,3	

Figure 9.03 Tests carried out on Cimangola Cement (Samples from Concrete Plants).

9.4.2 Aggregates

Aggregates should be sampled at the time concrete is sampled but only moisture content and cleanness and grading tests should be made on each of these samples, depending on whether these properties have been marginal. Tests of other aggregate properties should be made in other intervals for the record to show that they are unchanged from those approved for the work. If it is thought that there has been change or significant encroachment on specification limits, additional such tests should be made as a basis for any needed action and for the record to show what was done.

The quality and grading of aggregates significantly affects the fresh and hardened properties of RCC. The grading of both fine and coarse aggregates affect workability, and the ability to effectively compact or consolidate RCC. In addition to standard gradation analyses, high fine mixtures also require testing for **Atterberg** Limits of liquid and plastic index. The aggregate source, whether a new on-site source or a commercial off-site source, should be inspected and approved in advance (see **Action A** - Figure 9-01).

Moisture content and grading tests are performed during initial processing and stockpiling of aggregates. These tests should be performed at **least once per shift** during production (See Figure 9-02).

Producing sufficient aggregates at a stable moisture condition is important to accommodate high RCC production rates. Varying moisture in stockpiles will result in varying the workability of RCC. An increase or decrease in moisture of only a few tenths of one per cent can change the compacting characteristics of RCC. This is mostly affected if large amount of fines is used. Overly wet stockpiles limit the available water, which may be batched as ice if (not usual) cooling is required.

The high production rates achievable with RCC may require that a large reserve of aggregate be on hand prior to initiating placing. This is also advantageous from the standpoint of grading control and allows systematic and gradual plant adjustments to be made without drastically disrupting production. The stockpiles also permit easier maintenance of uniform moisture and temperature distribution in the aggregate, which in turn provides control of the mixture. This is particularly true if reclaim tunnels are used. If the material is withdrawn from the exterior stockpile surfaces, more attention may be needed to control variability in the gradation

DENOMINATION	AGGREGATE SIZE (mm)	USED FOR RCC	CONCRETE TYPE CVC-CONVETIONAL
CRUSHED SAND	5 -- 0	YES	YES
COARSE 1	19 -- 5	YES	YES
COARSE 2	38 -- 19	YES	YES
COARSE 3	76 -- 38	YES	YES
AGGREGATE G1	19 -- 0	YES	NO
AGGREGATE G2	64 -- 19	YES	NO

Figure 9.04 Granulometric ranges for aggregates production.

If out-of-specification material is produced, corrections should be initiated as soon as the cause is identified and materials that cannot be recovered by reworking or blending should be wasted.

The moisture content of aggregate stockpiles for aggregates having greater than 1-% absorption should be maintained at the highest practical level. Unsaturated aggregates may increase RCC porosity by absorbing water from minimum paste mixtures.

At Capanda dam [9.02] aggregates control was established using two types of samples **Production** and **Control**:

Production samples were taken weekly at the aggregates belt conveyor, between crushers and stockpiles. These samples allowed for routine checks of the crusher system classification and conditions also providing information also on control and balancing of stocked materials. During initial production phase, these samples were taken at daily and sometimes hourly intervals until the system was quality and quantity adjusted.

Control samples were taken weekly at each of the concrete batch plants allowing characterization of the aggregates on their immediate application to concrete. Granulometric ranges considered in the production of aggregates for conventional and RCC concretes are shown in Figure 9.03, where it is noted that the RCC was produced from the various granulometric ranges available. This was because RCC was produced both at conventional concrete plants (Batch) and also in continuous mixing plants (Pug Mill).

The combined aggregate "G1" (0-19mm) was obtained by combining crushed sand with Coarse 1, at the crusher system. In the same way, the combined aggregate "G2" (19-64mm) was obtained from the combination of Coarse 2 and 3, with a small reduction in size of Coarse 3. This reduction, although requiring more crushing effort, had the purpose of improving performance of the RCC Pug Mill-Continuous mixing Plant, ensuring less segregation both of the "G2" and of the RCC itself. Because the sand content of "G1" was insufficient for completion of RCC total grain size, an additional amount of crushed sand was supplied directly from the re-crushers for fillers, conveniently located within the system. Data obtained on aggregate control are presented in Figure 9.05.

PROPERTY	UNITY	CRUSHED	AGGREGATE				
		SAND	G1-(19-0)mm	G2-(64-19)mm	B1-(19-4,8)mm	B2-(38-19)mm	B3-(76-38)mm
APPARENT SPECIFIC GRAVITY	g/cm³	1,59	1,61	1,6	1,42	1,43	1,41
ABSOLUT SPECIFIC GRAVITY	g/cm³	2,65	2,65	2,66	2,65	2,66	2,66
ABSORPTION	%	0,9	0,77	0,33	0,6	0,42	0,45
ABRASION LOS - LOS ANGELES	%	(ON THE METASANDSTONE - ROCK FOR AGGREGATES PRODUCTION = 13,8)					
NUMBER OF SAMPLES	N	259	134	122	145	162	125

Figure 9.05 Physical characteristics of Capanda aggregates.

As mentioned in Chapters 5 and 6, the use of crushed sand was of fundamental importance for the Capanda Project concretes especially because it was possible to benefit from the use of crushed powder filler. On proportioning of RCC mixes, it was prescribed that concrete total grain size should have a minimum 10% content of particles less than 0.15mm (at sieve mesh # 100), and 7% of particles less than 0.075mm (at sieve mesh # 200). To better characterize the real amount of crushed powder, in the manufactured sand, comparative grain size analyses were carried out, with dry and wet screen on twin samples, obtaining the results shown in Figure 9.06. These comparison tests have evidenced that on wet screen grain size tests the retained material content on sieve mesh # 200 results about 80% greater than with dry screen testing.

TEST	% RETAINED ACCUMULATED ON SIEVE (mm)						
CONDITION	4,8	2,4	1,2	0,6	0,3	0,15	0,075
DRY SCREEN	8	39	58	69	78	87	94
WETT SCREEN	8	39	58	68	76	84	89

Figure 9.06 Comparison granulometric results with dry screen and wet screen (Average value for 31 samples)

9.4.3 Mixing Water

For the concrete plants at Capanda Project the water from the Kwanza River was used after sedimentation in the raw water reservoirs on site, with no chemical treatment. Samples were taken at the batching outlet in the concrete plants once a week for control purposes only. Results obtained are shown in Figure 9.07.

REQUIREMENT	UNIT	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
O2	mg /l	186	2,5	92,8	< 3
SOLID RESIDUE	mg /l	181	48,4	53,7	< 5000
CLORIDES	mg /l	185	3,6	66,7	< 500
SULPHATES	mg /l	186	5,2	136,5	< 300
pH		186	7,6	11,8	5,8 to 8

Figure 9.07 Control tests of mixing water

9.4.4 Admixtures

No admixtures were added to the RCC for Capanda. Horever, these products were used for CVC and sent to site backed by manufacture quality certificates. Control samples were taken weekly at each of the concrete plants. Results obtained are shown in Figure 9.08.

ADMIXTURE TYPE	REQUIREMENT	UNIT	NUMBRR OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
RETARDER /	SOLID RESIDUE	mg /l	118	31,1	12,2	32 to 37
WATER	SPECIFIC GRAVITY	g / cm ^{3}	118	1,15	3,5	1,15 to 1,17
REDUCER	pH		118	6,9	17,4	4 to 7
	SOLID RESIDUE	mg /l	117	8,8	20,5	7,5 to 9,5
AIR	SPECIFIC GRAVITY	g / cm ^{3}	117	1	1	1,01 to 1,02
ENTRAINING	pH		117	12,5	6,2	11 to 13
SUPER	SOLID RESIDUE	mg /l	16	32,2	6	32 to 37
PLASTICIZER	SPECIFIC GRAVITY	g / cm ^{3}	16	1,17	0,4	1,15 to 1,18
	pH		16	7	2,2	5 to 8

Figure 9.08 Control tests of concrete admixtures.

9.4.5 PVC - Membrane

A PVC membrane used as a supplementary safety element for impermeability of the upstream facing, has been studied in detail [9.03] and developed to comply with the specific conditions of the Capanda Dam. The Quality Control Plan determined that Delivery factory samples be taken before sent to site. Frequency was set for one sample to be taken every 1,000m² of membrane produced. Tests results obtained are shown in Figure 9.09.

REQUIREMENT PVC MEMBRANE	UNIT	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
THICKNESS	mm	23	2,49	0,96	> 2
HARDNESS	Shore "A"	23	91	0,56	
RUPTURE STRENGTH	kgf/cm²	23	181	3,96	> 150
ELONGATION AT RUPTURE	%	23	351	10,01	> 200
TEAR RESISTENCE	kgf/cm²	23	14	5,28	
HYDROSTATIC RESISTENCE	kgf/cm²	23	16,3	6,47	> 14
WATER ABSORPTION	%	23	0,39	4,13	< 0,5
SPECIFIC GRAVITY	g / cm³	23	1,24	0,53	1,2 to 1,3

Figure 9.09 Results of PVC membrane quality control.

9.4.6 PVC - Water Stops

Likewise, the Quality Control Plan determined that delivery factory samples be taken from the waterstops before these were sent to site. Frequency was set for one sample to be taken for every 200m produced. The water stops were sent to site backed by manufacturer's respective quality certificates. In addition, Control samples were taken on site with tests carried out by Itaipu Binational Laboratory. The results obtained are shown in Figure 9.10.

REQUIREMENT PVC WATER STOP	UNIT	NUMBER OF SAMPLES	AVERAGE	COEFFICIENT OF VARIATION %	LIMIT
HARDNESS	Shore "A"	10	83	0,74	75 to 85
RUPTURE STRENGTH	kgf/cm²	10	143	4,96	> 120
ELONGATION AT RUPTURE	%	10	306	7,32	> 280

Figure 9.10 Results of control tests for PVC. Water-Stop.

9.5 Proportioning and Mixing

9.5.1 General

As in conventional concrete, equipment used for volumetrically proportioning or weight batching of RCC must be carefully calibrated to meet project requirements. This calibration must be maintained throughout the construction period. Experience has shown that the appearance of freshly mixed RCC alone does not provide an adequate indication of the thoroughness with which the material has been mixed. A mixture with homogeneous appearance may not have cement well distributed. A mixture with virtually no cement may handle and appear the same as a lean mixture with cement. Mixer efficiency tests are needed to establish initial minimum mixing times (or retention times for continuous mixers) and maximum mixer loading. Periodic verification of the mixing time should be made during construction by additional tests.

The importance of performing concrete strength tests carefully and precisely cannot be overemphasized. In most acceptance confrontations the indicated strength of the concrete is the deciding factor. Usually other questions can be worked out if strength tests are good. If they are not, there is a real problem. So it is important that the tests results are not low due to carelessness and incompetence in sampling, molding, curing, and testing. Aside from dishonesty, there is little that can be done to make a test cylinder stronger than the potential of the original concrete. But there are many things that can reduce its strength. Well trained and supervised people should do this work with care to see primarily that the sample is truly representative and that the cylinder specimens are evenly filled and fully consolidated without voids or rock clusters in any portion; that they are kept wet with visible moisture on the surface at all times and in moderate room temperatures until testing; that capping for testing should be strong, thin, precisely flat, and especially not convex. This need for perfect planes applies also to the two loading surfaces of the testing machine. Convexity or other irregularity of end surfaces has seriously reduced test values and caused needless trouble and concern on too many occasions. **Don't let it happen to you! Constant alertness is the price of success in concrete construction just as it has been the price of liberty in the history of mankind!**

Evaluating RCC mixture proportions has two main aspects:

✓ First, establishing that materials are entering the mixer with the desired proportions.

✓ Second, to evaluate the workability of the RCC and the uniformity (or variability) of the mixture proportions after it leaves the mixer or after it has been placed.

The right amounts of materials in a mixer in relation to the volume it produces are of little use if the mixture contains areas, for example, with twice the design cement content and others with no cement or if the mixture has segregated badly.

9.5.2 Mixing Plant Layout

The mixing plant layout should provide easy access to aggregate stockpiles and methods of sampling all materials without stopping production. Sampling locations and equipment for cement, pozzolanic material, aggregates, admixtures, water and concrete should be determined to safely obtain representative materials.

4.5.3 Pre-batching and Batching Inspection Report

Batching and mixing concrete inspection includes documentation of required tests and verification that proper materials have been used, proper proportions batched, and proper mixing completed. Prior to batching for production, verification should be made that the batch plant conforms to the specified standards. Verification may be based on a certificate of inspection report of the plant incorporating the results of calibrations, uniformity tests, and plant conditions. A report of the uniformity tests of mixes should be based on mix proportions and materials similar to that used for the project. The capability and performance of the plant to conform to specified limits of weighing accuracy of each material must be verified and recorded.

The report of prebatching inspection may include the following:

a) Verification that scales have been calibrated against test weights prior to due date;

b) Evidence of test weight accuracy and approval certificate of scales must be displayed where they are easily seen and can be examined. This should include effective dates and dates of recalibration;

c) Verification that water measuring devices and admixture (if used) dispensers have been properly calibrated and that the calibration due date has not been passed;

d) Verification that moisture compensation probes have been calibrated to sand-moisture determinations performed by applicable test method.

9.5.4 Calibration

9.5.4.1 Batch-type Plant

Modern batch-type mixers are relatively uncomplicated to calibrate and operate. The primary concerns with RCC are matching aggregate feed rates and storage capacities to high production rates, finding the best batching sequence for each mixture, and getting all materials uniformly blended with a reasonable mix time. The combined charging, mixing, discharge, and return time determines the maximum production rate. Mixture proportions are input from manual or computer controls and are typically recorded by load cells.

Figure 9.11 Control panel at RCC batching plant.

9.5.4.2 Continuous mixing plant

Continuous mix plants ate relatively easy to calibrate and operate. Mixture proportions are converted to a continuous feed rate in tons/hr (kg/hr). Materials used for calibration tests are accumulated over a fixed period of time rather than being measured individually for a separate batch. As with batch type plants, materials may be individually fed into mixer from separate bins or they may be accumulated on a common final feed belt. This is determined by whether the mixer has, for example, one belt for all aggregate bins or multiple belts with one for each bin. Calibration with just one belt operating may not be the same as when the plant is in full operation with all feed belts operating. Load cells or weigh-bridges to provide weight controls rather than volumetric control, and computer print-outs have been used on some RCC projects but have not been necessary on other projects. Also, as with batch type plants, the mixer should be calibrated at the minimum, average, and maximum production rates expected.

Between October 1989 and June 1992 about 650,000m^3 of RCC were produced at Capanda dam site- Angola. For the RCC, conventional concrete plants (batch) were initially used producing about 150,000 m^3 of RCC. In May 1990, two other production plants began operation (Pug-Mill type) and each double horizontal shaft mixer enabled various ranges of production up to a maximum 120m^3/h.

Figure 9.12 Load cells under the belt conveyor to provide weight control.

All aggregates were gravimetrically proportioned using belt conveyors with variable speed and provided with rotation meters. Under each proportioning belt, weighbridges were mounted with load cells that generated electrical signals proportional to the load of material. An integrator panel processed all the information from the speed variator and weighbridge, indicating the instantaneous proportioning of the mix flow (ton/hr). After proportioning, the aggregates were handled to another belt conveyor, which after receiving cement fed the mixers.

Cement proportioning was done in the same way as for the aggregates, except for the addition of an automatic correction device. Inside the mixers, the water was sprinkled through bored internal piping, according to volumetric proportioning by flowmeters. Proportioning of all materials was monitored with digital indicators under which potentiometers were installed for speed adjustment of respective batchers.

For checking batchers, initial recommendations had fixed the same maximum deviations as allowed for conventional concrete batch plants. Later, based on practical findings helped by laboratory analysis information, maximum deviations were extended to as much as 3% for all materials. For checking batchers, standard weights were used coupled to the weighbridge with the batcher empty. Operating the proportioning belt at various speeds, the integrator panel made automatic calibration. After completion of automatic calibration, a direct check was made by sample collecting and timing process. For water, only this last procedure was used. For controlling production equipment, periodical inspections running a checklist were carried out as described in Figure 9.02.

Figure 9.13 Control panel at RCC mixing plant at Salto Caxias dam- Brazil.

9.5.5 Sampler

As with batch type plants, a diversion conveyor belt, or another equivalent system, is recommended to sample RCC at the plant without stopping the production on large projects.

Figure 9.14 Sampler used at RCC/CVC Plant.

9.5.6 Mixture variability test

Variability tests can be used to establish minimum mixture retention times and the effectiveness of the mixer feed procedure for both batch and continuous type mixers. They also are used to determine the more important issue of how well and uniformly the RCC is mixed at the placement after it has been delivered and spread. ASTM C-172 [9.04], annex A1 of ASTM C-94 [9.05], and Corps of Engineer method CRD C-55 [9.06] have all been used in modified form to conduct uniformity tests of fresh RCC, and to establish acceptable mixing/placing methods in the field. In ACI- 207 [9.07] there is a table showing the recommended maximum allowed variability index values as presented in Figure 9.15.

Beneficial re-mixing or damaging segregation that can occur in the delivery and spreading process should also be evaluated. A modified approach that takes into account the effect of mixing and handling involves random sampling from the placement. It combines the checking of within-batch variations with batch-to-batch variations.

CONTENT OR PROPERTY	SAMPLING AT MIXER	SAMPLING AT PLACEMENT
CEMENT	82.5	70
MOISTURE	91.5	75
UNIT WEIGHT OF THE AIR-FREE MORTAR	98.5	85
COARSE AGGREGATE	90.5	80

Figure 9.15 Maximum allowed variability index values. Note: Variability index =(smallest value/largest value) x 100 [9.07].

In this modified approach, a sample of RCC is taken from the placing area immediately after spreading but prior to rolling. This is done during the first, middle, and last third of a production shift. Modern and simple laboratory equipment, such as microwave ovens, or DMA (See Chapter 7) and calcium analyzers, provide results within a few hours. Samples are tested for the unit weight, amount of coarse aggregate, moisture, air content, unit weight of the air-free mortar, and the cement content. By comparing results of the three samples, the variability of the mixture can be established the same day it is tested.

At the start of production on a new project, an adequately long mixing time should be adopted to assure thorough mixing until test results are available. This can be slowly decreased by perhaps 10 seconds each day, until test results show that excessive variability in the product will occur if mixing time is further reduced. The mixing time established by testing can vary from plant to plant and mixture to mixture.

Experience has shown that the appearance of freshly mixed RCC alone does not adequately indicate how thoroughly the material has been mixed. The cement may not be properly distributed in a mixture with uniform appearance, and a mixture with virtually no cement may handle and appear the same as a lean mixture with cement. Mixer proofing efficiency testing is needed to establish minimum mixing times and mixer loading. Variability indexes can be specified for tests under ASTM C-94[9.05] or Corps of Engineers designation CRD C-55 [9.06].

Normally, mixer testing is concerned only with the mixer, comparing the components and quality of the concrete found in the first, middle, and last parts of the mixer drum. RCC is frequently made in continuous mixers, which do not lend themselves to such testing. Also, considerable beneficial re-mixing or damaging segregation can occur in the delivery and spreading process. A modified approach to mixer evaluation, which considers the effect of handling is appropriate. Such an approach simply combines concerns for "within batch" variations with "batch-to-batch" variation and is applicable to both continuous and batch-type operations.

A variety of RCC quality control tests have been developed to accommodate the wide range of consistencies, mixture proportions, and aggregate grading possible with RCC. Some tests are adapted from CVC procedures while others are adapted from soil cement or earthwork technology.

Either from previously established strength expectancy for the proportions and materials used, or from tests of preliminary batches of similar proportions, it should be reasonably well known before the concrete work starts what strength the mix should produce if the slump and air content are kept within the requested limits. Thus, strength tests of job concrete are primarily for the record to show to what degree the expected strength was obtained. If it is found that fewer than the required percent reached the required strength, it merely means a slight encroachment on the safety factor at that age. If it is believed that higher strength later will still be insufficient, an appropriate adjustment can be made in cement content.

Control of strength and any evaluation of strength tests should be carried out in accordance with ACI Standard 214, "Recommended Practice for Evaluation of Strength Test Results of Concrete" [9.08 and 9.09]. The earliest indication from strength tests that corrective action is needed is when the moving average of the five last tests encroaches the requested value for minimum required strength at that age. Many times if an appropriate adjustment in cement content has been made, a modest encroachment on 28-day strength will be acceptable on the basis of companion 91day or 180 day tests which show strengths well above requirements. It is strongly recommended that these be made.

Along with the immediate plotting of all strength tests and the moving average, the corresponding consistency, water and cementitious content and density determined for each test batch should be plotted.

At Capanda project, CVC concretes were produced in two batching-mixing plants with tilting conical mixer with 3m³ capacity per mixer. Nominal production of each plant was 120m³/h, with production reaching 130m³/h during peak periods. Quality control of CVC concrete production was made by taking routine samples of the concrete and its mixing materials. Sampling was made at the concrete plants where small field laboratories were installed. Moisture of the aggregates, for correction of mixing water, was determined every 2 hours for the small aggregates and at least twice a day for coarse aggregates. Tests were carried out on fresh mix samples (slump, entrained air content and temperature), aiming at control homogeneity and enable mixing corrections and adjustments.

Moldings of F 150mmx300mm test specimens for strength tests were made for every 200m³ produced or fraction thereof. At every 2,000 m³, additional test specimens were molded for modulus of elasticity and diametral (splitting) compression tensile strength tests. Tests over hardened concrete enable statistical evaluation of compliance to design requirements, based on the reliability established and dispersions obtained. To check production equipment, all batchers were checked monthly, during maintenance or long shutdown periods or on occurrence of any anomaly. The following figures have been established as maximum deviations for each batching: water and cement 1%; sand 2%; coarse aggregates 3%; admixtures 5%.

For preventive control, periodical check-lists were run on each equipment, to inspect the following items: mixing water piping system; storage conditions of the various materials; cement supply system conditions; mixing and batching plants conditions.

Mix design of the CVC used in the dam construction and the respective control parameters are shown in Figure 9.16.

USED AS	UNIT	FACING MIX	FACING MIX	BEDDING MIX	BEDDING MIX	PLINTH
REQUIRED STRENGTH	kgf/cm^2	120	120	120	120	160
AT AGE	Dias	90	90	90	90	28
IDENTIFICATION		E 38 03	E 38 04	E 19 07	E 19 08	C 38 01
SLUMP	cm	5 +/- 1	5 +/- 1	14 +/- 2	14 +/- 2	5 +/- 1
AIR ENTRAINED	%	4 +/-1	4 +/-1	4+/-1	4+/-1	4 +/-1
				PROPORTIONING MIX		
CEMENT	kg/m^3	230	200	260	230	265
WATER	kg/m^3	166	168	218	220	168
CRUSHED SAND	kg/m^3	740	840	1100	1155	675
COARSE B1(19-4,8)mm	kg/m^3	560	530	695	650	560
COARSE B2(38-19)mm	kg/m^3	600	570			630
SET RETARDER	kg/m^3	0,9	0,8	1	0,9	0,8
AIR ENTRAINING	kg/m^3	0,11	0,1	0,12	0,11	0,12
				COMPRESSIVE STRENGTH - STATISTICAL DATA		
SAMPLES FOR 3 DAYS AGE		39	286	71	89	89
AVERAGE	kgf/cm^2	85	80	66	59	124
COEFFICIENT OF VARIATION	%	26,4	25,1	21,1	26,4	24
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*0,37*	*0,40*	*0,25*	*0,26*	*0,47*
SAMPLES FOR 7 DAYS AGE		45	293	72	94	91
AVERAGE	kgf/cm^2	142	128	112	103	193
COEFFICIENT OF VARIATION	%	26,8	21,1	21	25,4	19,8
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*0,62*	*0,64*	*0,43*	*0,45*	*0,73*
SAMPLES FOR 28 DAYS AGE		82	545	143	174	84
AVERAGE	kgf/cm2	217	188	177	154	276
COEFFICIENT OF VARIATION	%	20,2	18	17,1	18,6	15,9
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*0,94*	*0,94*	*0,68*	*0,67*	*1,04*
SAMPLES FOR 90 DAYS AGE		78	433	139	150	
AVERAGE	kgf/cm^2	256	215	210	181	
COEFFICIENT OF VARIATION	%	17,6	17,3	16,7	17,1	
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*1,11*	*1,08*	*0,81*	*0,79*	

Figure 9.16 Mix design and statistical data on CVC concretes mainly used at Capanda dam- Angola [9.10].

9.5.7 Quality Control of RCC during production

Mix design and statistical data on RCC mixes mainly used in the dam construction and their respective control parameters are shown in Figure 9.17.

PRODUCED BY (MIXER TYPE)	UNIT	BATCH PLANT	BATCH PLANT	CONTINUOUS PLANT	CONTINUOUS PLANT
		GENERAL DATA			
REQUIRED STRENGTH	kgf/cm2	80	80	80	80
AT AGE	Dias	90	180	90	180
IDENTIFICATION		F 76 BT	G 76 BT	(F 64 PM)-(F 76 1 B)	(G 64 PM)-(G 76 2B)
		RCC PROPORTIONING MIX			
CEMENT	kg/m^3	80	70	80	70
WATER	kg/m^3	102	102	102	102
CRUSHED SAND	kg/m^3	1075	1085	294	348
COARSE B1 (19-4.8)mm	kg/m^3	520	520		
COARSE B2(38-19)mm	kg/m^3	470	470		
COARSE B3(76-38)mm	kg/m^3	200	200		
AGGREGATE G1 (19-0)mm	Kg/m^3			1200	1240
AGGREGATE G2(76/64-19)mm	Kg/m^3			768	660
		FRESH RCC MIXTURE - STATISTICAL DATA			
NUMBER OF SAMPLES		50	20	17	308
SPECIFIC GRAVITY - AVERAGE	kg/m^3	2415	2462	2460	2442
COEFFICIENT OF VARIATION	%	1,1	0.7	0,7	0,1
NUMBER OF SAMPLES		115	25	28	356
CEMENT CONTENT - AVERAGE	kg/m^3	77.6	68,4	82	70.2
COEFFICIENT OF VARIATION	%	6.3	5.6	10,3	9.2
DEVIATION FROM NOMINAL VALUE	kg/m^3	-2,4	-1,6	2	0,2
		COMPRESSIVE STRENGTH - STATISTICAL DATA			
SAMPLES FOR 3 DAYS AGE		29	17	9	66
COMPRESSIVE STRENGTH - AVERAGE	kgf/cm^2	41	38	42	40
COEFFICIENT OF VARIATION	%	19,9	25		27,7
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*0.51*	*0.54*	*0.53*	*0.57*
SAMPLES FOR 7 DAYS AGE		48	15	9	74
COMPRESSIVE STRENGTH - AVERAGE	kgf/cm^2	62	54	67	54
COEFFICIENT OF VARIATION	%	19.1	18.8		22.9
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*0,78*	*0.77*	*0,84*	*0,77*
SAMPLES FOR 28 DAYS AGE		50	16	9	57
COMPRESSIVE STRENGTH - AVERAGE	kgf/cm^2	86	78	93	78
COEFFICIENT OF VARIATION	%	17.2	13.1		18.1
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*1.08*	*1.11*	*1.16*	*1.11*
SAMPLES FOR 90 DAYS AGE		141	51	26	152
COMPRESSIVE STRENGTH - AVERAGE	kgf/cm^2	100	93	115	95
COEFFICIENT OF VARIATION	%	15,9	9.3	14,9	14
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*	*1.25*	*1.33*	*1.44*	*1.36*
SAMPLES FOR 180 DAYS AGE			18		13
COMPRESSIVE STRENGTH - AVERAGE	kgf/cm^2		95		111
COEFFICIENT OF VARIATION	%		8,4		11,1
MIX EFFICIENCY	*$(kgf/cm^2)/(kg/m^3)$*		*1.36*		*1.59*
DRILED CORES FROM DAM BODY TESTED BETWEEN 128 AND 223 DAYS AGE - STATISTICAL DATA					
SAMPLES AND AGE		*48 (FROM 128 TO 223 DAYS AGE)*			*127 (360 DAYS AGE)*
COMPRESSIVE STRENGTH - AVERAGE	*kgf/cm^2*	*138*			*127*
COEFFICIENT OF VARIATION	%	*19,50*			*24,40*
SAMPLES AND AGE		*9 (FROM 361 TO 419 DAYS AGE)*			
MODULUS OF ELASTICITY	*kgf/cm^2*	*255000*			
SAMPLES		*8*			
PERMEABILITY	*m/s*	*10 E-9 a 10 E-11*			

Figure 9.17 Statistical Data for Control of RCC produced at Conventional Gravimetric Plants (Batch) and at Continuous Mixing Plants with Gravimetric Batchers (Pug Mill) [9.10].

9.5.8 Cement Content Control in RCC Fresh Mix

ASTM methods C-1078 [9.11] and C-1079 [9.12] can be used to determine the cement and water content of fresh concrete by chemical titration or calcium ion analyzer. The sample size and specifics of sample preparation have been modified to facilitate the procedure with some RCC mixtures. The Heat of Neutralization test has also been used to determine the cement content of freshly mixed concrete. All methods must be calibrated for a given aggregate, mix water, and admixture. None of these methods are effective for determining the pozzolanic material content of concrete.

To check homogeneity of cement proportioning or mixers efficiency, daily tests were made with reconstitution of cement contents in the RCC fresh mix. This reconstitution was made by titration chemical process, determining the cement amount indirectly, from the calcium content present in the sample. This procedure required previous calibration with laboratory preparation of various RCC mixes with variable and strictly known cement proportioning, with always the same proportion among its various components, water included. For each mix, the necessary E.D.T.A. (Ethylene-Diamine-Tetra-Sodium Acetate) volume was determined for total content of CaO. Since the volume of E.D.T.A. spent, was directly proportional to the quantity of CaO (and therefore of cement) contained in the mix, a linear correlation was established between these two parameters. This correlation was called test calibration standard. Data obtained during control made through this method are shown in Figures 9.18 that also shows the results obtained in other RCC applications [9.13 to 9.16].

9.5.9 Moisture Content- Workability and Consistency Control at mixing plant

Once concrete proportions and cement content have been selected for the strength required and are being batched uniformly from the same aggregate, the consistency of the RCC is the primary item for inspection and control. A variable consistency is likely to add to variation in concrete strength. Excessive consistency usually decreases strength through increase water-cement ratio or stratification. RCC of insufficient consistency is likely to lead to poor compaction.

Various methods have been tried in an effort to measure the workability or compactibility or consistency of RCC. None of them have been universally successful or generally accepted. For example, although the modified VeBe test mentioned in Chapter 7 has been used successfully to duplicate workabilities of some RCC concrete mixtures, it does not seem adequate as a field control test of dry RCC mixtures. In reality, a laboratory workability test may be useful for mix design and research work. During construction, the gradation is essentially fixed, and the moisture can be controlled by observation. These factors taken together essentially define the workability of this zero-slump material.

It also appears that the variability of consistency measurements and compacted density increases directly with mixture stiffness and fines content. Compaction reduces the volume of entrapped air by forcing the aggregate particles into a smaller volume. The degree to which this is accomplished depends on the lubrication of the aggregate particles by the surrounding paste (water, cement, pozzolanic material and fines) and the combined effects of vibration and compacting effort. If the paste volume is inadequate or the paste is too fluid, there will be inadequate lubrication of particles for lateral movement and consolidation will be more difficult.

There will be little, if any, discernible change in the compacted surface of the RCC to indicate that full compaction has been accomplished. When the paste content is adequate to

DAM	BATCHER	THEORETICAL	CONTROLS										
SITE	TYPE	CEMENTITIOUS MIX CONTENT kg/m³	CEMENT CONTENT			COMPRESSIVE STRENGTH - STATISTICAL DATA							
			AVERAGE kg/m³	COEFFICIENT OF VARIATION (%)	DEVIATION FROM NOMINAL VALUE (kg/m³)	AVERAGED VALUES - kgf/cm²				COEFICIENT OF VARIATION - %			
						3 DAYS	7 DAYS	28 DAYS	90 DAYS	3 DAYS	7 DAYS	28 DAYS	90 DAYS
SACO NOVA OLINDA	VOLUMETRIC	75	53,4		-21,6		26	29	42				16
BRAZIL	CONTINUOUS	70	50,4		-19,6		26	29	34				18
SERRA DA MESA	VOLUMETRIC												
COFFERDAMS- BRAZIL	CONTINUOUS	60 + 140	188	23,5	-6	76	142	265		31	24	17	
CARAIBAS	VOLUMETRIC												
BRAZIL	CONTINUOUS	66	78,4	18	12,4		24	37	36		45,8	54,1	61,1
JORDÃO	GRAVIMETRIC	85	88	12	3		42	54	77		23,6	23,3	16,7
		75	72	13,3	-3		38	55	77		20	15,8	20,3
BRAZIL	CONTINUOUS	70	72	6,3	2		31	41	55		26,6	27,8	18,7
SALTO CAXIAS	GRAVIMETRIC	166	164	5,3	-2		92	119	160		21,2	16,5	16,8
BRAZIL	CONTINUOUS	100	104	4,7	4		36	50	82		19,3	16,0	16,3
URUGUA-I	GRAVIMETRIC	60	61,5	5,2	1,5		56,5	74	98		16	12	10
ARGENTINA	CONTINUOUS	90	91,1	6,8	1,1		75	96	121		12	10	12
	GRAVIMETRIC	80	77,6	6,3	-2,4	41	62	86	100	19,9	19,1	17,2	15,9
CAPANDA	BATCHER	70	68,4	5,6	-1,6	38	54	78	93	25	18,8	13,1	9,3
ANGOLA	GRAVIMETRIC	80	82	10,3	2	42	67	93	115				14,9
	CONTINUOUS	70	70,2	16,2	0,2	40	54	78	95	27,7	22,9	18,1	14

Figure 9.18 Reconstitution data of Capanda RCC Cement Content compared with contents of other applications. Note the proximity of the values measured, compared with the theoretical values when using Gravimetric Batch [9.10]

provide a measurable consistency, paste will rise to the surface and fill the voids between aggregates. The time required for this to be accomplished is an indication of the mixture's workability.

To a very large extent, the stability and watertightness of an RCC structure depend on the mixture proportions used and the resulting consistency and workability of the RCC. The inspector on an RCC placement is responsible for ensuring that RCC consistency and workability are adequate for complete compaction. Two testing procedures can be used at frequent intervals to determine if RCC being produced is of the correct consistency for compaction. The modified VeBe test is used to determine consistency and the nuclear densimeter is used to determine if compaction is adequate. The modified VeBe test constitutes the best test for controlling RCC consistency as an indicator of RCC workability and the ease with which RCC can be compacted. The VeBe time used during construction is determined initially during the mixture proportioning studies done in a laboratory. The time is then adjusted as necessary during the pre-construction engineering and design phase of the project when a preliminary test section is constructed. It is later further adjusted when the project test section is built after award of contract. Still further adjustments, as necessary, may be made to the VeBe time during construction. Once a VeBe time is established, the normal procedure is to maintain a consistent VeBe time for the RCC being produced by making batch water adjustments as necessary to compensate for changes in aggregate moisture and changes in humidity, wind, and temperature. The batch water adjustments should be made if two consecutive VeBe readings vary from a target VeBe time by 5 or more seconds. Changes to the established VeBe time should be made only to improve compaction and the resulting density.

The VeBe apparatus used to measure the consistency of no-slump CVC concrete is used to measure the consistency of wetter RCC mixtures. It provides an indication of the workability or ease of consolidating the concrete in place. When it is used for the wetter types of RCC mixtures, typical VeBe times are 10 to 30 seconds.

To check the influence that not applying the overload would have to the test results, the same sample of RCC was tested indicating a smaller dispersion in tests made with overload. Technique achieved with the Capanda RCC did **"not"** produce evidence of absolute applicability of this method, probably due to the low plasticity of the RCC, because of the cement content adopted and also the different cohesiveness of fine aggregates content. It was shown that extreme remolding-consistency time values do not always correspond to RCC with deficient compaction.

The moisture or water content is important for several reasons:

✓ to determine the W/C or W/(C+PM) ratio on projects that may use it in design or design specification requirement;

✓ to assure the optimum or desired moisture content for workability and compaction, and

✓ as one of the indicators of mixture variability.

Some moisture test methods are:

(a) Chemical tests (ASTM C-1079)
(b) Drying tests (hot-plate, oven, microwave)
(c) DMA- Brazilian (See Chapter 7)
(d) Nuclear tests- mostly useful for compaction control during the RCC placement

Chemical and drying tests can be performed on samples obtained either before or after compaction. The samples must be representative of the actual production, particularly with respect to the mortar/aggregate ratio and the time the sample is obtained.

9.5.9.1 Chemical tests

Two chemical tests are stated in ASTM C1079, "Determining Water Content of Freshly Mixed Concrete." Both procedures relate the water content of the concrete to the chloride ion concentration of the test sample either by volumetric titration or calorimetric technique. The methods require calibration for individual mixtures and materials, and recalibration for new reagents. A reasonably clean and unchanging laboratory environment is recommended for these test procedures.

9.5.9.2 Drying tests

Drying tests include hot plate, standard oven, or microwave oven to remove the water from a representative sample. The tests are adapted from soil and aggregate test procedures. The test accuracy is affected by both evaporation and chemical hydration of water. This in turn is a function of time, temperature, precipitation and humidity, mixture proportions, and materials properties (grading, absorption, and cement chemistry). The test result is significantly affected by where and when the sample is obtained. A sample tested directly out of the mixing plant may not be the same as a sample tested after being spread and compacted by a roller. Consequently, the location for sampling should be specified.

9.5.9.3 Water Content- DMA- Brazilian Method of Test

As mentioned in Chapter 7, Pacelli and *al* [9.17] developed a very simple and rapid method of test to determine the water content and unit weight of RCC. Aiming to establish an alternative to usual methods, a procedure for controlling the unit water of RCC and the unit weight of fresh concrete has been developed. Such method, known as " Water Measurer Device - WMD (DMA in Portuguese), allows the prompt control of unit water during the RCC fabrication.

This method has been conceived based on a physical principle, the density of materials compounding concrete. Water being a material with lower density, the more water in an RCC mix, the lower the density.

9.5.9.4 Nuclear tests

This is the most popular process used to determine the moisture content, based on the measurement of hydrogen ions of the material. Special gauging may be required for humidity, depending on the chemical composition of the materials.

9.5.9.5 Correction of Mixing Water

At Capanda project, the moisture of the aggregates was determined every 2 hours for crushed sand and for G1 aggregate and at least twice daily for the remaining aggregates. At alternating intervals, the moisture of the RCC mixing was also determined in the retained fraction of sieve mesh 19mm.

Moisture test made on the finer fraction resulted more convenient, precise and efficient compared with the test for full mass concrete, as this considered mainly the fraction containing fine matrix , which accounts mainly for RCC compactability.

In laboratory studies, the optimum water content for the RCC was set as 102 kg/m^3, which is the equivalent for moisture content (in mix) for full mass concrete of 4,1%. For the fine

RCC fraction of sieve mesh 19mm this moisture content corresponds to 6,2%. However, this moisture measured at the concrete plants could only be practiced during the night. It was noted that during warmer days, with wind blowing and low relative moisture content in the air, the finer RCC fraction moisture content needed to be raised about 8,5%, in order to compensate for strong evaporation after spreading. Tests on RCC samples taken after spreading and before compaction have confirmed this elevation. A similar situation (with other range of water content) was observed during construction at Jordão and Salto Caxias dam.

After a mixture design has been established, aggregate moisture contents are continually monitored with adjustments made to the batch weights of various materials so that the saturated surface dry (SSD) design proportioning is maintained.

9.5.10 Correction of Filler Content in Total RCC Granulometry

At Capanda, crushed sand accounted for about 47% (in mix) of total aggregates. As already mentioned, part of this sand was incorporated to Coarse 1 in the crusher system forming aggregate G1, with the supplementary sand content being supplied by the filler re-crushers, located near the continuous mixing plant (Pug Mill). Taking into consideration balance of aggregate requirements for the whole Project, aside from performance of the crusher system, the equipment was adjusted so that the sand content of aggregate G1 was between 55% and 60%. Grain size curve homogeneity of aggregate G1 had a strong effect on mix performance. Despite preventive and corrective actions, sometimes deviations from the limits of sand content as set above were found in this aggregate. Under these circumstances, proportioning of aggregate G1 and sand were adjusted, trying to keep to the total filler quantity as set in the theoretical mix. To this end, a simplified screening test was carried out in the field laboratory, using the same routine sample taken for determining moisture content, after cooling down. Once the sand content in aggregate G1 was established, the necessary corrections were made, using a calculation procedure somewhat similar to that used for mixing water correction due to free moisture of the aggregates. The process was simplified by using appropriate tables.

9.5.11 Grain Size Curve Reconstitution of RCC Mix

The RCC mixes used in Capanda Dam, were proportioned with aggregates having specific gravity of about 2,65 t/m^3, combined so as to obtain the smaller void index. To achieve this, a reference grain size curve was initially adopted for aggregates with D_{max}= 76 mm, as follows:

$$P = (d/D_{max})^{1/3} \times 100\% \text{ where}$$

P = Percent Passing;
d = size of the sieve (mm)
D_{max} = MSA (mm)

To minimize segregation, it is common practice to adjust the coarse fraction of this curve, reducing lightly the aggregate content of D_{max}= 76 mm. Alternatively, reduction of the aggregate D_{max} itself is resorted to. At Capanda, the D_{max} was reduced from 76mm to 64mm, for RCC produced by the continuous mixing plants (pug mill). For RCC produced in conventional concrete (batch) plants, the content of the aggregate D_{max} = 76 mm (Coarse 3) was reduced, not interfering with the specifications of aggregates for mixing CVC concretes of other structures for the works.

Figure 9.19 shows grain size range specified for the RCC, together with the ranges effectively obtained and their dispersions, in batch and continuous mixing plants. The grain size range specified was determined by the equation mentioned before, with small adjustments for fractions less than 0.3 mm.

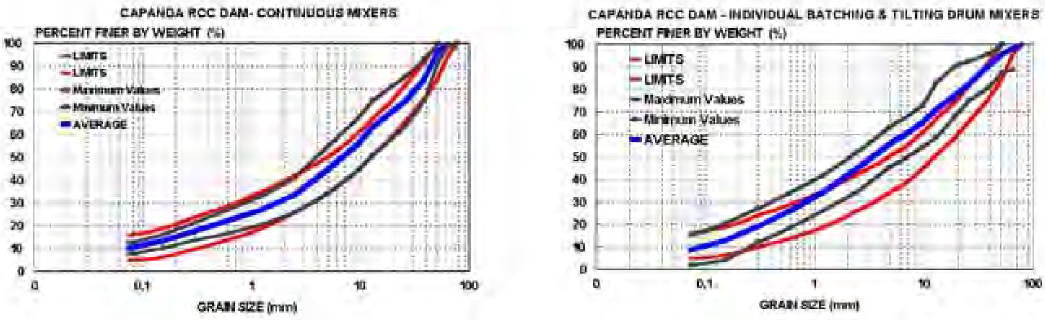


Figure 9.19 Granulometric curves for RCC Mixes from reconstitution tests. Note the proximity of average values compared with theoretical value used [9.10].

9.5.12 Molding of RCC Cylindrical Test Specimens

RCC test cylinders (Φ 150mm by 300mm) should be made using procedures suited to the consistency of the mixture, the maximum size aggregate (MSA), and the number of samples to be made before the mixture begins to dry out. Test specimens should be compacted in rigid molds or in removable liners supported during compaction by rigid molds. Wetter consistency mixtures with a VeBe time less than about 30 seconds are well suited to consolidation by ASTM method C- 1176 [9.18]. This procedure uses a vibrating table similar to the VeBe apparatus and a surcharge weight of approximately 9.1 kg. The RCC is consolidated in three layers. Other surcharges and modifications have also been used.

Mixtures that have VeBe times higher than 20 seconds or that do not respond at all to the VeBe test can be compacted in three layers with a pneumatic tamper similar to that one showed in Figure 9.23 with a 150mm smooth faced tamping foot. This has become a routine procedure for dry type RCC mixtures, but it does not yet have an ASTM or other industry standard test designation.

At Capanda Project, after each 12-hour work shift or approximately at every 1,000 m^3, a series of cylindrical test specimens (Φ 250mmx500mm) were casted with full mass RCC mix. Compacting of test specimens was performed with a manual pneumatic compactor, with ramming of 4 layers in 25 seconds each. After compacting and leveling of test specimens, the specific gravity of fresh RCC mix was determined at the field laboratory. Because the metallic molds are disassembled and roughly finished, the results may lack accuracy. Small volume variations may occur after assembly and disassembly. Test specimens were removed from the molds 24 hours after molding, and sent to the main laboratory for simple axial compressive strength tests at various ages.

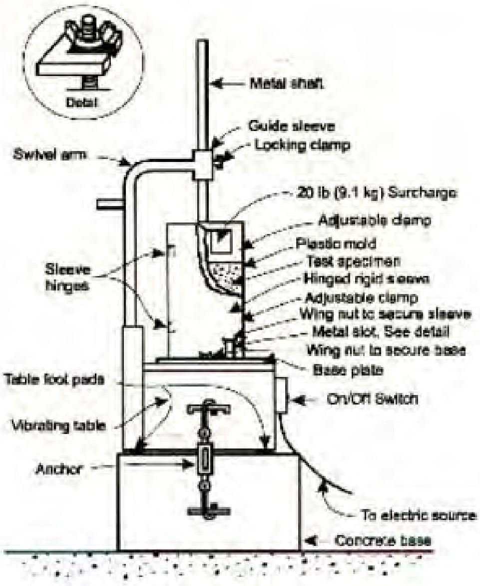


Figure 9.20 Vibrating Table used for Cylinder Preparation [9.18].

Figure 9.21 Vibrating Table being used for Cylinder Preparation-Itaipu Laboratory-1976 [9.19].

Figure 9-22 Screen shaker being used for Cylinder Preparation-Tucurui Laboratory-1980.

Figure 9.23 Pneumatic hand hammer being used for Cylinder Preparation-CESP Laboratory- 1993 [9.20].

Figure 9.24 Vibrating Table being used for Cylinder Preparation- COPEL-Salto Caxias Laboratory- 1997.

9.6 RCC Quality Control During Placement

9.6.1 General

RCC methodology has established the convenience of adopting additional controls on site during placement and compaction phases.

Inspection of construction operations is less specifically defined than that of materials and concrete production. It is nonetheless important and has prompted the preparation of several valuable guidelines.

Appearance tells much of how well the work was done, but by no means all. And if it is not what it should have been, it is too late to do much about it. Unlike the neatly tabulated results of strength tests in proof of the quality attained, the often hidden good results of construction inspection are not readily documented even though daily shift reports are required. Accordingly, construction inspection will encourage quality by seeing and approving or disapproving, step by step, while action can still be taken if necessary for corrections.

Checkout cards for each RCC placement with initials of foremen and inspectors attesting that all elements were properly ready for RCC will do much to get quality construction. This will include such items as preparation and cleanup of foundation and construction joint surfaces, correct dimensions and tightness of forms, adequacy of facilities for each concrete placement including rollers, proper use of suitable starting mixes, avoidance or scattering of separated coarse aggregate, curing and protection, and repairs.

Inspection forces will be most effective in getting correct performance of these unnumbered aspects of good concrete construction when it is understood on the job that the work was organized and managed in such a way that the inspection staff was there as free agents of management expected to get the desired and specified performance paid for.

The inspector on the placement operations should watch all details that are related to the overall success of RCC placement operations. The following list indicates some of the items to be checked:

a. Lift surfaces have been adequately cleaned prior to placement of bedding mortars or RCC;

b. Bedding mortar is placed at the required thickness and correct consistency and is adequately spread;

c. RCC is deposited, spread, and compacted only on fresh bedding mortar that has not begun to dry or set;

d. RCC is deposited on lift surfaces in the proper location and spread in the required layer thickness, and the action of the dozers is controlled in a manner to eliminate voids and ensure proper compaction;

e. RCC as it is deposited and spread is of the required workability as determined by the VeBe tests and by observing spreading and compaction operations;

f. Compaction of the RCC occurs while RCC is still fresh and has not begun to lose workability;

g. Lift surfaces are maintained in a moist state at all times;

h. Internal vibration at interfaces between RCC and CVC concrete is in the right location and done correctly with immersion vibrators in the right number and adequate size and for sufficient duration;

i. CVC concrete is deposited and consolidated in those areas where it is required such as around waterstops and drains, against abutments, and other locations as shown on the plans;

j. Installation of contraction joints, if required, is completed prior to compaction by rollers and before RCC has begun to lose workability;

k. The passes in a specified translation speed for the vibratory roller on each lift of RCC are obtained.

l. All testing, including VeBe tests, nuclear density tests, aggregate moisture, and grading tests are taken, monitored, and evaluated.

9.6.2 Visual Observation as an Inspection Tool

An inspector should be present at all times that RCC is being placed, and he should observe the details listed. To determine if RCC, as delivered, spread, and compacted, is of the correct workability, some visual features should be observed. Usually, if the RCC is too dry for proper compaction, obvious signs are: increased segregation of the mixture, aggregate particles on the surface that are cracked by the roller, and little or no reworking of the RCC adjacent to the dozer as the RCC is spread. Cracking of aggregate particles creates a visible scattering of rock flour around the aggregate particles. In addition, concrete that is too dry will not show the development of paste at the surface after three or four roller passes as it should, and individual larger-sized aggregate particles will begin to dry within 10 to 15 minutes after spreading during warm weather. If closely spaced surface cracking is observed as the roller moves over the surface, the mixture is probably slightly dry. The RCC is likely too wet if heavy equipment produces deep rutting. The mixture proportions, therefore, may have to be adjusted. An increase in segregation of large aggregate particles from the mixture may be caused by too much or too little water, and its occurrence should be reported by the inspector and conditions corrected as soon as it is observed.

9.6.3 Construction Joints Preparation and Treatment

Prior to placement of RCC over foundation all semi-loose rock debris must be removed and foundations washed out with water. In the deeper elevations of the riverbed, placement of dental concrete was required at various cavities. As a general rule, CVC concrete was applied to all contact foundation rock surfaces prior to RCC placement. Required treatment of horizontal joints between RCC layers refer to superficial cleaning and application of bedding mix in order to comply with minimum bonding conditions between layers.

Contract specifications usually state when and how a lift surface is to be cleaned prior to the next placement; however, there can be several approaches as to which type and how much treatment will be necessary. The amount of treatment will depend on variables such as weather conditions, whether or not a bedding mortar is used, the condition of the previous lift surface, the interval between placements, etc. Judgment is required both by the government inspector and the contractor in providing the appropriate lift surface treatment for any particular placement condition. Requiring the contractor to meet "the letter of the law" may under some circumstances result in unnecessary delays or cause more problems than solutions.

Cleaning can be made using compressed air, an activity better performed with the surface reasonably dry. Immediately after cleaning, the curing process continues, executed with water sprinkling and compressed air. The concrete surface can be treated with removal of cement slurry. This activity can start after partial hardening of the concrete.

The use of Bedding Mix can be mandatory on the construction joint surface for the layer to be executed. At Capanda project, bedding mix was applied whenever the bedding time of

Figure 9.25 Inspection of the PVC Membrane bonding condition at Urugua-i and Capanda Dams.

the RCC layers exceeded 8 hours. Inter-connection of the various segments of the PVC membrane to the upstream facing constitutes a particular type of joint treatment. The membrane was incorporated to precast concrete pieces, with dimensions 2.0mx4.0m. They were joined on the dam site by bonding a strip also made of PVC, using a bonder specially designed for this purpose. In some cases, the classic vulcanization process with hot air jet was used. Before bonding, all surfaces were cleaned with steel brushes and solvents. The bonding quality was checked during execution of the works or later, by means of a sharp point tool.

9.6.4 CVC and RCC Concrete Placement

The details of RCC placement should be documented and thoroughly discussed. The plan should include RCC transportation, spreading, compaction, curing, cleanup, preparatory operations, concurrent operations, material supply, and any other operation that may influence RCC placement. It should also include a detailed listing of equipment and crew composition. In many cases, this discussion serves to resolve numerous issues that may not have been adequately addressed in the contract documents.

An important element of quality control in RCC is visual monitoring of the delivery, dumping, and spreading operation. Segregation, contamination, and timing of operations should be carefully monitored. Deficient procedures should be corrected immediately to prevent contamination of lift surfaces by hauling equipment, to prevent the freshly spread compacted surfaces from fraying, and to avoid cold joints and segregation of RCC layers.

To identify cold joints and to distinguish between joints, which require special treatment for bond and those, which can be covered without a bonding mix, a record should be kept of the elapsed time between lifts or of the maturity of each lift prior to placing the subsequent lift.

To assure proper bonding, the joint or lift upon which fresh RCC is to be placed must be clean and damp. When a dry or damaged surface develops, or if its specified maturity limit is

Figure 9.26 Action to reduce the segregation at Salto Caxias dam.

exceeded, joint treatment is necessary before placing the next layer. This may include cleaning the surface with air jets and providing a bedding mixture.

The placing foreman or inspector controls mixture water adjustments by observation of compaction during placing, radio communication should be provided between the placement and mixing plant to provide information for continual and immediate control of moisture. The plant should maintain a record of all water adjustments and total water content in mixtures.

Actions to control or prevent segregation within the RCC can be generally defined; however, due to changing site conditions, procedures may have to be adjusted. An increase in segregation as the RCC comes off the conveyor or out of end-dump trucks will require considerably more dozer action to distribute the segregated materials (rock pockets) and rework them into the surrounding RCC. When RCC becomes dryer, more effort is required both by the dozer and vibratory-roller operator to achieve a uniformly compacted material that is free of voids. Segregation is also more likely to occur during RCC start-up operations at the beginning of a shift or when placing RCC and conventional concrete against an abutment (or other hard surface such as pipes, forms, instrumentation blackouts, etc.). The government inspector, placement foreman, dozer operator, vibratory-roller operator, and concrete finishers all must be aware of these and other problem areas and be ready to take necessary action to prevent permanent voids from occurring.

At Capanda, before placement of each layer, horizontal reference strips were painted indicating the layer height on the various elements that define its contour. In large layers, auxiliary landmarks were placed near the spreading area border. Facing mix was placed directly from the concrete truck-mixers, which moved parallel to the upstream facing. This concrete was previously compacted to a height of 40cm, supplying the bulldozer tractor operator with the required level

Figure 9.27 Horizontal reference strip painted at the upstream precast panel at Capanda Dam.

Figure 9.28 Bedding mix placed directly from the concrete truck-mixer.

reference for spreading RCC at this same height. To ensure the required binding of facing mixing and RCC, the first was proportioned with setting retarder admixture at a ratio variable according to climatic conditions, extension and particular placement conditions. Bedding mix was also placed directly from the concrete truck-mixers, which moved at a low speed while a workman maneuvered the discharge nozzle attempting to cover the largest area possible. Bedding was completed with wood or metallic rakes, up to a final thickness of 2 to 3 cm.

Transportation of RCC from the mixing plants to placement front was made by 3-axle Rear Dump trucks with $10m^3$ capacity. A belt conveyor was also used from the mixing plants to a transfer hopper feeding two near vertical pipes anchored to the rock slope, which loaded RCC to the trucks 50m below at the placement front. RCC placement was done in layers of approximately 45cm of loose thickness, which became 40cm after compacting.

On warmer and windy days it was necessary to sprinkle water "fog" even before compacting, to compensate for surface drying due to evaporation. Placement of all concretes was done with the surface as close as possible to a "saturated dry surface" condition.

A fine water spray may be used to moisten the RCC prior to compaction if it begins to surface dry, but water should not be sprayed onto the fresh RCC to provide additional moisture for workability. After compacting, the surface should be cured with a fine spray for a minimum of 14 days or until the next lift is placed.

The RCC surface should be protected from freezing, drying, or precipitation. RCC does not bleed like conventional concrete, so it can be covered quickly with plastic or insulating mats to reduce evaporation or protect the surface from rain, dust, or snow. The small additional cost of covering the fresh RCC surface with plastic is easily offset by the high cost of cleanup and production delays in regions of frequent rain with little wind. If rain is imminent or starting, the fresh RCC should be compacted immediately.

9.6.5 Moisture Adjustment During RCC Placement

Compaction visual examination is confirmed by in-place moisture and density tests using a properly calibrated method.

After a mixture has been established, the aggregate moisture content can be continually monitored with adjustments made to the batch weights of various materials so that consistency and mixture yield can be maintained relatively constant. The major advantage to this approach is that an accurate record of the actual water content used is established and can be used as the basis for periodic revision of the mixture design. This practice also indicates the variation in water demand during construction.

A less scientific approach to moisture control performed by the placing foreman or inspector is to control water addition directly by observation. This method has been used with

Figure 9.29 DMA apparatus being used for measurements of RCC unit water content

acceptable results. It provides continual and immediate control of moisture without complicated testing. The plant will have a record of water additions, but the actual mixing water corrected to SSD condition will not be accurately known.

There are different approaches to control and adjustment of mixing water during production. One follows traditional concrete testing concepts while the other reacts to observations during placing. Regardless of which approach is used, the most important measure is to ensure that the RCC has the proper consistency for compaction and is uniform from load to load. Besides the Chemical (ASTM C-1079) test, DMA-Brazilian and Drying tests (hot plate, oven, microwave) methods previously mentioned there is a Nuclear test

When used to determine moisture content, the nuclear gauge actually measures hydrogen content, which is in turn related to moisture content. The gauge reading must be adjusted or calibrated for any chemical composition error, similar to the density reading. The result is affected by stratification of moisture in the lift and may change with compaction by rollers or trucks, or from surface moisture changes due to precipitation, curing, or drying.

The nuclear gauge moisture content is normally determined on compacted RCC. The single probe gauge tests moisture at the surface (backscatter mode), while the double-probe gauge tests moisture at depth with a direct transmission approach. Since the single-probe nuclear gauge tests only the surface moisture content, it is not reliable for determining in-place moisture content. The double-probe gauge can test moisture content of RCC at depths ranging from 50mm to 610mm). The moisture content should be the average of the bottom, mid-point, and top of the lift measurements with this gauge.

The nuclear gauge can be used for hour-to-hour in-place total moisture indications. These moisture indications should be correlated with occasional oven-dried companion test samples.

A record of in-place moisture content can be obtained concurrently with nuclear density testing. A nuclear gauge in the direct transmission mode with a probe capable of penetrating the full depth of the lift should be used. The double probe gauge, which shows moisture determinations at any depth in the lift, is preferred. A control chart that shows the moisture content of each test for each day, the standard deviation, the average, and the moving average for the last 50 tests is helpful. Such data should be considered as both historical and as a guide in quality control. The correct moisture of the mixture may vary from day to day and within each day depending on temperature, variations in the quantity and quality of fines, delivery time, etc.

9.6.6 Compacting Control of RCC Layers - Density and Compaction Ratio

9.6.6.1 Checking the Compaction Equipment

Most vibrating rollers have multiple frequency, amplitude settings and travelling speed. Frequency and amplitude may be displayed on the roller or indicated by "compaction meters" installed in the equipment. Normally, the vibration is interlocked with the motor drive and cannot be checked without the roller moving. Portable tachometers can be placed on the lift surface to test the equipment as it passes by. Amplitude is not easily tested in the field. This is usually a factory calibration test. If there is reason to believe the equipment is not working properly, the equipment manufacturer should be consulted.

Density tests using the proposed equipment should be performed as soon as possible, with consideration for safety and not interfering with other placing activities. The contractor should be aware that nuclear gauges must be attended or secured at all times, typically requiring personnel and a small truck at the test location. The lift may be re-rolled if it fails to meet the required density if it has not yet set or reached the time allowed for completion of compaction. Finish passes with the roller in static mode or with smooth rubber tire equipment may tighten up the top surface before testing.

Compaction is affected by the roller travelling speed as mentioned in Chapter 8. This condition must be considered during the RCC layer compaction and the speed should be recorded.

Sometimes, because of limited laboratory techniques and equipment, density and compressive strength cylinders made in the laboratory may not be representative of the quality achievable in the field. If these limitations are not recognized, they can result in the unwarranted use of extra cement or pozzolanic material, a more restrictive aggregate specification than is required, or over-design. During construction, comparisons should be made to see how closely laboratory procedures simulate field compaction and achieve similar qualities.

Low densities are the result of various deficiencies including high or low moisture, incomplete rolling, incorrect vibratory amplitude or frequency or speed time delay before rolling, poor gradation or segregation, and non-representative testing.

Two approaches to quality control of RCC density are **"method"** and **"performance"**. For routine control during construction, specifying a method consisting of a minimum number of passes with required rolling equipment is easier and has been used successfully. Occasionally, actual density tests should be performed to verify that the specified passes are routinely providing the required density. Specifying performance with a minimum density and an average required density regardless of the number of passes is an alternate approach that requires more testing but provides tighter control of placement.

A reporting procedure similar to that used for moisture content is useful. Results for density testing can easily be recorded on a control chart that graphically shows the results of each test for each day, the standard deviation for each day, the average for each day, and the moving average of the last 50 tests.

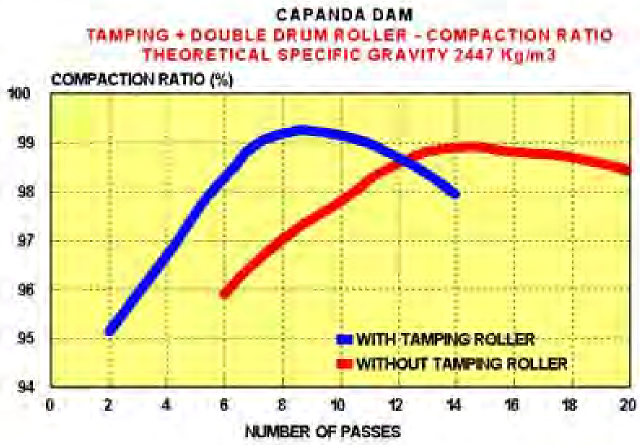


Figure 9.30 Compaction Ratio with different number of passes of Rollers.

For RCC compacting at Capanda, basically two types of rollers were employed: Double Drum Roller with two 10ton static weight drums and Drum Roller with one 10ton static weight drum and 31ton dynamic impact, under 1770rpm frequency.

Figure 9.30 illustrates the typical behavior of Capanda RCC compaction (in terms of compaction ratio) in function of the number of passes of a double drum roller. In addition to the rollers mentioned, a static 9ton pneumatic roller sometimes was also used for superficial sealing of the layer in order to reduce the work and prevent excessive removal of material during construction joint cleaning. Finally, an evaluation of performance of the tamping drum roller was also made to check density behavior in the middle and base of each layer.

9.6.6.2 Field Density and Compaction ratio

Density measurements should be continually taken during placing of RCC using a nuclear density gauge before, during, and following compaction. A single-probe or double-probe nuclear gauge provides reliable information when large- number readings are taken. However, the two-probe gauge provides the capability of monitoring RCC densities at all depths within the limit of fresh RCC. Data from nuclear-gauge readings can be used during the compaction process to confirm that the mixture proportions are correct for the required densities, for determining if densities are uniform throughout the lift, and for identifying rock pockets or segregation. Field nuclear-gauge readings should be compared on a continuous basis to RCC unit weight measured in the project laboratory. To ensure the accuracy of the nuclear gauges being used, a test block should be made during the early stages of the project and kept available. The nuclear gauges must be checked daily against a source of known density. The actual density of the test block should be determined by measuring and weighing the block or weighing cores taken from the test block.

The maximum achievable RCC density in practice is measured from fresh samples obtained at the mixing plant or from the placement. The samples are then consolidated or compacted in a field laboratory using the VeBe procedure (see Chapter 7 and Figures 9.20 to 9.24) or one of the compaction methods discussed later. The density test is used as a tool to find out the degree of compaction or air void content. Air voids for both air-entrained and non air-entrained RCC can be determined by compacting or consolidating the fresh RCC.

It is common to perform field density tests to establish or verify reasonable density requirements during construction. One approach to specifications is to base final field density requirements for the dam on density test results during placement of a control section. These tests may indicate that adjustments in mixture proportions are necessary in order to achieve the desired density, that the equipment and procedures for placement need to be modified, or that the density requirements should be adjusted.

The in-place density of RCC layers can be determined using various procedures. It is however advisable that the procedure used enables not only determination of the compaction value but possibly a supplementary or corrective action of the compacting operation based on the results obtained. Therefore, process swiftness and safety are fundamentally important. For the Capanda Project, compacting control was made using nuclear densimeter. Three methods however have been evaluated and studied and these are described in the following sub-items:

Method Using a Nuclear Densimeter: This is the most popular process used for the compaction control of RCC layers. It provides a gamma ray source of known intensity in the interior of the compacted layer. Measuring the emerging radiation volume at the surface, density is inversely proportional to that volume. Commercial equipment available in the market, the "densimeters", are factory gauged to measure materials with ranging densities between 1,600 and 3,000 kg/m^3 and special gauging is seldom required. Such devices also determine the moisture content, based on the measurement of hydrogen ions of the material. Special gauging may be required for humidity, depending on the chemical composition of the materials.

Two types of apparatus are commercially available for the nuclear test, a single-probe (Figure 9.31) and a double-probe (Figure 9.32) nuclear density gauge. Photons emitted by a radioactive source housed in the source probe are counted by a detector. For a given material, the density is proportional to the count rate of photons. The detector is located in the gauge housing for the single-probe gauge and in a second probe for the double-probe gauge. Testing may take 5 to 15 minutes depending on the number of positions that the gauge is rotated (for the single probe device), the ease of driving the probe hole, and the number of depths at which densities are checked. In many countries, gauges must be licensed by a Nuclear Regulatory Commission and operators must receive an approved training.

Both the single and double probe gauge have limitations due to design and gauge geometry. The single-probe gauge can measure up to 300-mm depth. The single probe gauge takes the average density of the lift from the bottom of the inserted probe to the top surface. However, the density result is heavily weighed to the more easily compacted top of the lift than the lower portion of the lift, which is more difficult to compact. A 10% drop in density in the bottom 50-mm

Figure 9.31 Single-probe nuclear density gauge.

Figure 9.32 Double-probe nuclear density gauge.

of the lift 3may only be recorded as a one- % drop in overall density with the single-probe gauge. Although not totally accurate, an indication of the change in density with depth can be obtained by comparing results at full depth and mid-depth.

Geometry-related problems of the single probe gauge are avoided with the double-probe gauge. The density is measured horizontally from the source probe to the detector probe at the same depth. Thus, individual "strata" are measured at different depths. The double-probe gauge can measure up to 610mm depth. Though more desirable than the single-probe gauge, the double-probe apparatus is more difficult and time consuming to use. The apparatus may not be readily available at private testing laboratories and it is more expensive. If the two pilot holes for the probes are not properly aligned in the RCC, the probes may not penetrate to the bottom of the holes, and the results will show more variation than actually exists in the RCC.

Density measured by nuclear gauges is affected by the chemical composition of the concrete components and may not be the "true" density. The gauge must be corrected for chemical composition error by determining the true density of fresh RCC compacted to different densities in a rigid calibrated container according to ASTM C-1040 [9.21] or some other acceptable standard, and comparing that density to the density indicated by the gauge. When testing RCC mixtures, particularly those with a MSA greater than 50mm, the probe holes must be driven into the fresh concrete quickly and not disturb the in-place density of the concrete. Voids created by driving the probe through larger aggregate can give erroneously low-density readings. Some projects have minimized this problem and variability of results by pouring a very fluid slurry of pozzolanic material or retarded cement and water into the hole prior to inserting the probe.

Attempts to use the sand cone test for in-place density for RCC have had little success. Material has squeezed into the excavated hole, resulting in tests in excess of the theoretical air-free density. The test is slower than the nuclear density test, the RCC sample is hydrating, (not necessarily drying) during the hour that it typically takes to excavate the hole, and personnel are in the way of production equipment during the extended time it takes to do the test compared to using the nuclear gauge.

The layer to be tested will have a vertical hole made by means of a hardened steel-point chisel. A metal template helps to maintain the chisel vertical during the spiking. Three measurements are taken for every test. The device is turned around the stem containing the radioactive source. This is the procedure to obtain a representative average value for a cone with a 50cm diameter, approximately. The practice observed in Capanda provides the following information:

✓ **Test duration**: 10 to 12 minutes, approximately, which makes it a quick and efficient test.

SPECIFIC GRAVITY COMPARISON AT VARIOUS DEPTH				
DEPTH (cm) LAYER	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
0 to 10	40	2419	0,8	98,86%
0 to 20	40	2421	0,4	98,94%
0 to 30	40	2413	0,3	98,61%
COMPACTION CONTROL OF EACH LAYER				
TOTAL RCC VOLUME (m^3)	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
650.622	5240	2412	0,5	98,57%
CONTROL OF THE FRESH RCC MIXES				
TOTAL RCC VOLUME (m^3)	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
650.622	395	from 2415 to 2462	from 0,1 to 1,1	from 98,69 % to 100,6%
COMPACTION CONTROL AT THE INTERFACE OF FACING MIX AND RCC				
NOMINAL VALUE FOR FACING MIX	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
2303 Kg/m^3	92	2364	3,7	96,61%
SPECIFIC GRAVITY COMPARISON FROM DIFFERENT METHOD OF TEST				
METHOD OF TEST	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
WATER VOLUME	16	2470	2,3	100,94%
NUCLEAR DENSIMETER	16	2413	0,3	98,61%
SAND VOLUME	45	2408	0,3	98,41%
NUCLEAR DENSIMETER	45	2410	0,2	98,49%
SPECIFIC GRAVITY COMPARISON FROM CORES AT HORIZONTAL AND VERTICAL DIRECTIONS				
CORING DIRECTION	NUMBER OF SAMPLES	SPECIFIC GRAVITY AVERAGE (kg/m^3)	COEFFICIENT OF VARIATION (%)	COMPACTION RATIO RELATED NOMINAL RCC
VERTICAL	103	2418	0,9	98,81%
HORIZONTAL AT TOP	21	2446	0,7	99,96%
HORIZONTAL AT BASE	19	2355	0,7	96,24%

Figure 9.33 Tests and statistical data about Density - Miscellaneous Procedure.

✓ **Inconsistent Results**: in some cases, the test hole is not vertical and this causes the loss of results. This aspect is related to the hardness and dimension of the coarse aggregate used in RCC.

✓ **Systematic Errors**: affected by the material roughness being tested. Such roughness refers to cavities outside the material under tests and within the Gamma Rays path. They may occur between the base of the device and the layer's surface, and also between the device stem and the wall of the test hole. Taking into consideration that the cavities are fulfilled with air, the roughness tends to minimize the result of the material being tested. Normally, for every millimeter of cavities' thickness, there is a negative deviation of about $10kg/m^3$ in the density value. This hypothesis may be reinforced by the analysis of the results presented in Figure 9.33 which were obtained through measurements in various depths for 40 test samples.

It is observed that the average density value measured (on drilled core samples) in the first 10 cm of the layer was $2{,}419kg/m^3$ Nevertheless, for tests carried out with RCC samples representing this same layer region, the average value of $2{,}446kg/m^3$.

It was also noticed that the variation of the measurement factor decreases according to the depth. This leads to the conclusion that there is a greater variance for tests carried out near the regions of greater roughness.

Alternatively, when maintaining the nuclear densimeters, the "water volume method" was normaly used. Density tests results obtained are also summarized in Figure 9.33. To meet the required compacted RCC behavior, some densities were additionally determined for the RCC "seam" regions next to the conventional concrete of the dam waterproofing face, hereto named "interface".

Water Volume Method: - This process was adopted at the beginning of the works, parallel to the use of the nuclear densimeter. It comprises basically the execution of a manual cavity in the material being tested; the volume of the hole is then measured deducting the weight of the material. The cavity is coated with a plastic film and then filled with water provided in a gauged container. Cavities were executed with a diameter of 30cm and vertical walls from the base to the layer being tested. This provided a volume of 25 liters, and 60kg of RCC, approximately. The results from this test in Capanda lead to the following comments:

✓ **Test duration**: 50 to 60 minutes; this is considered to be a hard and slow test in terms of RCC technology;

✓ **Inconsistent Results**: because of the angular aggregate;

✓ **Systematic Errors**: because of the aggregate's dimensions and hardness, irregularities in the walls of the hole make the spreading of the plastic film difficult, tending to decrease the measured volume. Consequently, densities result bigger than what they really are.

Sand Volume Method: - This method uses the same basic concept of the Water Volume Method: the only difference is the measurement process of the cavity volume which, in this case, is performed with standardized and calibrated sand. Standardized sand means a monograin sand with a known and constant density. Cavity dimensions and sample characteristics were the same used in the previous process. The practice resulting from this test in Capanda lead to the following comments:

✓ **Test duration**: 70 to 80 minutes; this is considered to be a hard and slow test in terms of RCC technology;

✓ **Inconsistent Results and Systematic Errors**: the effect of the cavity walls' irregularities is less identifiable in this test because there is no coating. If negative slopes are avoided for walls and if the test area is isolated from vibrating equipment, the precision of this method is considered satisfactory.

Direct method on samples drilled from the dam core:- This method determines the density directly from the sample, using the Archimedes postulate. This method allows only for checking and confirming control data because it can only be carried out after the sample extraction.

Correlation Between the Various Densimeter Processes: - Compaction control of the RCC layers is basically executed by means of a nuclear densimeter, currently accepted as the most quick and efficient method to control big masses of this material. However, the densimeter available at the site had a stem with no more than 30cm. Taking into consideration that the RCC layers are poured from a height of 40cm, the density of the last 10cm are disregarded. So it was necessary a criteria for the evaluation of the average density in the entire layer depth (up to 40cm), based on the results obtained for the maximum depth available of 30cm. In short, the initial tendency of the nuclear results to present positive deviations because they do not cover the layer bottom is, in reality, offset by the general tendency for negative deviations caused by surface irregularities (cavities) found in the Gamma Ray path. When determining the density in laboratory from the extracted samples, the RCC samples' weight was determined by precision scales and the volume determined by the water dipping process (Archimedes). Since this is a typical laboratory process, time, risk and precision factors are irrelevant.

The reduced number of available samples may be mentioned as an obstacle to becoming a routine test, due to difficulties and the basic cost of drilling the cores for samples.

Figure 9.33 shows the tests with samples horizontally drilled, containing the construction joint in its intermediate plan. Such samples presented in their lower part the top of a given layer, and in their upper part, the base of the next layer. Due to the internal dimensions of the extracting ring (200mm), each half represents an average of 100mm from top and base of two consecutive layers. All of the tested samples were drilled from layer joints without "bedding-mix" treatment. Theoretically, layers' base treated with "bedding-mix" tend to present higher density values due to the sealing of the RCC cavities, caused by the rising of the fluid mortar from the "bedding-mix". An average value of 2,418kg/m^3 was found for the vertical samples, as in Figure 9.33; it is verified that the average density of the RCC met the minimum value specified. At the interface region, the conventional concrete application and the RCC, the density obtained showed the ratio of 2,364kg/m^3 (interface) to 2,412kg/m^3 (for all the layers controlled).

Consolidation at Interface between RCC and CVC concrete: - As mentioned in the previous paragraph consolidation at the interface of RCC and conventional concrete is a critical area of concrete construction that, if not executed properly, can and likely will result in voids. Such voids, because of their location and distribution, may allow leakage through a structure. If RCC and conventional concrete are fresh, of proper consistency, and consolidated with immersion vibrators on a proper spacing, the consolidation procedure is straightforward, easy to execute, and will result in a high quality, void-free product. On a day-in, day-out basis, however, this has been difficult to achieve.

This is a construction procedure in which attempts to compensate for a developing problem may actually intensify the problem. For example, while extra efforts are being made to consolidate concrete that has begun to set or stiffen in one area, concrete materials in another area are becoming progressively older and thus harder to consolidate.

Eventually a condition develops in which the contractor has lost control and no amount of effort will prevent permanent voids from occurring. The contractor and OGA personnel should be aware of the urgency for rapid adjustments to prevent this situation from occurring. Such adjustments may include immediate addition of extra crews and interruption of RCC placement until consolidation of the conventional concrete/RCC interface is again on schedule. Again, judgment and cooperation should be used in establishing criteria for when and under what conditions these extra procedures are to be initiated.

9.7 Compressive Strength

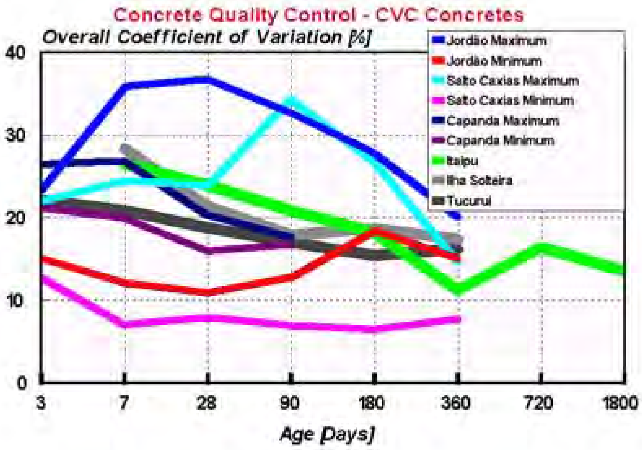
Compressive test specimens of mixtures with a consistency measurable by vibration time, will fully consolidate under extended external vibration. Full consolidation is achieved when paste rises to the surface. Over vibration is not a problem because of the very low entrainment of air in mixtures of this stiffness. Cylinders will require longer periods of vibration than the consistency measurements because of the difference in shape of the containers. A surcharge weight may be needed for mixtures that require more than 30sec of vibration for consolidation by the standard VeBe. Test specimens molded in this fashion correlate extremely well with cores when tested at the same age.

Test specimens of mixtures of unmeasurable consistency will not fully consolidate under external vibration and must be molded by some other means. The key to preparing test specimens of unmeasurable consistency RCC appears to be that of correlating the compacting effort in tamping the cylinders with the compacting effort of the field placement.

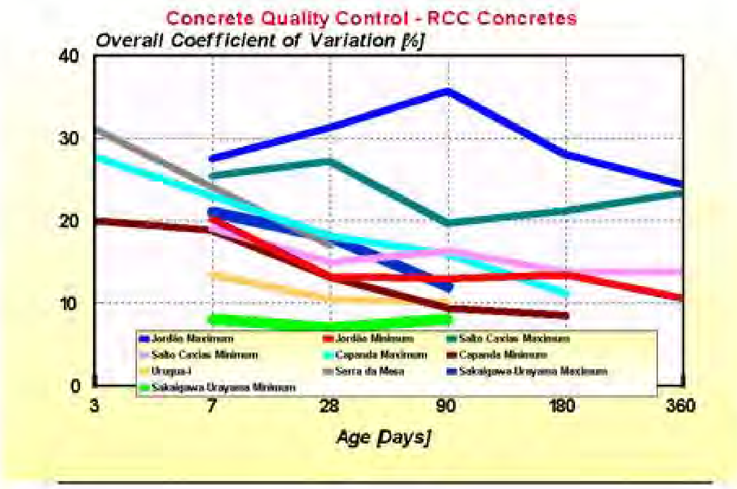
Figure 9.34 RCC Specimens with irregularities at the top.

RCC strength test specimens may have extremely low early-age compressive strengths, which makes handling, stripping and capping difficult. A procedure that minimizes the problem of handling and storing these cylinders is to compact the specimens in thin or pre-cut metal, PVC, or plastic liners that are supported by rigid molds during compaction. The sample and liner is removed from the rigid mold after compaction. The liner then stays on the sample until it is tested.

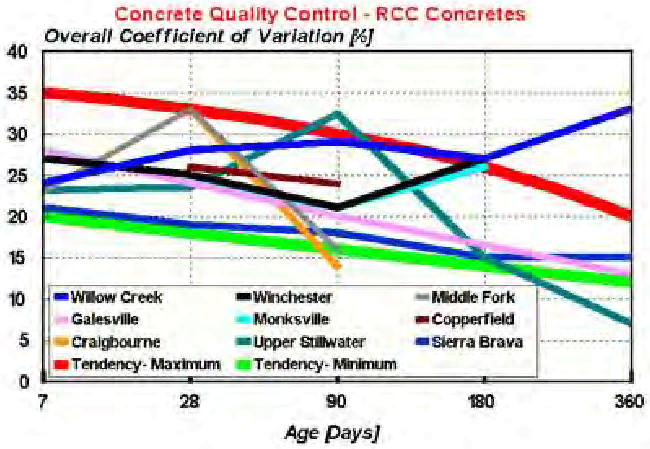
Because of the rapid rate of RCC production and the fact that most projects use design ages of 90 days to 2 years, RCC strength tests have limited use as a Quality Control tool. By the time reliable results indicating a low ultimate strength are available, the works are well beyond the location where the questionable material was used.



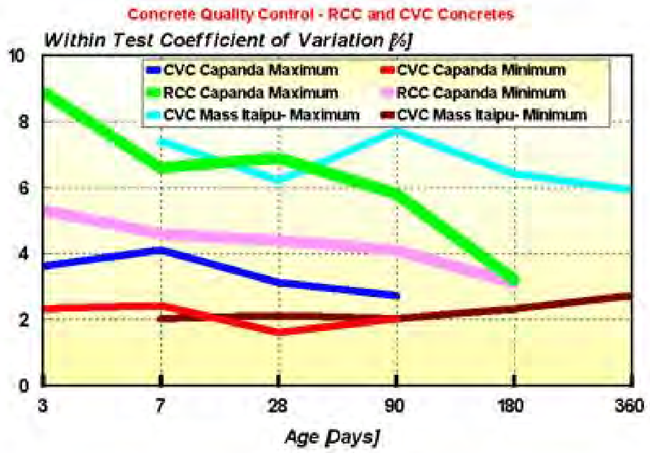
a



b



c



d

Note: This analysis may adopt both the criteria of ACI 214-65 - "Recommended Practice for Evaluation of Compression Tests Results of Field Concrete"[9.08], and of ACI 214-77 - "Recommended Practice for Evaluation of Strength Tests Results of Concrete"[9.09].

Figure 9.35 Data on Coefficients of Variation obtained in RCC control compared with values of Coefficients of Variation for compressive strength of Conventional Mass Concretes and RCC in other Projects.

Initially, RCC projects followed the habit from conventional concrete of making many cylinders for compression tests; many projects requested a set of cylinders per shift for testing all ages of 3, 7, 28, 90, 180, and 365 days. Some later RCC projects started making fewer cylinders, with one set every two or three shifts of production for testing at fewer ages of 7, 28, and 90 days. Then every third set would include additional ages. Although some designers still require substantial cylinders for historical information, the trend has been to minimize the number of cylinders and put more emphasis on inspection of the actual work as it is being done. If required, cores can be taken after completion of the project for more meaningful historical information.

Accelerated cure (ASTM C-684 [9.22]) of cylinders and mortar cubes has been used in an effort to get an earlier indication of ultimate strength potentials and variability in cementitious materials. Some projects have found this information useful, while others have found it to be cumbersome and not indicative of actual final strengths or variability. Accelerated cure appears to have more potential for success with higher cementitious content mixtures and conventional aggregate.

For the RCC used in Capanda, the minimum compressive strength required was (f'ck) 80kgf/cm^2, at an age of 180 days, with a deficient quantile of 20% (reduced normal variable "t"= 0,84). For supplementary assurance, initial compression evaluation was concentrated at the age of 90 days. Statistical data obtained are shown in Figure 9.35.

Figure 9.35 shows variation coefficients obtained in the RCC control for Capanda, compared with the same parameters for other projects, as well as with same control parameters for CVC mass concrete with cementitious content (cement+pozzolanic material) between 84kg/m^3 and 134kg/m^3, used in projects for Ilha Solteira Dam, Tucurui Dam and Itaipu Dam [9.16]. Parameters of these conventional concretes refer to a universe of approximately 25,000 samples representing about 8,800,000 m^3. Figure 9.35 also shows a comparison values for coefficients of variation, for compressive strength for CVC concrete mainly used in Capanda. Determination of the specific gravity for these test specimens has resulted in the values shown in Figure 9.33.

Quality performance of concrete plants, concrete and operators control may be evaluated by the dispersion in the results for compressive strength obtained from the concrete produced by them. In the same way, quality of the strength tests may be evaluated from its own internal dispersion from control. Internal dispersion of the test is evaluated from the difference between the individual values obtained for strength tests in specimens of the same series, broken at the same age.

Detailed studies [9.23] in statistic control of concrete quality have demonstrated that the Coefficient of Variation (Vn) is not a very representative parameter for concretes with medium strength of up to 210kgf/cm^2. Therefore, dispersion measured by coefficients of variation, as recommended by ACI 214-65, is more appropriate for concrete with low cementitious content mixes. These same studies have also revealed that standard deviation remains practically constant for concrete with strengths higher than 210kg/cm^2. In this case, dispersion measure from Standard Deviation, as recommended by ACI 214-77, becomes more appropriate for structural type concrete or for concrete with high cementitious content. For dispersion measure within the test, (i.e., variety of molding process, handling, cure, coating and application of compression load to test specimens) the Coefficient of Variation is recommended by both norms. Figure 9.36 shows the various control standards and application criteria.

The test data on samples obtained from the drilled cores is a tool to compare the data from standard control and the dam body, as shown in Figure 9.17.

	STANDARDS FOR CONCRETE CONTROL - (ACI 214 - BEFORE MAY/ 76)					
	CLASS OF OPERATION	COEFFICIENT OF VARIATION (%)				
		EXCELLENT	GOOD	FAIR	POOR	
OVERALL	GENERAL CONSTRUCTION TESTING	< 10	10 to 15	15 to 20	>20	
VARIATION	LABORATORY TRIAL BATCHES	<5	5 to 7	7 to 10	>10	
WITHIN TEST	FIELD CONTROL TESTING	< 4	4 to 5	5 to 6	> 6	
VARIATION	LABORATORY TRIAL BATCHES	< 3	3 to 4	4 to 5	> 5	
	STANDARDS FOR CONCRETE CONTROL - (ACI 214 - AFTER MAY/ 76)					
	CLASS OF OPERATION		COEFFICIENT OF VARIATION (%)			
		EXCELLENT	VERY GOOD	GOOD	FAIR	POOR
OVERALL	GENERAL CONSTRUCTION TESTING	< 28,1	28,1 to 35,2	35,2 to 32,2	42,2 to 49,2	> 49,2
VARIATION	LABORATORY TRIAL BATCHES	< 14,1	14,1 to 17,6	17,6 to 21,1	21,1 to 24,6	> 24,6
WITHIN TEST	FIELD CONTROL TESTING		COEFFICIENT OF VARIATION (%)			
WITHIN TEST	FIELD CONTROL TESTING	< 3	3 to 4	4 to 5	5 to 6	> 6
VARIATION	LABORATORY TRIAL BATCHES	< 2	2 to 3	3 to 4	4 to 5	> 5

Figure 9.36 Standards of concrete production controls and tests [9.08 and 9.09].

9.8 Temperature Control

The RCC temperature depends on the temperature of concrete ingredients and average ambient conditions. When a maximum or minimum temperature is specified it is usually determined just before or after compaction. The temperature is normally determined by thermometers or thermocouples embedded in the concrete.

Since many specifications for mass structures limit the placing temperature of the RCC, a procedure must be established to lower and control the temperature of the mix. Temperature must be recorded at the time of placement.

The benefit of pre-cooling the mix by the addition of ice or chilled water is minimal when compared to conventional concrete because of the relatively low volume of total water in the mixture. From a quality control standpoint special attention should be given to the mix if the use of ice is attempted. Because there is little slurry or fluidity, additional mixing may be necessary to insure that all of the ice melts and that it is then given enough time to mix with the other ingredients as water rather than chunks of ice.

9.9 Grade and Alignment Control

The compaction equipment used in RCC construction is typically insensitive to minor and gradual variations in lift thickness. A tolerance of about ±15 % of the lift thickness is reasonable, with maximum limits of 50mm in a 300-mm lift. Such limits are easily achieved by using a standard rotating beam laser level and a rodman with a receiver target who spot-checks and assists the spreading equipment operator. More accurate control can be achieved through the use of a laser-controlled blade on spreading equipment, but this is usually not necessary.

Where an RCC lift spreads into a rising bedrock foundation area becoming thinner, the lift should be terminated before it becomes too thin (approximately twice the maximum aggregate size). This results in a thicker section of the subsequent lift in the area where the previous lift terminates.

Alignment control can be provided by laser or by conventional survey, depending upon what is required considering both appearance of the finished structure and technical requirements. The top edge of unformed sloping faces should be given particular attention. A successful procedure has been to overbuild slightly each layer past the design line, and then paint a line on top of the lift at the location where the subsequent layer terminates to act as a placing guide. Building back a narrow area is extremely difficult if the width of any layer is not spread and compacted out to the design line.

Figure 9.37 Laser ray for grade control at Urugua-i dam-Argentina.

Figure 9.38 Laser sensor for grade control installed at dozer blade at Upper Stillwater dam - USA.

9.10 Test Fill Section

9.10.1 General

The construction of a project test fill section by the contractor (after award of the contract and before beginning production operations) is essential whenever RCC is an option or requirement as a further aid in training both inspection personnel and contractor personnel. The experience gained on a test fill section will provide a common basis of knowledge between government and contractor personnel and allows for the contractor to try new and innovative construction techniques in work not affecting the safety or function of the project.

The test fill section provides an opportunity to adjust the RCC mixture proportions. The test fill section should be designed to demonstrate the contractor's capability to produce the quality and quantity of RCC required by contract specifications. A project test fill section should be constructed sufficiently early in the contract to allow the contractor time to increase the size of his batching, mixing, or transporting system, if necessary, to modify placing, spreading, and compaction techniques, or to modify any other operation that is considered essential to the success of the job. The test fill section should never be part of the permanent structure.

Just as the use of test fills is valuable for quality assurance in embankment dam construction, test sections or "demonstration" sections are important in RCC construction. Numerous large-scale test sections have been made for research purposes and by designers in this developing technology, but the contractor on each new dam should be required to build a test section with important objectives in mind. Such a program should be integrated with the training and orientation of the supervisors, inspectors, and workmen, as discussed in 9.3. The test section should reproduce actual placement conditions and provide experience for all concerned. As a result, it should be located near the dam and use the same equipment specified for the dam. Supervision should be carried out by the same people.

Points of concern will include optimization of the RCC mixture and water content, segregation control, compaction, face treatment and forming, line and grade control, calibration of nuclear gauges, and a shakedown of the testing laboratory, all leading to quality dam building.

One of the primary purposes of a test section is for the contractor to demonstrate equipment and procedures to be used for mixing, handling, and placing RCC and conventional concrete, and to pre-qualify compaction procedures and equipment. It also serves as a training and practice area for both inspection and construction personnel. Many projects refer to the test section as a trial, practice, or equipment calibration exercise. It is important to recognize that especially if the section is small or full production equipment is not available, the same quality expected under full production conditions will be difficult or impossible to obtain.

A test section is preferred over starting immediately on the dam because the first placement is typically at a critical section of the structure at its base. An alternative is to place the test section in a non-critical section of the dam such as foundation replacement material, or as part of the stilling basin.

Test section construction gives the contractor the opportunity to test and trouble shoot the construction process and equipment, and to evaluate various alternative methods. It gives the owner and engineer the opportunity to evaluate the contractor's methods and estimate whether they are appropriate for the project. Test section construction provides orientation and guidance to inspectors, quality control staff, and field construction staff. Individuals who must work together on a day-to-day basis can observe, together, acceptable and unacceptable performance and procedures. Special efforts are needed to fully realize the benefits of the test section. It is often beneficial for the entire contract administration field staff as well as the contractor's field supervision staff and placing crews to be present for test section construction. The test section is a good opportunity for inspection and laboratory personnel and the contractor to work out communication procedures. A wrap-up session is recommended.

It may be necessary to construct the test section well in advance of the dam so as to allow enough time for evaluation of the RCC mixture in both the fresh and hardened conditions, and to make adjustments if appropriate. This can be the final phase to the mixture-proportioning program. In other cases, it may be appropriate to do the test as part of initial construction in a non-critical part of the dam or in a temporary structure, but this prevents evaluation of long-term properties of the RCC production. Typically, the test section is two to four lifts high and includes at least one lift joint requiring joint surface cleanup. The facing system should also be evaluated in the test section. Test section construction should be staged so that numerous operations are not required at the same time.

Workability and density of the RCC mixture are evaluated by laboratory testing and any mixture proportion adjustments can be fine-tuned during construction of the test section. This may include adjusting the water content, cement plus pozzolanic content, or sand/aggregate ratio. The test section can also be used to determine field density requirements.

Figure 9.39 Test Fill Section at Itaipu (1977)- Topographic survey to check the number of roller passes and RCC top of layer settlement.

Methods of evaluating lift joint quality, a critical part of RCC dams, include coring, sawing, test trenches, and demolition of the test section with heavy equipment. Cores representative of the mass may be difficult to recover at early ages and/or with low cementitious content mixtures. To increase core recovery, cement might be substituted for pozzolanic in the top lifts. A split inner tube core barrel increases core recovery and minimizes drilling damage, particularly at lift joints.

9.10.2 Aspects to be Evaluated

The data collection included the following main aspects:

✓ Performance of the CVC and RCC;
✓ Foundation and construction joints treatment;
✓ CVC and RCC placement and spreading;
✓ CVC and RCC consolidation - including the interface between them;
✓ Choice of the minimum number of compactor roller passes to meet the required density;
✓ Checking the ratio between compaction and layers height;
✓ Anchor length between CVC and RCC to simulate the anchor to be adopted in the spillway area;
✓ Formwork system for the downstream and upstream facing;
✓ Use of precast concrete pieces to the conformance of the drainage gallery;
✓ Induction conformance method of the contraction joints.
✓ RCC and CVC production and transport system;
✓ Curing System;
✓ Team performance.

Figure 9.40 trench Test Fill Section- CESP Laboratory – Ilha Solteira - Brazil (1993).

9.10.3 Tests Program

A specific test program must be developed and exhaustively discussed. Tests must be scheduled for every concrete layer placed at the fill. Test specimens molded during the fill execution (cylindrical molds) by means of a vibrating table or pneumatic compactor must be planned to establish:

✓ Compressive Strength;
✓ Tensile Splitting Strength;
✓ Modulus of Elasticity.

Figure 9.41 RCC placement at the Test Fill- Capanda Site – Angola (1989).

Many drilling cores must be considered with recovery of the samples for evaluations at ages ranging from 90 to 360 days. The purpose of the tests is to evaluate:

✓ RCC contact and the foundation rock;

✓ Performance of the construction joints under various types of treatment and for different delay time intervals between layer placement.

✓ RCC interface performance and conventional concrete facing ;

✓ Mortar and Concrete Performance (CVC) used as "Bedding Mix" in the construction joints between layers.

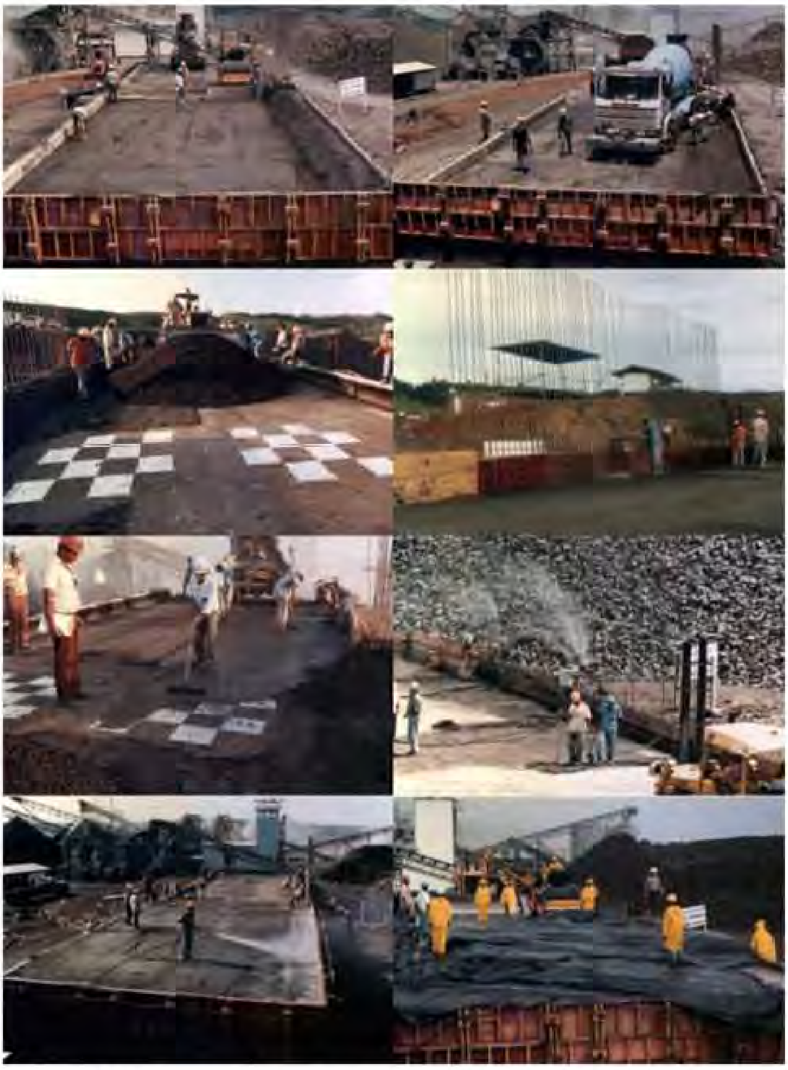


Figure 9.42 General View of the Test Fill during execution- Foundation Preparation; Forms Preparation; Face Mix & Bedding Mix placement; Spreading RCC; RCC Compaction; Contraction Joint Form-Inducer- Salto Caxias Site- Brazil (1996).

When the fill was completed, approximately 60 days after execution of the last layer, the samples of the delimited areas started to be cored, as shown in Figure 9.43. These were identified, packed in wooden boxes (Figure 9.44) and sent to be tested at the laboratory or tested "in situ" (Figures 9.45 and 9.46), as scheduled.

Figure 9.43 Drilling cores from the Test Fill- Jordão Site- Brazil.

Figure 9.44 Packaging of the samples to be tested- Jordão Site- Brazil.

Figure 9.45 RCC block-specimens being cut by a diamond saw blade – Salto Caxias Site-Brazil.

Figure 9.46 RCC block-specimens under testing – Salto Caxias Site-Brazil.

9.11 Instrumentation

Any dam is subjected to external loads that cause deformations as well as seepage through the structure and its foundation. Loads and the dam's response to them should be monitored for any sign of abnormal behavior, and corrective action should be taken before the problem becomes a threat to the dam's safety.

In developing a program to monitor the performance of an RCC dam, primary consideration should be given to obtaining information with which the dam's safety can be evaluated. Of secondary importance is obtaining information to check initial design assumptions in order to provide improved design criteria or construction methods for future RCC dams.

The monitoring of completed RCC dams should consist of measurements obtained from instruments and visual inspections. Neither instrumentation nor visual inspection is sufficient on its own. Visual inspection and simple monitoring can take many forms and should be performed regularly. Seepage is the single-most-important item that can be evaluated in this manner. Some questions that should be answered in inspecting for seepage are:

1. Where is the seepage occurring: through the entire dam or at selected places, such as cracks or horizontal lift lines within the dam's structure, or through the dam's foundation?

2. What is the magnitude of the seepage? Is it reducing over time with a constant reservoir level?

3. What is the color, chemistry, or pH of the seepage water? has the seepage water a high alkalinity, or has it a reduced water quality or an anpleasant visual downstream? Does it contain any sediment?

4. Have any calcium carbonate deposits been noticed that clog drain holes or appear on the downstream face, in the gallery, or in waterways downstream of the dam?

Of special importance is an abrupt increase in seepage. Based on performance of existing RCC dams, it is assumed that seepage will reduce with time and that wet spots will eventually dry up. Therefore, if a significant increase in seepage is noted without a rise in reservoir level or if new leaking cracks are noticed, there is reason for concern. The situation should be analyzed to determine the cause and if any remedial action is required. It should be kept in mind that during cold weather, seepage may increase because of thermal contraction that opens up existing cracks or creates new ones. Drains should be reestablished if they become clogged.

Other problems that can be visually detected include movement of the dam, its appurtenances, and abutments; freeze-thaw or other deterioration; erosion in the structure or on downstream surfaces following a flood; or cracking or other damage from an earthquake.

Cores extracted from the dam can be an excellent tool for post-construction analysis. In addition to being tested to determine the properties of the RCC, including bonding between lifts, the cores can be visually inspected. Inspection of cores for voids can provide an indication of the degree of compaction, segregation, and permeability, usually at the bottom of the lift.

The amount of instrumentation provided depends on site and operational conditions as well as the owner's needs. Instrumentation takes on greater significance with higher dams, poorer or more complex foundation conditions, and locations where a dam failure would have significant consequences. A private owner of a single low-budget dam may not be as interested in the secondary function of instrumentation as a large governmental agency that builds many dams at differing site conditions over a long period of time.

The instrumentation program should be determined by the dam's designer, who best understands the dam's purpose, design assumptions, and potential problems. The designer should determine which items should be monitored at all times to help evaluate the safety of the dam and what information is needed over the long term to check design assumptions.

Once the desired primary and secondary functions are determined, the type, number, and location of the instruments can be selected based on reliability and cost. The location of instruments in an RCC dam can be quite important, because numerous or poorly located instruments can slow the placement of the material.

Figure 9.47 Instruments arranged mainly in one section at Capanda dam - Angola.

9.12 Laboratory

A facility to house the assurance control testing equipment and to provide working space for the inspectors shall be provided at an approved location within the plant or on an immediately adjacent floor. The laboratory area mentioned in this paragraph is adjacent to and separate from the sampling facilities. This room shall have a floor approximately 100m^2 in area, shall be reasonably soundproof and dust-proof, shall be air-conditioned and lighted. The control room shall be located in an area adjacent to the batch board where the inspector can readily observe the batch board and batch plant operator. It must also be provided with an exterior window, which will allow ready observation of all concrete transporting vehicles leaving the immediate area of the batch plant. Enclosed toilet facilities near the control room shall be furnished and kept clean. Drinking water shall be provided.

9.13 Summary

The following recommendations can be summarized:

I. Inspection is not an end in itself, but rather a part or subsystem of an overall Quality Assurance system;

II. The overall Quality Assurance system starts with essential and key social parameters that have to be considered and met;

III. The engineer should be involved in order to be able to provide his input and influence the overall decisions;

IV. When the engineer is responsible for the design, he determines what is needed in the drawings and specifications in order to provide the owner with the structure or plant that will perform the service needed at a minimum cost and consistent with the quality required;

V. Quality is more than quality of materials. It should be thought of as the quality of the finished project judged by how well it serves society: physically, functionally, emotionally, environmentally, and economically;

VI. Specifications should be in tune with nature and designed to provide clear requirements that can be met by reasonable men trying to do the work;

VII. Inspection starts during the construction phase or subsystem. There are three basic approaches to conducting the construction operations:

(a) Conventional construction where the owner is represented by the engineer and a contractor does the work - still the best approach in most situations;

(b) Turnkey type of construction, most useful in very complicated and highly technical and specialized facilities;

(c) Construction-manager approach in which the owner delegates the managing of the construction phase to a construction manager, who may differ from the design organization, with a contractor doing the actual work - lack of continuity;

VIII. Quality Control by the various producers or contractor requires inspection as well as inspection for acceptance by whoever represents the owner;

IX. Inspection is, therefore, a key element in the construction phase;

X. Inspection is seeing that good construction in accordance with the plans and specifications is accomplished;

XI. The inspector has to be technically knowledgeable in the field of inspection he is charged with;

XII. All these qualities are expected and proper therefore training and straight attitudes are required and have to be adequately paid for. It is time that proper training be required and commensurate pay be allowed for this work. Maybe a practical school with a degree in inspection can find a place in our educational systems;

XIII. Communication is the most essential element in inspection. Pre-construction conferences and regular meetings during construction between all parties are essential to get the work done properly and efficiently, to eliminate adversary relationships, and to maintain a team effort;

XIV. The inspector should be proud of his work and be a full-fledged member of the engineering team.

9.14 REFERENCES

9.01 ASTM-E-105. "Practice for Probability Sampling of Materials", in: Annual Book of ASTM Standards, 1994.

9.02 ANDRIOLO, F. R. and SCHMIDT, M. T. "The Capanda RCC dam in Angola", in: International Water Power & Dam Construction, United Kingdom, vol. 44, nº 2, February 1992.

9.03 ANDRIOLO, F. R. "Desenvolvimento de mantas de P.V.C. - Opção Técnica e Econômica para Impermeabilização de barragens", in: Proceedings of the XIX Seminário Nacional de Grandes de Barragens. Aracaju, Brazil, March/1991.

9.04 ASTM C-172. "Method of Sampling Freshly Mixed Concrete", in: Annual Book of ASTM Standards, 1994.

9.05 ASTM C-94. "Specification for Ready Mixed Concrete", in: Annual Book of ASTM. Standards, 1994.

9.06 CRD C-55. "Test Method for Within-Batch Uniformity of Freshly Mixed Concrete", in: Handbook For Concrete and Cement. US Army Engineer, August/1994.

9.07 ACI - Committee 207. "Mass Concrete for Dams and Other Massive Structures". Detroit: American Concrete Institute, 1980.

9.08 ACI 214-65. "Recommended Practice For Evaluation Of Compression Tests Results Of Field Concrete". Detroit: American Concrete Institute, 1975.

9.09 ACI 214-77. "Recommended Practice For Evaluation Of Strength Tests Results Of Concrete". Detroit: American Concrete Institute, 1980.

9.10 TAVARES, M.; SCHMIDT, M. T.; RESENDE, F. D.; FONTOURA, P. A. F. and ANDRIOLO, F. R. "Capanda – Angola - hydroelectric development. Quality control of materials and conventional and roller compacted concretes", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

9.11 ASTM C-1078. "Test Methods for Determining the Cement Content of Freshly Mixed Concrete", in: Annual Book of ASTM Standards, 1996.

9.12 ASTM C-1079. "Test Methods for Determining the Water Content of Freshly Mixed Concrete", Annual Book of ASTM Standards, 1996.

9.13 REZENDE, S. P.; CARVALHO, L. H.; QUIN, J. T. "Inspection and Control of the Saco Dam Construction - Nova Olinda, PB", in: XVIII National Seminar of Large Dams. Foz de Iguaçu, Brazil, 1989.

9.14 QUIN, J. T.; CARVALHO, L. H.; REZENDE, S. P. "Construction of the Saco Dam - Nova Olinda, Pb", in: XVIII - National Seminar of Large Dams. Foz de Iguaçu, Brazil, 1989.

9.15 MODE, A. C. M.; DIAS, E. G.; CARMO, J. B. M.; FARAGE, J. F.; SILVA, J. V.; FONTOURA, J. T. F.; GRACA, N. G.; PACELLI A. W. "Construction and Control of Roller Compacted Concrete for the Climbing Cofferdams of the Serra da Mesa Power Plant - São Felix Hydroelectric Development", in: XVIII National Seminar of Large Dams. Foz do Iguaçu, Brazil, 1989.

9.16 ANDRIOLO, F. R.; GOLIK, M. A. "Uruguai (CCR) - Quality Control of the Concrete Poured in the Dam Major Tramo", in: XVIII National Seminar of Large Dams. Foz de Iguaçu, Brazil, 1989.

9.17 ANDRADE, Walton Pacelli de. "Water Content – DMA - Brazilian Method", 1997.

9.18 ASTM C- 1176. "Standard Practice for Making Roller Compacted Concrete in Cylinder Molds Using a Vibrating Table", in: Annual Book of ASTM Standards, 1996.

9.19 ANDRIOLO, F. R.; BETIOLI, I.; SCANDIUZZI, L. "Concreto Adensado com Rolo Vibratório", in: Proceedings of the XIII Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, April/1980.

9.20 OLIVEIRA, P. J.; SALLES, F. M. and ANDRIOLO, F. R. "Studies of various types of RCC mix designs. Laboratory test results", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

9.21 ASTM C – 1040. "Test Method for Density of Unhardened Concrete in Place by Nuclear Methods", in: Annual Book of ASTM Standards, 1996.

9.22 ASTM C-684. "Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens", in: Annual Book of ASTM Standards, 1996.

9.23 Report C-06/80. "Strength Parameters Analysis of the Mass Concretes of the Itaipu Main Structures", in: Itaipu Binacional Brazil/Paraguay, February/1979.

9.24 "Engineering and Design, Roller Compacted Concrete", in: Engineering, Manual nº 1110-2-2006. Washington, D. C.: U.S. Army Corps of Engineers, February 1992.

9.25 "Guidelines for Designing and Constructing Roller-Compacted Concrete Dams", in: ACER Technical Memorandum nº 8. Denver: U. S. Bureau of Reclamation, 1987.

9.26 "Engineering and Design, Roller Compacted Concrete", in: Engineering, Manual nº 1110-2-2006. Washington, D. C.: U.S. Army Corps of Engineers, February 1992.

9.27 Bureau of Reclamation, "Procedure for Determining Cement of Soil Cement(Heat of Neutralization Method) - (Preliminary), Denver, Co.

10

Costs

10.1 Main Aspects

The use of RCC technique in the construction of dams and pavements has started formally in the beginning of the 70's and came to a summit ten years later. In 1996, about two hundred dams have already been built with this technology.

This constant evolution is meaningful and widely known. However, some issues are still under debate regarding costs of the many waterproofing face alternatives, the use of the bedding mix and the cost of RCC itself, as well.

Roller compacted concrete is usually just one of the several possible technical solutions for a proposed dam. If RCC is selected for the final design, it is because the estimated cost is favorable when compared with other technically acceptable alternatives. Both owner and the contractor want their actual cost to be as near as their estimated cost. RCC has recently showed an economically attractive material for gravity dam construction, replacing the use of conventional concrete and even challenging the economics of earthfill and rockfill embankment dams.

RCC has made gravity dam construction competitive with embankment dam construction. In general, the greater the average height of the dam, the greater will be the economic attractiveness of RCC gravity dam and even more to an arch-gravity section. An additional economic advantage of RCC gravity dam is the ability to simply build an inexpensive overflow spillway. Comparatively, a separate side channel spillway, necessary in the case of embankment dams, may often account for as much as 20% to 30% of the total dam project cost. Further economic advantages of RCC gravity dam are achieved in the intake tower design and construction. With greatly reduced volumes in the RCC gravity dam, construction may also be completed in a much shorter time with resulting economic savings.

Roller compacted concrete technology has matured to the point that RCC dams are ready to take their rightful place among the major dam types. In RCC dam concept, inherent safety, aesthetic and maintenance advantages of a concrete dam are combined with a low cost and high production rates usually associated with earthfill or rockfill embankments.

High production in an RCC dam, however, is governed by more than the size of the contractor's batch plant. The designer should always be conscious about how his design, specifications and control measures may affect the production rate. Small obstructions can make a large difference in the sustained average rate of RCC production. The same warning applies to the contractor. The contractor should design carefully the plant and the rest of the operation and staff it well; otherwise he may fail to obtain the expected production by a wide margin. The economic success of an RCC placing operation is not measured by daily or even monthly production records, but by a sustained average production rate for the entire dam. These generalizations are well known to designers and contractors.

The greatest economic benefit is that diversion capacity and upstream cofferdam may be smaller. This is due to fast construction using RCC method together with its erosion resistance. If construction is planned to coincide with a period of low stream flow, the diversion scheme may be designed for a lower flow rather than a five to ten year frequency flood.

If the cofferdam is overtopped, damage may be minimal as demonstrated during the construction of several dams, as the large flow that happened during Salto Caxias dam construction in Brazil.

The use of RCC in dam construction placed by conventional earthwork techniques results in a much lower unit cost per cubic yard of concrete placed, as compared to gravity concrete dams built by conventional mass concrete placement techniques. The reason for this economy is the construction technique used, basically similar to embankment dams construction techniques.

At a given height, the RCC gravity dam contains a much smaller volume of construction material. This, together with the speed of the RCC construction method, results in a much shorter construction time than that required for embankment dams. Therefore, RCC construction has a considerable appeal in areas where the construction season is short, and has an economic advantage when considering the time-factor cost.

Appurtenant structure location or elimination and construction alternatives provided by RCC also offer additional economic advantages. Spillway, energy dissipator and intake structure requirements specifically may have an adverse impact on overall economics of the embankment dam construction. With RCC gravity dam, floodwater may be spilled directly over the dam crest by an overflow spillway, thus eliminating the need for a conventional separate side channel spillway. Such structure may typically constitute a significant item regarding construction budget.

Major economic advantages may also be achieved with RCC overflow sections by using a stepped spillway chute or ski jump flip bucket as energy dissipators. The stepped spillway chute consists of steps, approximately 0.3m wide and 0.6m high each step. This spillway chute results in energy dissipation as the water cascades down the steps. Thus, only a relatively small stilling basin, also built in RCC, is required at the exit end of such overflow stepped spillway chute. A ski jump flip bucket is a large bucket structure that remains above the flood tailwater level and dissipates energy by flipping or spraying the spillway flows into the air. Such energy dissipator may be built on a very economic basis by overbuilding the toe of an RCC gravity dam. This system can be most cost effective whenever the stepped spillway chute cannot be used, thus eliminating the need for an otherwise large and expensive energy dissipator.

This is really a great advantage when the non-controlled spillway type is considered. When a gated-spillway is necessary, as usually adopted for large hydroelectric projects, the assembling time needs to be well balanced in the schedule planning and sometimes, the raising time period becomes a mandatory action, and thus the design of this structure on one of the banks may be translated in a safe and less risky solution. It is very important that all these considerations be part of an overall view and analysis.

Another structure to take into consideration is the water intake tower. If a multi-port intake structure extending to or near the full height of the reservoir for water quality blending is required, it can be easily anchored to the vertical upstream face of an RCC gravity dam. In the case of an embankment dam, this type of tower is usually freestanding in the reservoir or built up on the reservoir side slope. A freestanding tower is considerably more expensive regarding structural design and construction than an intake tower anchored to the vertical upstream face of a gravity dam. This difference in structural requirements becomes even more conspicuous in areas with known or potential high seismic forces. In addition to the advantage relative to the intake tower, a narrower base width in the RCC gravity dam structure will also allow a shorter (i.e., less expensive) outlet conduit.

In addition to these particular aspects of RCC gravity dam construction, excellent opportunities for economic benefits are possible to achieve while optimizing dam height versus spillway width through Probable Maximum Flood (PMF) design criteria evaluation. Height optimization of earthfill or rockfill embankment dams involves making design adjustments between dam height, spillway width, and optimum flow. Large separate side channel spillways may lead to dramatic economic consequences because require substantial and expensive rock excavation and concrete lining. Additional dam height to allow prescribed freeboard below the crest should also be considered. Such optimization is similar for RCC gravity structures except that the design criteria may be met by manipulating a single structure, which is not restricted by exterior facilities (i.e., separate side channel spillways). Minimum dam height may be optimized as simply as by expanding the overflow spillway portion of the RCC gravity dam structure, thereby reducing flood pool height until it adjusts to design criteria. An additional opportunity for dam height reduction may arise by the consideration that RCC gravity structures are not erodible and freeboard may no longer be required.

A general cost comparison between RCC gravity dam structures and conventionally built mass concrete dams indicates that the use of RCC along with conventional earthwork placement techniques results in lower ultimate unit cost of concrete.

10.2 Total Cost of a Project

It is difficult to estimate the cost of a completed dam project due to the varied requirements and the many items involved. Some of the items that are not considered in the simplified estimating procedure presented here include mobilization, reservoir clearing, diversion and water control, foundation excavation, grouting, drains, galleries, downstream face, spillway, intake structure, outlet conduit, energy dissipators, and instrumentation.

It is emphasized that the estimated total cost is highly dependent on the complexity of the project. For example, a project with a significant hydropower component would probably have a direct construction cost larger than a flood control project.

As previously mentioned in Chapter 1:

"Since the 70's many studies have been made in Brazil by different laboratories showing the properties and potentiality of RCC, although the first dam built with RCC technology had occurred only during the 80's.

It was during the 90's, mainly by adopting RCC technology for the Jordão and Salto Caxias Dams projects, that this technique has reached its majority. The bid system adopted by COPEL (Companhia Paranaense de Energia, a governmental energy agency from the Paraná State-Brazil) for the Jordão Dam, which allowed the Contractor to chose between a Concrete Faced RockFill Dam or an RCC Dam, pointed out to time and costs, as outstanding advantages for RCC technology."

Figure 10.1 shows total bid prices for different projects and as a conclusion, it indicates the reduction of price presented by the RCC alternative.

Project	Basic Alternative and Cost (10^6 US$)	Second Alternative and Cost (10^6 US$)	RCC Alternative Estimated Cost (10^6 US$)	RCC Volume (1,000 m^3)	Low Bid Price (10^6 US$)	Advantage (%)
A	B	C	D	E	F	G = [(B or C)-F]/(B or C)
Willow Creek	Rockfill with clay core (27.0)		(17.0)	330.0	(14.1)	47.8
Monksville	Rockfill concrete faced (25.6)	Earthfill (20.3)	(18.1)	220.0	(17.0)	16.3
Galesville	Earthfill			170.0		15.0
Upper Stillwater	Rockfill concrete faced (82.0)		(75.9)	1.100.0	(60.6)	26.0
Urugua-i	Rockfill concrete faced (130.0)			600.0	105.0	19.2
Jordão (lowest bid prices)	Rockfill concrete faced (39.3)			600.0	(34.5)	12.2

Figure 10.01 Bid prices comparison between different alternatives for 6 projects. [10.01 to 10.13].

Additional data on the mentioned projects should be taken into consideration:

Willow Creek Dam - It was completed in approximately **one-third of the estimated time** required for an alternative rockfill design;

Upper Stillwater Dam - Original bid price was $61 million, Engineer's estimate was $76 million, and final price was $106 million. Foundation change accounted for $18 million from which nearly $16 million was due to RCC related changes and $10 million in several smaller extras and adjusting orders accounted for the cost increase;

Urugua-i Dam - It was completed in approximately 11 months less than the alternative rockfill design;

Payment Item Description	UNIT	Lowest RCC	Average RCC	Lowest CFRD	Average CFRD
Common Excavation	US$/$m^3$	1.53	2.45	1.22	1.96
Rock Excavation in Pit	US$/$m^3$	5.42	6.16	5.25	4.83
CVC Concrete- f'c 16 MPa	US$/$m^3$	63.30	78.31	78.13	106.30
CVC Concrete- f'c 21 MPa	US$/$m^3$	59.61	95.92	88.78	124.68
CVC Concrete- f'c 26 MPa	US$/$m^3$	84.76	130.33	106.59	142.82
Furnishing and Installing Reinforcement Steel	US$/$m^3$	1.02	1.10	0.89	1.00
RCC Concrete- f'c 8,5 MPa (Less rock excavation for aggregates)	US$/$m^3$	20.22	24.50		
Rockfill (Handling & Compaction)	US$/$m^3$			0.50	0.65
Transition (Crushing + Handling + Compaction)	US$/$m^3$			8.89	9.08

Figure 10.02 Jordão bid unit costs comparison [10.11].

Payment Item Description	UNIT	Engineering Report CFRD	Engineering Report RCC	Bid Offers CFRD	Bid Offers RCC
Common Excavation	US$/m ^{3}	5.00	5.00	1.96	2.45
Rock Excavation in Pit	US$/m ^{3}	12.00	17.00	4.83	5.25
CVC Concrete- f'c 16 MPa	US$/m ^{3}	122.00	122.00	106.30	78.31
Furnishing and Installing Reinforcement Steel	US$/m ^{3}	1.43	1.43	1.00	1.10
RCC Concrete-f'c8,5 MPa (Less rock excavation for aggregates)	US$/m ^{3}		44.37		24.50
Rockfill (Handling & Compaction)	US$/m ^{3}	4.10		0.65	
Transition (Crushing + Handling + Compaction)	US$/m ^{3}	18.60		9.08	

Figure 10.03 Jordão Cost Comparison between Engineering Report and Bid Offers [10.11]

Jordão Dam – The first evaluation [10.11] of the bid prices showed a substantial reduction if compared to bid prices charged for similar works, even if such comparison was based on previous project adopted as a reference. Figures 10.02 and 10.03 show average unit costs submitted for similar jobs for RCC and CFRD (Concrete Faced Rockfill Dam) options and the unit costs of the competing companies that offered a lower global cost for each of the construction techniques. Substantial reduction in costs can be seen when comparing the Engineering Report and Design Study in which average costs for CFRD and RCC bids were mentioned. Cost reduction between the Engineering Report and actual bids has similar benefit in both construction processes. The same remark was applicable to compare both alternatives.

However, as previously mentioned in Chapter 4, in spite of the rise in popularity of the RCC method throughout the world, some dam owners, engineers and public dam safety officials still offer resistance to the new technology. There has been reluctance to design new RCC dams higher than the previous highest dam and in some cases RCC dams have been compared unfavourably with other dam types strictly on the basis of precedence.

Frequent comments are: ***"I don't want a leaky dam"; "RCC isn't concrete"; "You get what you pay for"***; or ***"RCC can be accepted for small dams but I wouldn't risk it on a high dam".***

It is important to have all these concepts in mind, including further questions: ***"How much does the development cost? What about mistakes, corrections, lessons, failures?"***

All professionals involved – owner, designer, consultant, contractor, governmental agency – should be aware of the risks and benefits, looking for a ***Safe, Durable, Economical, Rapid and highly Qualified Solution.***

Based on those arguments, engineering studies[10.12] for Salto Caxias (a 1,240MW hydroelectric power development on the Iguaçu River, in the South of Brazil) was carried out considering different approaches to power demands, economic criteria and hydrologic risks. More than forty alternatives were analyzed. Hydrologic data, especially those corresponding to the very large floods of 1983 and 1992, supported the need of substantial increase of the spillway and diversion facilities, as compared with initial capacities figured.

For these studies, a concrete face rockfill dam (CFRD), an earthcore rockfill dam (ECRD) and an RCC dam (RCCD) were considered with different schemes of spillway and diversion facilities. They led to the development of technical and economical analyses for seven optimized layouts. The initial studies concluded that both RCCD and CFRD equally fitted the site and could be managed into an economical and technically sound layout. While technically feasible, ECRD resulted in higher costs and additional difficulties to keep the same construction schedule followed by the other ones.

For a wide dam site like Salto Caxias, appropriate types of dam were considered:

(a) rolled compacted concrete dam – RCCD;
(b) concrete face rockfill dam – CFRD; and
(c) earthcore rockfill dams – ECRD

Although they were also suitable to the site, conventional mass concrete gravity dams and concrete buttress dams were not considered on account of their higher costs.

RCC Dam - A typical cross section of an RCC dam corresponds to a gravity section with a crest width of 7.5m. The upstream slope is vertical and the downstream slope has an inclination of 0.75(H):1.0(V), below elevation 315.0. It reaches a maximum height of about 67m above foundation, on the riverbed. For comparative studies, the adopted RCC mix was taken as 60kg of cement, 30kg of fly-ash and 70kg of rock fines per RCC cubic meter. For seepage control, a 5m wide richer concrete zone was considered next to the upstream vertical slope, with an estimated average 90-day strength of about 10 MPa. Additionally, a bonding layer of cement mortar was considered on top of every RCC layer. Induced contraction joints were designed at each 20 to 25m along the dam axis. At the upstream part, joints incorporated a drain hole placed between two sheets of PVC waterstop. A drainage gallery was provided 5m downstream the upstream face, along the entire length of the dam, plus a second gallery at a higher elevation along the spillway section.

Concrete Faced Rockfill Dam - The concrete faced rockfill dam section had upstream and downstream slopes of 1.3(H):1.0(V). The plinth foundation was located on hard sound basalt and its width was determined by the conventional rule of 1/20 of the hydrostatic head. The concrete face was set with a constant thickness of 0.4m, complemented by a 6m high parapet wall at the crest, to reduce rockfill volume. The dam was designed to be built in two phases, with a transversal construction joint. The second phase cofferdam was tied to the first phase dam, resting on top of the already built concrete face.

Earthcore Rockfill Dam - An ECRD alternative seemed also competitive, since it allowed the incorporation of the upstream cofferdam into the main dam body. However, it presented serious construction constraints related to clay core rate and rockfill placement that should be adjusted to the required excavation schedule. The selected typical section had external slopes of 1.65(H):1.0(V) at upstream, and 1.5(H):1.0(V) at downstream. The inclined earthcore had an upstream slope of 0.6(H):1.0(V), and a downstream slope of 0.3(H):1.0(V).

All layouts considered had the same dam axis and featured good rock foundations and good underground and open excavation conditions. Therefore, local geological conditions did not favor any particular alternative. Cost analyses for each layout alternative were carried out, making use of updated unit costs supplied by COPEL. However, there was (at that time) no reliable information concerning RCC costs, for such a large dam as Salto Caxias. Therefore, corresponding unit costs were estimated based on the proportion of several components. Comparative analyses were also made, resulting in an unit cost of US$ 40.00 per RCC cubic meter, including manufacturing of coarse and fine aggregates, concretes and formworks and excluding costs of cement, fly-ash and rock excavations. Totals direct cost and differential direct cost related to dam-diversion-spillway structures, estimated for the several alternative layouts examined, were as follows:

Analysis of the impact of key unit costs of dam/spillway/diversion structures on the total estimated cost of the RCC alternative was carried out. These are the significant remarks to be made:

(a) for the cost scenarios examined, RCC unit cost, including rock excavations and manufacture of the aggregates, manufacture and placement of concrete, formworks and cementitious material, may vary from US$ 60 up to US$ 85 per cubic meter and, even so, this alternative remained less costly than the concrete face rockfill dam alternative;

(b) in order to result in equal total direct costs, the unit cost of RCC should be of the order of US$ 100 per cubic meter.

Preliminary evaluation of the construction time for the dam and spillway works, in both alternatives, indicates a time period of 30 months. However, although cofferdams dimensioning and diversion conduits were based on different flood recurrences, a further risk may be associated to CFRD: if it is not possible to reach embankment elevations higher than the cofferdam crest in time for the wet season, overtopping of embankment will cause more damages than in the corresponding rolled concrete dam.

As a result of this analysis, RCCD alternative was confirmed to be more convenient than the corresponding CFRD one, both for technical and economical reasons. Following the studies, RCC dam alternative was selected to be further developed for the basic design of Salto Caxias Power plant. Project documents based on this RCC dam layout, covering main civil works and facilities, were completed and presented for bidding. In December 1994, the main contractor was defined and hired by COPEL. It is interesting to note that the contractual RCC unit price including manufacture of concrete, aggregates, formworks, cementitious materials and the rock for aggregate production amounted to ***US$ 25.50 per cubic meter.***

10.3 Estimating Cost For Roller Compacted Concrete

The curve in Figure 10.04 represents the total cost of placed RCC, including cement and pozzolanic material, based on actual bid prices submitted for 48 [10.01 to 10.13] dam projects in the world, since 1981. Nine out of this total are located in Brazil. In order to provide a general view, curves were fitted: average curve, and two envelope curves – maximum values and minimum values.

The values plotted in the chart represent the total cost of cementitious material (cement+pozzolanic material), aggregates (coarse, fine, filler), mixing, hauling, spreading, compacting and curing.

10.3.1 Cost of RCC

Construction cost accounts of RCC and conventional concrete dams indicate that the cost per cubic meter of RCC is considerably less than conventionally placed concrete. Approximate cost of RCC range from 25% to 50% less than conventionally placed concrete. Differences in savings usually depend on both the complexity of placement and the total quantities of concrete placed. Savings associated with RCC are primarily due to reduced forming, placement and compaction costs, as well as reduced construction times. Figure 10.04 shows the costs of RCC used in jobs of different size throughout the world.

The cost curve is based on the assumption that suitable aggregates are available at or

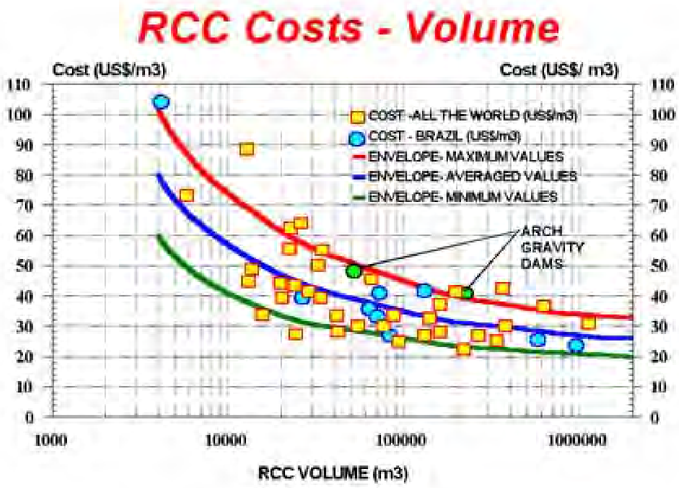


Figure 10.04 Costs of RCC used in 48 jobs of different sizes and materials, throughout the world [10.01 to 10.13].

ITEM	Range Cost (%)
Cement	20-----------30
Pozzolanic Material	6-----------2
Admixture	1-----------2
Contraction Joint	3-----------2
Placement	70---------64
Aggregates	35----------30
Batching	4------------5
Mixing	6-------------5
Conveying	0------------8
Compacting	5------------4
Curing	2------------1
Clean-up; Joint preparation	3------------4
Bedding Mortar Mix	5-------------7
TOTAL	100

Figure 10.05 RCC percentual cost breakdown.

near the dam site. If aggregates must be imported or a higher cementitious content RCC is desired, such as for a high-paste-content RCC, the cost as determined from the curve should be increased to account for the additional cost of these items. Similarly, if less cement and pozzolanic material are desired in the RCC mix, the cost may be decreased accordingly. In developing estimated costs for preliminary designs, the engineer may want to add a contingency factor to the unit cost of RCC derived from the curve. The envelope curves were fitted based on these variations.

The cost per unit volume is a function of the volume required where lower costs are associated to larger volumes, as shown in Figure 10.04.

Another approach is provided by Figure 10.05 with a typical RCC percent cost breakdown per cubic meter.

RCC cost listed in Figure 10.05 display the cost of aggregates and all other construction operations related to processing as a single item separated from the cost of cement and pozzolanic material. The total cost per unit volume is then the sum of the aggregates and processing cost plus the cost of the cementitious materials.

10.3.2 Cost of Upstream Face

The cost of conventional facing concrete, including cementitious materials, covers the cost of forming the vertical upstream face in most cases. These and other items can be considered once the design is detailed to feasibility level of study. For dams with less than 100,000m^3 of RCC, the cost of the upstream face may be considerably more expensive when expressed as an added cost per cubic meter of RCC.

10.3.3 Mobilization Cost

Mobilization costs have ranged from an unbalanced low value of 5% to a high as 15% of the total low bid. If there is no mobilization bid item listed in a unit price contract, it is expected that the unit cost of RCC and other items that require plant or special construction equipment will be increased accordingly.

10.4 Example

10.4.1 Conditioning Factors, Premises and Basic Reference Costs

10.4.1.1 General

In order to compare and adopt reference data, one should consider a Hypothetical Dam. The Basic Reference refers to the possibilities of producing RCC in sites where labor is relatively cheap (as is the case of Brazil and in many countries of South America, and other countries as well). To avoid bias, a comparison with higher cost labor was also made (with United States and Europe as references).

10.4.1.2 Hypothetical Dam Data

· RCC volume	= 600.000m^3
· Volume of conventional concrete	= 100.000m^3
· Dam height	= 80m
· Crest length	= 600m
· Dam front area	= 32,000m^2
· Distance between blocks	= 20m
· Contraction joint area	= 20,000m^2
· Spillway Surface	= 25,000m^2
· Downstream surface area except for spillway	= 18,000m^2
· Galleries surface area	= 8,000m^2
· Spillway (length) incorporated to the dam	= 300m
· Construction time period	= 18 months
· Production peak	= 50,000m^3/month

Figure 10.06 Hypothetical Dam Data.

10.4.1.3 Technical Requirements

· Coarse aggregate crushed from excavated rock	= Crushed
· Fine aggregate (variable distance source 50-100-150-200 km)	= Natural sand
· Fine aggregate (manufactured - produced in the site)	= Crushed sand
· Aggregate Specific Gravity (Basalt)	= 2.9t/ m^3
· Aggregates Apparent Specific Gravity	= 1.65t/ m^3
· Pozzolanic material - Supplier source 1000 km far	= Fly-ash
· Cement	= (plant 500km far)
· Air Entrained Admixture - Conventional Concrete	= 0.5kg/ m^3
· Plasticizer Retarder Admixture - Conventional Concrete	= 1.5kg/ m^3
· Granulometric curve for RCC Aggregates composition	= $p = 100\% \times (d/Dmax)^{1/3}$
· Minimum Required Strength for RCC (fck)	= 8,0 MPa at 180 days age
· Compaction Ratio	= 98%
· Face, Bedding, Gallery Conventional Concretes (Cement Content)	= 180kg/ m^3
· Concrete of Spillway Face (Cement Content)	= 300kg/ m^3

Figure 10.07 Relevant Technical Data..

10.4.1.4 Estimated Facilities Data

·Effective capacity of the concrete plant - Monthly peak/hour months	= 50,000/400= 125 m^3/h
·Cement needed: RCC = (80Kgf/cm²x1.20[STATISTICAL]/	= 65adopted
1.5[MIXEFFICIENCY])	= 70 Kg/m^3
· Quantity of water	= 100 Kg/m^3
· Aggregate Volume for the concrete (L/m^3) = [1000-(5%air)-	= 828 L
· (70/3.15cement)-100Lwater]	
· Quantity of aggregates (t/m^3) = (828 Lx 2.9t/ m^3)	= 2,400 Kg/m^3
· Bulk aggregates (2.400 t/1.65 t/m^3) (m^3 aggregate) / (m^3 concrete)	= 1.45 m^3
· Effective capacity of the crushing plant = (125m^3/h)x	= 185 m^3/h
· (1.45 m^3aggregate/ m^3concrete)	
· Average distance for concrete transportation (round trip)	= 2 km
· Rear Dump truck - capacity 25 t	= 20 m^3/h
· Truck Mixer - capacity 7 m^3	= 10 m^3/h
· Belt conveyor 2 x (L = 700m, 24")	= 125 m^3/h
· 10 t Vibratory Roller - Reference type Dynapac CC - 431	= 125 m^3/h
· Small Vibratory Roller	= 30 m^3/h
· Front blade Bulldozer - Reference type Cat D6	= 150 m^3/h
· Compressed air - installed	= 2,500 pcm

Figure 10.08 Equipment and Facilities Data.

10.4.1.5 Basic Equipment and Unit Costs

Crushing plant: considering a unit cost of US$1.5/$m^3$

Concrete batch and mixing plant: considering a unit cost of US$1.0/$m^3$

Concrete pre-cooling system: assuming that conventional concretes should be placed at 15°C with a temperature decrease of 15°C.

This system would act only on conventional concretes, in a proportion of 10% of the total, that is, 5,000m^3 at peak. Considering an amount of approximately US$ 2.5/m^3 for face conventional concrete.

10.4.2 Rock exploitation, loading, storage, reloading and transportation from quarries

Assuming an amount of US$4.5/$m^3$ of rock at cutting, and a ratio of (density of massive quarry / apparent density after crushed) = 2.7/1.65, it will correspond to US$ 4.5 (1.65/2.7) = US$ 2.75/m^3 of loose bulk aggregates. With losses of 5%, included the result is US$ 2.9/m^3 of stockpiled loose aggregate.

10.4.3 Transportation

· **Truck option**: considering unit costs of US$ 2.2/m^3 (*Note) and US$ 4.11/m^3 (**Note) for dumper rear and US$ 4.5/m^3 (*) and US$ 6.0/m^3 (**) for trucker mixer based on:

1. 22 t - 25 t dump truck adopted, with a 20m³/h productivity
2. 7m³-capacity mixer truck with a 10m³/h productivity
3. Accesses: assuming an access of approximately 5km long

NOTES:
(*) Low cost labor sites (**) High cost labor sites
· **Belt conveyor option**: considering unit cost of US$ 2.97/m³

10.4.4 CCR Spreading

Front-blade bulldozer selected, equivalent to Cat-D-6 to perform 125m³/h, corresponding to US$ 0.28/m³ (*) and US$ 0.50/m³ (**)

10.4.5 Compaction

Vibratory Roller selected, equivalent to Dynapac CC-431 to perform 125m³/h, corresponding to US$ 0.32/m³ (*) and US$ 0.52/m³ (**)

For confined zones, CG-11 small vibratory roller is adopted for a production of 30m³/h, corresponding to US$ 0.3/m³ (*) and US$ 0.5/m³ (**)

For conventional concretes, compressed air vibrators are selected, with a 10m³/h capacity, corresponding to US$ 0.2/m³ (*) and US$ 2/m³ (**)

10.4.6 Construction Joints Preparation and Clean-Up

The basic preparation will be performed with an air and water jet (low pressure), and the bedding mix concrete will be taken as a parameter for analysis; 2,500 pcm of installed air are necessary, corresponding to US$ 0.48/m³.

10.4.7 Forms

· **Upstream Face**: Metal lined wooden form selected, with a 1.5-mm steel cover sheet, 25 reuses, at a cost of US$ 15/m² – considered at the face concrete

· **Spillway Face:** Slipping form selected, at a cost of US$ 8/m² – considered at the spillway concrete

· **Galleries:** Metal lined wooden form selected, with a 1.5-mm cover sheet, 25 reuses, at a cost of US$ 15/m² – considered in the RCC

· **Downstream Steps:** Metal form selected, with 20 reuses, at a cost of US$ 6/m² – considered at RCC

· **Induced Joints for Contraction Joints:** Selected forms induced through insertion of a recoverable metal blade and a 0.3-mm PVC sheet; cost assumed = US$ 1.00/m² – considered in the RCC

10.4.8 Transportation of Cement, Fly-ash and Natural Sand

· **Cement or Fly-ash truck** = a cost of US$ 0.03/t.km (*) and US$ 0,04/t.km (**) was assumed (considering one-way distance)

Unit Costs for Concrete indicated in Figure 10.11 resulted from these basic compositions:

CONCRETE TYPE	COST (US$/m³)	CONTRIBUTION (%)			
		EQUIPMENT	MATERIAL	LABOR	AUXILIARY
REINFORCED CONCRETE FACE EM e= 1m	126,61	15	25	12	48
MASS CONVENTIONAL CONCRETE FACE e= 1m	78,62	24	40	8	28
MASS CONVENTIONAL CONCRETE FACE & PRECOOLED e= 1m	82,03	27	38	7	27
REINFORCED CONCRETE e= 0,5m IN SECOND STAGE	133,5	13	26	7	54
PRESCATED CONCRETE & P.V C. MEMBRANE & PROTECTION e=0,5m	119,9	17	41	8	34
DAM BODY IN RCC & BEDDING MIX ON 30% AT CONSTRUCTION JOINTS	27,4	25	51	11	13
DAM BODY IN RCC & BEDDING MIX ON 100% AT CONSTRUCTION JOINTS	30,88	23	45	10	22
RCC CRUSHED AGGREGATES & FILLER NO FLY-ASH	26,99	38	50	6	7

Figure 10.11 - Unit costs attained due to low cost labor.

10.4.13 RCC Cost

According to cost compositions for each option of material, reference values mentioned in Figure 10.12 may be attained.

CONCRETE TYPE	COST (US$/m³)	CONTRIBUTION (%)			
		EQUIPMENT	MATERIAL	LABOR	AUXILIARY
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH	26,99	38	50	6	7
RCC CRUSHED COARSE AGGREGATES+ NATURAL SAND at 50km + FLY-ASH at 1000Km	38,47	37	54	4	5
RCC CRUSHED COARSE AGGREGATES+ NATURAL SAND at 100km +FLY-ASH at 1000Km	39,01	38	53	4	5
RCC CRUSHED COARSE AGGREGATES+ NATURAL SAND at 150km +FLY-ASH at 1000Km	39,83	39	52	4	5
RCC CRUSHED COARSE AGGREGATES+ NATURAL SAND at 200km +FLY-ASH at 1000Km	40,49	41	51	4	4

Figure 10.12 Available Materials - Unit Costs Comparison.

10.4.14 Upstream Face Cost

According to cost compositions for each option of upstream face, reference values mentioned in Figure 10.13 may be attained.

10.4.15 Cost Influence of Labor

According to cost compositions for each option of labor, RCC unit cost values mentioned in Figure 10.14 may be attained.

UPSTREAM FACE TYPE	COST (US$/m³)	DIFFERENC (%)
REINFORCED CONCRETE FACE e= 1m	126,61	60
MASS CONVENTIONAL CONCRETE FACE e= 1m	78,62	0 [BASIS]
MASS CONVENTIONAL CONCRETE FACE & PRECOOLED e= 1m	82,03	4
REINFORCED CONCRETE e= 0,5m IN SECOND STAGE	133,5	70
PRESCATED CONCRETE & P.V C. MEMBRANE & PROTECTION	119,9	53

Figure 10.13 Upstream Face Types - Unit Costs Comparison.

CONCRETE TYPE	COST (US$/m³)	CONTRIBUTION (%)			
		EQUIPMENT	MATERIAL	LABOR	AUXILIARY
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH - LOW COST LABOR	26,99	38	50	6	7
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH - HIGH COST LABOR	33,03	38	41	13	6

Figure 10.14 Variation of Labor Cost – Unit Costs Comparison.

10.4.16 Transport Equipment Type Influence

Values shown in Figure 10.15 are obtained when cost compositions for each RCC transport option are taken into account.

CONCRETE TYPE	COST (US$/m³)	CONTRIBUTION (%)			
		EQUIPMENT	MATERIAL	LABOR	AUXILIARY
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH - LOW COST LABOR -REAR DUMP TRUCK	26,99	38	50	6	7
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH - HIGH COST LABOR -REAR DUMP TRUCK	34,57	40	39	15	5
RCC CRUSHED AGGREGATES + FILLER + NO FLY-ASH - HIGH COST LABOR -BELT CONVEYOR	33,03	38	41	13	6

Figure 10.15- Types of Transport - RCC Unit Cost Comparison.

10.4.17 Unit Cost of the Hypothetical Dam

The values shown in Figure 10.16 indicate unit costs for each type of Dam, taking into account cost composition for each adopted upstream face alternative (here included the face type option, RCC body itself and the spillway face).

HYPOTHETICAL DAM TYPE	COST (US$/m³)	DIFFERENCE (%)
RCC + REINFORCED CONCRETE FACE 1m THICK+ SPILLWAY CONCRETE FACE	43,07	46
RCC + CONVENTIONAL MASS CONCRETE FACE, 1m THICK + SPILLWAY CONCRETE FACE	36,33	23
RCC +PRECOOLED MASS CONCRETE FACE, 1m THICK + SPILLWAY CONCRETE FACE	36,81	25
RCC + REINFORCED CONCRETE 0,5m THICK IN SECOND STAGE + SPILLWAY CONCRETE FACE	44,03	49
RCC +PRESCATED CONCRETE & P.V C. MEMBRANE & PROTECTION e=0,5m + SPILLWAY CONCRETE FACE	41,13	40
DAM BODY IN RCC & BEDDING MIX ON 30% AT CONSTRUCTION JOINTS + SPILLWAY CONCRETE FACE	29,48	0 [BASIS]
DAM BODY IN RCC & BEDDING MIX ON 100% AT CONSTRUCTION JOINTS + SPILLWAY CONCRETE FACE	32,90	12

Figure 10.16 Composed unit costs comparison made for the entire dam, with four different face options

10.4.18 General Comparisons

Curves shown in Figure 10.04 were based on RCC costs for different dams sites and included the parameters analyzed in this Chapter.

· The values obtained by the performed analysis were consistent when compared to those proposed for the Jordão Dam [10.11], as in Figure 10.04 (US$ 25.64/m³ - the rock for aggregates and forms included);

· Comparisons referring to available materials show the advantages of adopting artificial sand with fines, when compared to other analyzed options. However, it is highly recommended that the technical and economical evaluation of each local material available should be performed.

· Evaluations made on all types of considered parameters show that the adoption of a face mass concrete, with 1.0m of average thickness (for a 80m high dam), with no reinforcement and simultaneously executed with RCC presents the smallest composite cost. Other options have corresponding increases;

· It is clear that higher dams (with more than 40m) may be totally built in RCC, with known and allowable permeability, mainly when the admixtures make use of fines that show low cost dams. Comparisons between labor costs may reflect each country's distinctiveness regarding availability of low cost and ample or high cost and rare labor. Excepting that, in general, available labor costs must be examined with the respective current productivity of the work market (as it has herein considered). Usually, low cost & ample labor offers low productivity.

Comparisons regarding the transport system clearly indicate that when labor cost increases it is necessary to find a more adequate handling of concretes through more productive systems and less labor application.

10.5 REFERENCES

10.01 LOGIE, C. V. "Economic Considerations in Selection of a Roller Compacted Concrete Dam", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

10.02 "RCC - Concrete Dams and Pavements That Are Built Faster and Cost Less", in: RCC Newsletter; PCA. Skokie, Illinois, nº 1, July 1985.

10.03 FORBES, B. A. "The Development and Testing of Roller-Compacted Concrete for Dams in Australia", in: Transactions, Sixteenth International Congress on Large Dams. San Francisco, vol. III, Q62, June 1988.

10.04 HOPMAN, D. R. and CHAMBERS, D. R. "Construction of Elk Creek Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference, San Diego, California ASCE. New York, March 1988..

10.05 LOGIE, C. V. and OLIVERSON, J. F. "Roller Compacted Concrete Mix Design for Pamo Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

10.06 TARBOX, G. S. and HANSEN, K. D. "Planning, Design and Cost Estimates for RCC Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

10.07 MOREIRA, J. E. "General Report - TEMA IV", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August/1987.

10.08 ANDRIOLO, F. R. "General Report - TEMA I", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April/1989.

10.09 REZENDE, Paulo Fernando Vieira Souto. "Concreto Compactado a Rolo, Altenativa de Projeto Viável ou Não?", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz de Iguaçu, Brazil, April/1989.

10.10 HOLLINGWORTH, F. and GERINGER, J. J. "Roller Compacted Concrete Arch/Gravity Dams – South African Experience", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

10.11 BLINDER, S.; TONIATTI, N. B. and KREMPEL, A. F. "RCC and CFR Dams - Costs Comparison", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

10.12 KAMEL, K. S. F.; BABÁ, L. J. N.; BLINDER, S. and RAUEN, J. "Selection Studies for Salto Caxias RCC dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

10.13 BLINDER, Simão; TONIATTI, Nelson Buhr; KREMPEL, Antonio Fernando. "CCR X EFC Comparativo de Custos", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April/1995.

11

Other Use

11.1 General Considerations

Roller compacted concrete (RCC) has been used for various functions due to its basic properties as high compressive strength and shear resistance, low permeability, and high erosion resistance when compared to non-stabilized materials.

The material and method are not limited to the construction of concrete dams in general or to gravity or arch-gravity dams. There are many potential applications in all types of dams as well as for repair, modification or replacement of existing fill dams. Many of the early (see Chapter 3) applications of RCC were part of the design of an embankment dam.

RCC has been used for foundation improvement, upstream slope protection, for central core, spillways, and downstream overtopping protection in the design of new embankment dams. RCC has been used since the 1970's for heavy-duty pavements and roads.

Figure 11.01 Backfill at downstream access ramp of Diversion Structure at Itaipu Dam.

11.2 Foundation Improvement and Back-filling

RCC has been used as foundation improvement or back-filling as at Ohkawa dam in Japan. Since the conditions of the rock foundation and topography at the damsite were unfavorable, it was necessary to place a long base mat of concrete. Preliminary surveys and studies were carried out during 1975-1976, while the construction was started in 1977, being one of the first applications of RCC [11.01]

At Itaipu dam site RCC was used to form a backfill downstream access ramp of diversion structure during May 1978 [11.02]

RCC was used to backfill part of the Xingó Dam Spillway, in Brazil. There are also other examples as the use at Bellefonte Nuclear Plant [11.03].

11.3 Cofferdams

The first RCC cofferdam was used for the rehabilitation of Tarbela Dam [11.04 to 11.07]. A composite earthfill and RCC cofferdam was constructed downstream of the auxiliar spillway plunge pool to allow dewatering of the construction site. The RCC half of the cofferdam was on the water side and was subjected to high-velocity flow and wave action from discharges from one of the outlet tunnels.

The earthfill portion of the cofferdam was completely washed away during the first season of spillway operation but the remaining RCC portion has remained in place even after being subjected to spillway flows up to 11,300 m^3/s.

Figure 11.02 Serra da Mesa cofferdam during construction (Courtesy: W. Pacelli, FURNAS).

Figure 11.03 Serra da Mesa cofferdam, during one of the overtoppings. (Courtesy: W. Pacelli, FURNAS)

RCC has also been used for Ohkawa dam upstream cofferdam in 1976 [11.01]. RCC has also been used for both the upstream and downstream cofferdams for the rockfill clay core of Serra da Mesa Dam [11.08] in Brazil, during 1988. These cofferdams were overtopped as mentioned in Chapter 3.

The same application was done for the cofferdams of the conventional-concrete Yantan Dam [11.09] as well as for either an upstream cofferdam at Agigawa Dam in Japan, as at Revelstoke dam in Canada, and for other dams in China.

The use of RCC for cofferdams and mass diversion walls offers the advantage of fast construction and erosion resistance. The erosion resistance is useful in withstanding wave action and allowing safe overtopping of the cofferdam.

11.4 Embankments and Slope Protection

11.4.1 Overtopping Protection

The erosion resistance of RCC allows the use of the material in several ways to allow embankment dams to be safely overtopped by floods. RCC can be used to protect the downstream slope of an earth or rockfill dam, as a cap on the crest of an embankment, or as a downstream gravity section.

The use of RCC on the downstream slope of concrete-faced rockfill dams provides overtopping protection during construction. The first time that RCC was used for this purpose was at Xingo Dam, a 150-m concrete-faced rockfill dam in Brazil. To ensure that the dam could pass a 1-in-200-year flood without failure from overtopping, a zone of RCC with drains was placed across the dam on the downstream toe.

Figure 11.04 Overtopping protection at Xingó Dam during construction, Brazil. (Courtesy: Alberto J. Cavalcanti-CHESF)

Figure 11.05 Overtopping protection at Xingó Dam during construction, Brazil. (Courtesy: Alberto J. Cavalcanti-CHESF)

Figure 11.06 Overtopping protection at Xingó Dam by the end of construction, Brazil. (Courtesy: Alberto J. Cavalcanti-CHESF)

Figure 11.07 RCC used to increase safety during overtopping at Ocoee no. 2 Dam , a 9.1-m high rockfill.

Many embankment dams in the United States [11.10] and elsewhere are unable to pass current design floods safely, unless using RCC on the downstream slope. Many older embankments in the United States are unable to safely, unless pass floods meeting current criteria of at least one-half the theoretical Probable Maximum Flood (PMF). Available measures include raising the dam and spillway crest to increase storage capacity, or building a new spillway or enlarging the existing spillway to increase its capacity. Site restrictions or economics frequently make these alternatives not feasible or unattractive to the Owner. The functional use of the reservoir also usually makes breaching the dam unacceptable as a permanent solution.

Thus, providing embankment overtopping protection may be the only reasonable solution available to keep the dam from failing during a major, but infrequent, flood event. This is especially true for small embankment dams needing the pass low-to-moderate depths of overtopping flows. The basic concept for the design of RCC overtopping protection is to provide a cover on the downstream face that has sufficient weight and durability to resist displacement and erosion during the infrequent overtopping of the armoured embankment.

Because RCC overtopping protection projects are usually of small volume, exposed, and need to be built quickly prior the start of an adverse season, mixture proportions are quite simple and conservative.

Figure 11.08 RCC used to increase safety during overtopping at Hico Springs Detention Basin. (Courtesy: ROTEC Industries)

11.4.2 Wave Protection

Soil-cement has been used for upstream slope protection for earth dams for more than 25 years, primarily in the United States (see Figure 2.02- Chapter 2), mainly in Texas State. On-site, sands are stabilized with cement to form a continuous erosion-resistant facing that competes with rock riprap.

In some embankment dams, in Brazil (Paraná River Basin), where there are mycrocristaline basalt with expansive clay in the matrix, soil-cement (at Rosana Dam) and RCC (at Porto Primavera Dam) have been used for wave protection instead of rockfill.

The RCC barrier was chosen instead of rip-rap due the lack of large rock blocks at the site. It is 10m high and a 5-m width. RCC was poured in 0.35m high layers. A lean RCC with 100 kg/m^3 of Portland Pozzolan Cement was used. The downstream water level has already reached the RCC protection and its behavior is considered as very good.

Figure 11.09 Wave protection at Porto Primavera Dam during construction, Brazil. (Courtesy: Flávio M. Salles - CESP)

Figure 11.10 Wave protection at Porto Primavera Dam by the end of the construction, Brazil. (Courtesy: Flávio M. Salles - CESP)

11.5 Rehabilitation and Replacement

The first fast placement of large volumes of RCC for extensive repairs was at Tarbela Dam in Pakistan [11.04 to 11.07; 11.10] and caused a major impact on the dam-building community. More than 2.5 million m^3 of RCC was used for rehabilitation of the world's largest engineered embankment. Its problems arose following the initial filling in 1974.

Although most of the dam rehabilitation projects in the United States have involved embankment dams, RCC has been used to structurally upgrade four existing concrete or masonry dams. In all four cases the need for the upgrading also demanded strengthening for seismic loadings.

For Gibraltar dam, a concrete arch; Littlerock dam, a multiple concrete arch; and Camp Dyer Diversion dam, a rubble-masonry gravity day, upgrading the dam to withstand a higher magnitude earthquake than originally designed was the primary reason for the improvements. At Santa Cruz dam, the reasons for the rehabilitation were threefold: first to increase seismic safety of the existing concrete arch, second to improve structural stability of the arch and its abutments during overtopping, and third to replace freeze-thaw damaged concrete on the downstream face.

In all cases the RCC was placed adjacent to downstream of the existing concrete structure. Except for Santa Cruz, the existing arch or multiple arch was transformed into a concrete gravity structure.

11.6 Central core

The first example of the use of RCC for the central core of an embankment was for the 64-m Shihmen cofferdam in Taiwan, in 1960 [11.10] .

11.7 Spillway

Generally, RCC spillways are gravity overflow sections located at the central portion of a longer earth embankment. Their design is identical to that for an RCC gravity section, taking into account the flow over the structure. Hence, the sections had to be designed to accommodate maximum uplift pressures.

The scheduling of construction of RCC spillways in relation to the adjacent sections of embankment is an important consideration. It is preferable to raise the spillway and embankment together when construction employes RCC.

11.8 Pavements

11.8.1 General

Roller-compacted concrete pavement (RCCP) is a technology that involves the use of conventional materials and construction equipment in an unconventional application. The result is a time saving of construction of the concrete pavement, which ultimately translates into a significant cost saving.

RCC has been used since the 1970's in several parts of the world, firstly in water control structures. During that same period, a soil-cement type mixture with a 12% to 14% Portland cement content was being used for heavy-duty pavements in the forest industry of British Columbia, Canada [11.11]. Because the materials and the mixing process for both dams and pavements are similar, the term "roller-compacted concrete" has been chosen to describe the heavy-duty pavement construction process.

Figure 11.11 RCC used as stock pavement in Salto Caxias dam, Brazil.

It is important that the reader had a clear understanding of what is meant by "roller compacted concrete" when related to heavy-duty pavements. RCC for paving differs from its application in water control structures in the following respects:

✓ The surface of RCC pavement is subjected to abrasion from traffic, log stackers, container carriers, and military vehicles;

✓ In winter weather, RCC must withstand the action of freezing and thawing cycles and the possible application of deicing salt; and

✓ RCC heavy-duty pavement has a much higher Portland cement content than that used in dams. Pozzolanic material as fly-ash is sometimes used in the range of 15% to 20% by weight of total cementitious materials.

Figure 11.12 RCC used for road pavement in Spain.
(Courtesy: Carlos Jofré- IECA)

In general terms, CVC concrete used in pavements is proportioned to satisfy a design flexural strength and maintain the workability within a reasonable water-cement ratio. Other important factors considered in the mix design are durability and economy. Soil-cement is proportioned in large part for durability, with such a water content as to obtain maximum density as well as overall economy. RCCP (Roller compacted concrete pavement) mixtures cannot be designed totally as a CVC concrete mixture or as a soil-cement mixture but must be designed on the basis of the key features of both these applications of cement in pavement construction. In addition, construction involves the use of asphalt equipment and techniques, which must be taken into consideration.

The expected in situ properties of RCCP are significant in their performance and consequently also to thickness design due to a high flexural strength as compared to that of conventional concrete pavements. Increased flexural strength may affect thickness design in one of two ways:

❑ **first,** the increased flexural strength may be included in the selection of a design thickness, and

❑ **second,** existing acceptable thickness may be retained by using a factor of safety to reduce the higher RCCP flexural strengths to a value numerically comparable with that of conventional concrete pavement. Therefore, it accommodates the increased strength through an increased confidence level.

During mix design and construction, RCCP must be treated as a transition material, which requires consideration from technologies as of Portland cement concrete, soil-cement, and asphalt-concrete. It is perhaps unusual to draw from such diverse technologies but it is also interesting. When basic issues on materials, construction, and performance are exposed against existing knowledge, cause and effect are easily explained. In the future, with wider application, RCCP will not appear to be an unknown technology but will be applied without hesitation.

Confusion about RCCP durability due to laboratory test results should no longer exist. On the other hand, density from the standpoint of a laboratory standard or field constructability has not been fully defined. The crux of the matter is what density can be achieved with the existing compaction equipment and what is the relation of this field density with the laboratory standard density.

Hydration in concrete is assumed to take place, but under certain climatic conditions, RCCP is characterized by marginal water content, which may be critical for hydration. Experience with different curing techniques has determined that the use of a curing compound is not adequate because discontinuities in the membrane can allow loss of the marginal moisture. On the other hand, water spray and wet sand are adequate because a positive moist condition is maintained for hydration at the RCCP surface. Wetted burlap will accomplish the same purpose but coordination has yet to be worked out for application, maintenance, and conflict with paving operations.

Allowing uncontrolled cracking is an expediency that may result in decreased performance and increased maintenance needs. Sawing can be accomplished for control of crack patterns in two-lane pavements and may help to control transverse cracking in broader pavement areas. However, longitudinal cracking in broad paved areas will be difficult to control.

Increased flexural strength of RCCP translates into approximately a 1-in. reduction in design thickness. A minimum RCCP thickness for a pavement to maintain its integrity has not been defined. Defining this minimum thickness will involve evaluation.

Figure 11.13 RCC used for road pavement in Japan. (Courtesy: Carlos Jofré - IECA)

Figure 11.14 RCC pavement for heavy utilities.
(Courtesy: Carlos Jofré- IECA)

11.8.2 Historical Development

The large use of RCC as material for pavements has started actually in Great Britain in the 40's during the experimental tests at Crawley, Surrey, Leicester, North Walles and Bracknell.

Remarkable events can be mentioned, [11.12] as the following:

1910	Pavements for urban streets at Grand Forks, North Dakota-USA
1935	Pavements for urban streets in Belgium
1940 – 1944	Roads at Crawley and London- Great Britain
1950	Experimental pavement road at US 441-Florida-USA
1950 – 1960	Roads at Texas; South Carolina and others States – USA
1960 – 1990	Roads in USA
1970 – 1990	Roads in Spain
1972 – 1990	Roads in Brazil
1986 – 1990	Roads using High Strength RCC in Australia
1986 – 1990	Experimental pavement roads in Argentina; Chile; Uruguay; South Africa

The use of RCCP in Brazil has started historically as:

1946	Pavement at Anhangabau Valley
1950	Pavement in Congonhas Airport in São Paulo
1954	Pavements in Rio de Janeiro
1989	Pavements in the São Mateus and Santana metropolitan areas in São Paulo city
1990	Road pavements in Rio Grande do Sul, Santa Catarina, São Paulo and Pernambuco States.

Figure 11.15 Aerial view of a bulk-terminal for cereals and minerals over a hydraulic earth-fill (2,700,000m³) at Sepetiba bay, Rio de Janeiro, Brazil. (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda.)

Figure 11.16 Other aerial view of a bulk-terminal for cereals and minerals with an area of 187,000m². (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda.)

Figure 11.17 Spreading and leveling the RCC (total volume – 84,150m³) for the terminal pavement at Sepetiba bay, Rio de Janeiro State, Brazil. (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda.)

Figure 11.18 Spreading and leveling machine used for RCC pavement at Sepetiba bay, Rio de Janeiro state, Brazil. (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda)

Figure 11.19 Spreading and leveling machine used for RCC pavement at Sepetiba bay, Rio de Janeiro state, Brazil. (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda)

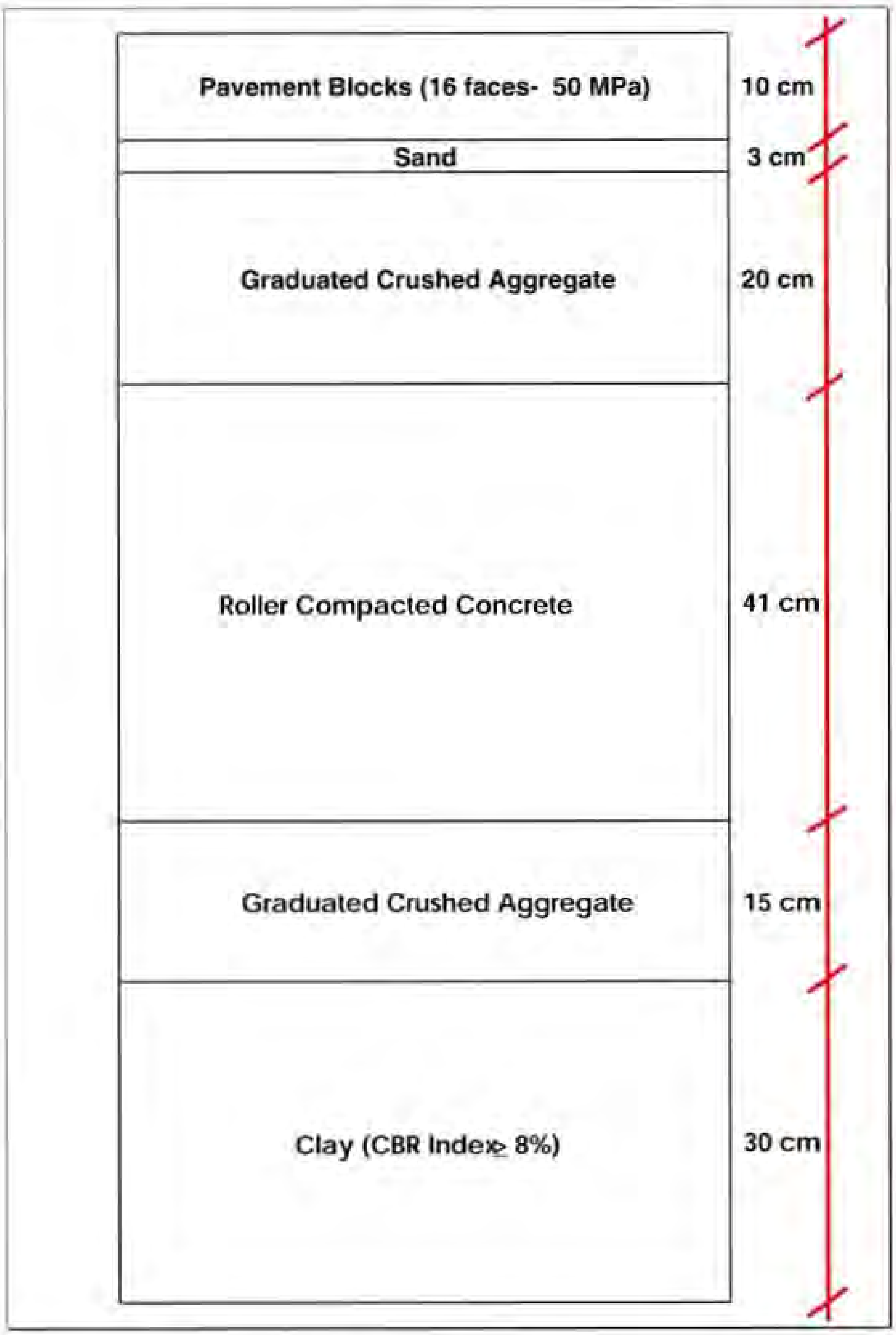


Figure 11.20 Structural detail of the pavement for the Sepetiba Terminal, Rio de Janeiro, Brazil. (Courtesy: Carlos Yukio Suzuki-Planservi Engenharia Ltda.)

11.8.3 Design

Pavement thickness design criteria are generally based on an envelope of failures recorded in pavement test sections or performance observations of prototype pavements. In some cases, design criteria have been modified as a result of laboratory tests. However, the incorporation of laboratory data into design criteria has been infrequent because there is an inability to directly compare field performance and laboratory test results.

In pavement design the flexural strength is a significant design factor. Laboratory flexural strength tests of pavement samples indicate that RCCP can develop a 25% higher flexural strength than a CVC concrete pavement. In large part, this higher flexural strength will come from a higher density achieved by field compaction applied during construction. Taking advantage of this higher strength depends upon being able to achieve the necessary density uniformly within construction practices. A second consideration must be given to the question of whether the higher-density, higher modulus concrete mixture will have a different fatigue relationship from that of CVC concrete. A related concern is the minimum thickness required for the RCCP to maintain its integrity.

Figure 11.21 Spreading and leveling machine used for RCC pavement in Spain. (Courtesy: Carlos Jofré-IECA)

Adequate mix proportioning, uniformity of material, and moisture and density control will ensure a desired flexural strength for design. It is doubtful that significant differences in fatigue properties will exist for RCCP. Too many other factors affect the quality and performance of the concrete and will predominate. Performance of RCCP related to loading has been very satisfactory.

One measure of the concrete pavement performance is the amount of cracking it suffers. Cracking of CVC concrete pavements is minimized through proper spacing of sawn joints. Unless the same approach is adopted for RCCP, uncontrolled cracking will occur with discontinuities that would lead to further undesired cracking. This would be a natural and not unexpected phenomenon, and increased thickness may be required to compensate for such occurrences. Foundation strength is less significant in concrete pavement thickness design.

11.8.4 Quality Control

RCCP needs to be controlled in the same way and concepts that RCC in other uses. Two specimens should be tested, each at 7, 14, and 28 days. The specimens should be tested for splitting tensile strength according to ASTM C- 496 [11.13]. Cylinders of RCC used with high fly-ash contents or for airfield pavements may be tested at 90 days.

Cores should be taken from the RCCP when the pavement is 7 days old. One core should be taken at every fifth nuclear gauge density test site within 0.6m to 1.5m of depth in the test hole. The density and thickness of the core should be measured, and the core should be field cured under conditions similar to the RCCP curing conditions. The cores should be tested for splitting tensile strength when they are 28 days old.

The finished surface of the RCCP should not vary more than 10mm from the testing edge of a 3.0-m straightedge. Smoothness should be checked as closely as possible behind the finishing roller, and an excessive variation in the surface should be corrected with the finishing roller. Particular attention should be paid to smoothness across fresh and cold joints, because this is usually a critical area for surface variations. A skilled vibratory roller operator is essential in minimizing smoothness problems. The final surface texture of the RCCP should resemble that of an asphaltic-concrete pavement surface.

Inspections are vital in the quality control operations. At least one inspector should be stationed at the mixing plant and one at the job site to ensure that a high quality pavement is being built.

At the mixing plant, the inspector should check mixing times occasionally and spot-check the consistency and appearance of the mix coming out the plant. He should also coordinate the aggregate moisture content tests, the gradation tests, calibration of the plant, and washout test to see whether they are performed properly and within the right frequency.

Figure 11.22 Joint cutting machines used for RCC pavement in Spain. (Courtesy: Carlos Jofré-IECA)

At the job site, the inspector should make sure that the base course and cold joints are moistened before the RCC is placed against them and that the RCC is placed and compacted within the proper tire requirements. The paving operation should be checked to ensure that proper grade control is continuously maintained and that no gaps or discontinuities are left in the pavement before rolling. The inspector should make sure that the roller begins compaction at the proper time and that the proper rolling pattern and number of passes are followed. Adequate smoothness across joints should be assured as well as the tightness of the surface texture after final rolling. He should spot -check the final compacted thickness of the RCCP on occasion and make corrections if appropriate. He should enforce that same the curing procedures are implemented as specified. The inspector should make sure that all exposed surfaces of the RCCP are permanently kept moist and that the curing compound, if used, is applied properly and in a continuous way.

Figure 11.23 Road RCC pavement in Serra do Rio do Rastro, Brazil.

Figure 11.24 Road RCC pavement in Brazil.

Figure 11.25 RCC flexure test for pavement. (Courtesy: Carlos Jofré-IECA).

Figure 11.26 RCC specific gravitty test for pavement. (Courtesy: Carlos Jofré-IECA).

11.8.4 Cost

The aggregate for RCC may have a very wide gradation curve. Many sources can be considered for RCC raw material that otherwise would be unsuitable for a regular gravel base course. It has been found that aggregates with as much as 14% passing the No. 200 (0,075mm) mesh sieve produce compressive strengths of 27.6 MPa or more at 28 days.

The acceptability of previously rejected gravel pits also means shorter haul distances and further cost saving. The reduced need to open new aggregate pits might reduce environmental impact, surely a significant cost benefit.

The total thickness of an RCC pavement is much less than that for a flexible pavement of the same load-carrying capacity. In cut situations this means a saving in excavation cost. In fill locations it means that lower-cost fill material can be placed to within a few inches of the final RCC base grade, thus saving the cost of expensive gravel.

11.09 REFERENCES

11.01 SHIMIZU, S. and TAKEMURA, K. "Test Fill of RCD at the Upstream Cofferdam of Ohkawa Dam", in: Concrete Journal. Japan Concrete Institute, April 1978.

11.02 Technical Report - RT-03/78. Divisão de Controle de Concreto - Itaipu Binacional. Foz de Iguaçu, Brazil, February/1978.

11.03 CANNON, R. W. *Bellefonte Nuclear Plant - Roller Compacted Concrete – Summary of Concrete Placement and Evaluation of Core Recovery.* Report nº CEB- 76-38, Tennessee Valley Authority. Knoxville, Tennessee, 1977.

11.04 "Repairs at Tarbela dam race spring snowmelt", in: Engineering News - Record. New York, vol. 193, nº 19, October 31, 1974.

11.05 MARSHALL, T. "Tarbela rescue: 380,000 m^3 plug beats the flood", in: New Civil Engineer, Institution of Civil Engineers. London, 27 April 1975.

11.06 "Repair and Reconstruction of the Tunnels at Tarbela.", in: Water Power & Dam Construction. United Kingdom, June-July 1975.

11.07 "Major Erosion Bits Tarbela Dam Again", in: Engineering News - Record. New York, vol. 199, nº 12, 22 September, 1977.

11.08 BARROS, Paulo Antonio de; ANDRADE, Walton Pacelli de; MOURA, Francisco Itamar. "Ensecadeiras Galgáveis em Concreto Compactado a Rolo - Aproveitamento Hidroelétrico de São Félix – Usina Serra Da Mesa", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April/1989.

11.09 YOUCHANG, Lin; JIALI, Huang and YANJI, Huang. "The Technique on RCC Dam Construction of Yantan Project", in: Proceedings Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

11.10 HANSEN, K. D. and REINHARDT, W. C. *Roller Compacted Concrete. McGraw-Hill.* New York, 1991.

11.11 PIGGOTT, Robert W.; NAAS, Olav. "Roller Compacted Concrete Pavements in British Columbia - Canada", in: Proccedings of the Roller Compacted Concrete Symposium at the ASCE Convention. Denver, May 1985.

11.12 DNER. "Manual de Pavimentos de Concreto Rolado", Volume I/III. Rio de Janeiro, 1992.

11.13 ASTM-C – 496. "Test for Splitting Tensile Strength of Cylinders Concrete Specimens", in: annual Book of Standards, 1996.

11.14 RAGAN, Steven A. "Proportioning RCC Pavement Mixtures", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.15 HESS, John R. "RCC Storage Pads at Tooele Army Depot, Utah", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.16 DELVA, Kevin L. "Rennick Yard RCC Pavement Design and Construction", in: Roller Compacted Concrete II- Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.17 SCHWEIZER, Eric; RABA, Gary W. "Roller Compacted Concrete With Marginal Aggregates", in: Roller Compacted Concrete II- Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.18 KEIFER Jr., Oswin. "Corps of Engineers Experience With RCC Pavements", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.19 PITTMAN, David W. "RCC Pavement Construction and Quality Control", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.20 ROLLINGS, Raymond S. "Design of Roller Compacted Concrete Pavements", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.21 JOFRÉ, Carlos; FERNANDEZ, Rafael; JOSA, Alejandro; MOLINA, Fermin. "Spanish Experience With RCC Pavements", in: Roller Compacted Concrete II - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1988.

11.22 WHITE, Thomas D. "Mix Design. Thickness Design and Construction of Roller-Compacted Concrete Pavement", in: Transportation Research Board National Research Council- Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.23 PIGGOTT, Robert W. "Roller-Compacted Concrete for Heavy-Duty Pavements: Past Performance, Recent Projects, and Recommended Construction Methods", in: Transportation Research Board National Research Council- Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.24 PITTMAN, David W. "Construction of Roller-Compacted Concrete Paviments", Transportation Research Board National Research Council- Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.25 ABRAMS, Jory M; JACKSHA, Jerry L.; NORTON, Robert L. and IRVINE, David J. "RollerCompacted Concrete Pavement at Portland International Airport", in: Transportation Research Board National Research Council- Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.26 RAGAN, Steveil A. "Evaluation of The Frost Resistance of Roller-Compacted Concrete Pavements", in: Transportation Research Board National Research Council - Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.27 STEWART, Rita F. and SCHEXNAYDER, Cliff J. "Construction Techniques For Roller-Compacted Concrete", in: Transportation Research Board National Research Council- Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.28 FRIZELL, K. H. "Hydraulics of Stepped Spillways For RCC Darns and Dam Rehabilitations", in: Transportation Research Board National Research Council - Proceedings of The RCC Pavements and Concrete Construction Conference. Washington DC, 1981.

11.29 WONG, Noel C.; FELDSHER, Theodore B.; WRIGHT, Robert S. and JOHNSON, David H. "Final Design and Construction of Gilbraltar Dam Strengthening", in: Roller Compacted Concrete III- Proceedings of The RCC Specialty Conference. San Diego, California. ASCE: 1992.

11.30 METCALF, Megan; DOLEN, Timothy P. and HENDRICKS, Paul A. "Santa Cruz Dam Modification", in: Roller Compacted Concrete III - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1992.

11.31 MAROLD, W. J. "Design of The Boney Falls RCC Emergency Spillway", in: Roller Compacted Concrete III - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1992.

11.32 DITCHEY, Eric J. "Rehabilitating Small Earth Embankments With RCC", in: Roller Compacted Concrete III - Proceedings of The RCC Specialty Conference. San Diego, California: ASCE, 1992.

11.33 TRICHES, Glicério; CARDOSO, Samuel H. "Misturas Granulares Cimentadas Para Serem Empregadas na Pavimentação Como Concreto Compactado A Rolo: Estudo Do Comportamento Da Fadiga", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.34 TRICHES, Glicério; CARDOSO, Samuel H. "Misturas Granulares Cimentadas Para Serem Empregadas Como Concreto Compactado A Rolo Na Pavimentação Estudo Das Propriedades Mecânicas", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.35 TRICHES, Glicério; CARDOSO, Samuel H. "Dimensionamento de Camadas de Concreto Compactado a Rolo Para Fins de Pavimentação Rodoviaria", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.36 GODINHO, Dalter Pacheco; GROSSI, Luiz Carlos. "Construção de Pavimentos de Concreto Rolado", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.37 GODINHO, Dalter Pacheco; GROSSI, Luiz Carlos. "Controle Estatístico de Qualidade de Pavimentos de Concreto Rolado", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.38 CARVALHO, Marcos Dutra de. "O Estado-da-Arte do Dimensionamento de Pavimentos com Camadas de Concreto Rolado", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.39 CARVALHO, Marcos Dutra de. "Dimensionamento de Pavimentos de Concreto Rolado Para Veículos Especiais", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.40 PITTA, Marcio Rocha; DIAZ, Patricio Hurtado. "Estado-del-Arte de Los Pavimentos de Concreto Compactado con Rodillo", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

11.41 CARVALLO, Marcos Dutra de. "O Concreto Rolado Como Camada Final de Base e Revestimento de Pavimentos Urbanos", in: Proceedings of The I Simpósio de obras em Concreto Compactado com Rolo. São Paulo, Brazil: CBGB-IBRACON, 1995.

12

Performance of RCC Dams

12.1 General

It is important for designers to obtain accurate records or reports on performance of dams in service to enable comparison between actual and predicted performances and to learn from unanticipated or unsatisfactory performance. By doing so the state of the art moves forward. RCC dam designers should be complimented because of the amount of information published on the performance of their dams. While most of the results have been positive, other were negative, especially with respect to seepage and seepage-related phenomena.

As reservoirs of the first generation of RCC dams have been filled, several have exhibited significant amounts of seepage, a fact that has been of concern to prospective dam owners. The key to proper dam design is a combination of seepage reduction and seepage collection to safely and economically meet operating requirements of the project.

Figure 12.01 Downstream view of a CVC Dam with seepage through the dam body.

The majority of the RCC projects built up to then around the world were directed to flood control, seasonal storage, or irrigation, where seepage loss has not been a major concern. As the next generation of higher, multi-purpose RCC dams are designed and built, demand for water tightness steadilly increases.

The economic advantage of RCC combined with a long-term safety record of concrete dams has led to rapid acceptance of RCC dams throughout the world. By the end of 1996, there were data available on 156 RCC dams higher than 15m or containing more than 10,000m³ of RCC, which had been completed in more than 10 countries, in all the six continents (see Chapter 3): North America with 32; Asia, 50; Africa, 17; Europe, 27; Oceania, 7; and Central and South Americas, 23.

The first question that a dam owner frequently raises concerning RCC is ***"what about seepage?"*** [12.01]. It results from the publicity surrounding initial filling of the first few reservoirs impounded by RCC dams, especially Willow Creek Dam (see Figure 12.01). To date, many RCC dams impound reservoirs. Seepage measurements have ranged from negligible (Shimajigawa, Winchester and Arabie) to approximately 170 l/s (Willow Creek). The source of seepage flow has primarily been through RCC lift joints and cracks, and the RCC itself or a combination thereof, as described ahead.

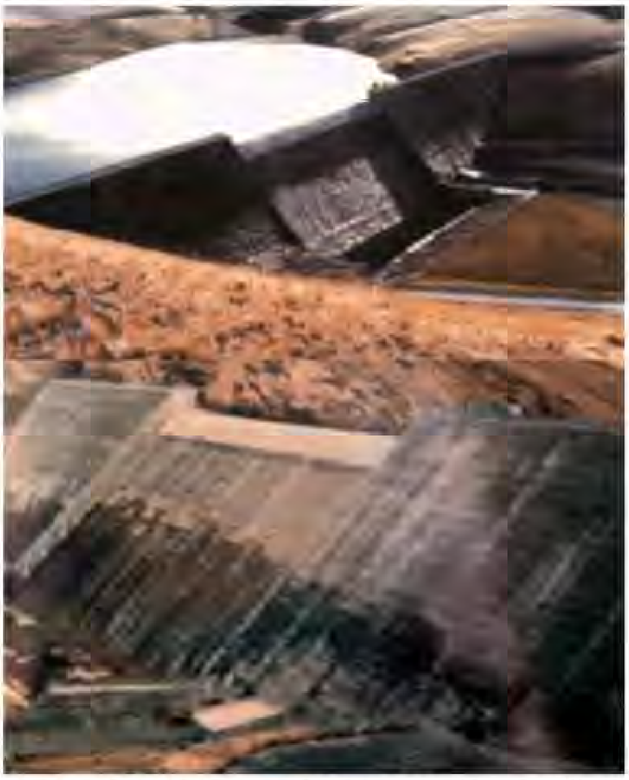


Figure 12.02 Downstream view of Willow Creek Dam showing seepage through the dam body.

Seepage at Willow Creek Dam generally ranged from 1.0 l/s to 38.0l/s. Although a portion of the recorded seepage was transmitted through the rock foundations, a significant percentage leaked through joints, cracks, or the mass concrete itself. There was no pattern to seepage recorded in this survey, except that seepage usually decreased with time.

Therefore, while RCC dams do not necessarily leak more than conventional dams, those ones leaking seem to do so at a higher rate than CVC dams. The design of seepage control systems for RCC dams should be based on the same rationale as for CVC and embankment dams. Namelly, the effect of seepage on the operation, safety and economics of the project. The owner should consider all theses variables in order to develop a satisfactory design to his needs.

Dams are built for a variety of purposes, from flood control to storage, to hydroelectric power production. Seepage affects the economics of these project purposes in different ways.

The primary concern with seepage in all dams, regardless of their purpose, is its effect on the safety of the structure. In concrete gravity dams this usually pertains to controlling uplift pressures that might adversely affect stability. Therefore, it is generally a design priority to control uplift pressures resulting from seepage by providing drainage.

The second aspect of seepage related to design is the impact on project economics. The economic need of the dam to hold water dictates in large part to what extent seepage should be reduced. The amount of money expended on seepage reduction is usually determined by the economic need to retain water.

12.2 Factors Affecting Seepage

An unjointed mass of roller compacted concrete (RCC) can be easily proportioned and compacted, to become essentially impermeable and "watertight". This can be checked by permeability tests of several field-placed RCC mixes. RCC is placed in layers resulting in seepage along the interface of each layer This potential seepage should be taken into consideration during design and be controlled by some appropriate method for structural stability, aesthetics, water loss control, and durability requirements.

Different approaches can be taken into account when dealing with this seepage. The most basic concept is to simply overdesign the dam to be stable under 100% of uplift conditions, collect the seepage internally or externally, and let it flow downstream.

Another approach is to use a special bedding mix or a joint preparation procedure between the layers, near the upstream face, to stop seepage or satisfactorily restrict it. A third approach common nowadays makes use of a CVC facing cast monolithically with each RCC layer. A further concept frequently considered is a waterproof membrane attached to the upstream face. However, it deserves a special thought concerning reverse pressures, durability and the contact of abutment and foundation tie-in.

RCC has been used much more frequently and for many more purposes than it is usually realized. Benefitting from both experience and some original thought, different methods were developed to obtain watertightness and seepage control, as mentioned in Chapter 4.

Seepage through completed RCC dams may be divided into four categories [12.01]:

- **Foundation**: Seepage through rock foundation which is usually controlled by grouting and drainage. There is no difference in foundation seepage under RCC dam and conventional concrete gravity dam.

- **Lift Joints**: Most seepage through RCC dams has been attributed to seepage along horizontal joints between RCC lifts. This is caused primarily due to segregation of coarse aggregate at the lift boundaries and the resulting lack of continuity from one lift to another. Another cause is by contamination of the freshly placed surface due to construction traffic, or by excessive time between lifts, either of which contributes to a preferencial seepage path along the joint.

Figure 12.03 Segregation of coarse aggregate between lifts endeavoring lack of continuity

- **RCC Permeability:** Permeability of RCC itself is controlled by a combination of factors involving aggregate gradation, content of cementitious materials and density. Laboratory tests on RCC core from several projects have shown the permeability of the first generation RCC (see Chapter 7) to range from 10^{-5} to 10^{-8} m/s and the second generation RCC (high fines content) to an improved range from 10^{-8} to 10^{-12} m/s. Tests on lift joints have shown the overall permeability of the RCC mass to range from 10^{-5} to 10^{-8} m/s;

- **Cracking:** Cracking and its associated leakage are both inescapable and intractable problems, which characterize to an extent all RCC dams. Uncontrolled transverse vertical cracks have occurred in three RCC dams (Upper Stillwater; Copperfield; Galesville). These cracks contributed significantly to seepage, although it was impossible to determine exactly what percentage of total seepage flow percolated through the cracks. Cracks are the result of tensile stresses within the dam, caused by shrinkage associated with cooling of the RCC and stress concentrations at abrupt changes in the foundation, and are extended by thermal shock caused by cold water penetrating the cracks. Cracking potential in RCC dams is unique to each site and depends on heat rise within the mass, ambient temperature, RCC thermal, elastic and strength characteristics, and geometric configuration of the dam section.

12.3 Durability Considerations

12.3.1 General

Durability of RCC dams is directly related to the properties of the exposed concrete, whether placed by a conventional method or by the RCC method.

From reference [12.02], it can be observed:

"... Designers of concrete structures are mostly interested in the strength characteristics of the material; for variety of reasons, they must now become durability conscious. Whereas properly constitued, placed, and cured concrete enjoys a long service life under most natural and industrial environments, premature failures of concrete structures do occur and they provide valuable lessosn for control of factors responsible for lack of durability...

....Water is generally involved in every form of deterioration, and in porous solids permeability of the material to water usually determines the rate of deterioration...

...Before a discussion of important aspects of durability of concrete, a few general remarks on the subject will helpful. First, water, which is the primary agent of both creation and destruction of many natural materials, happens to be central to most durability problems in concrete... ... As a vehicle for transport of aggressive ions, water can also be a source of chemical process of degradation. Second, the physical-chemical phenomena associated with water movements in porous solids are controlled by the permeability of the solid...."

CVC or RCC dams are structures designed to retain water. In that way, it is very important to manage the permeability of the structure body to reduce cracks, lift joint discontinuities and permeability itself.

12.3.2 Calcium Leakage

The appearance of calcium carbonate ($CaCO_3$) in the gallery, on the downstream face or at the bottom of the waterway downstream of the dam, has been reported on most completed RCC dams. Calcium carbonate (also called calcite) is formed when calcium hydroxide released from the cement hydration process is carried by seepage water to a surface where it combines with carbon dioxide from the air, as indicated by the following formula:

$$Ca(OH)_2 + CO_2 \simeq CaCO_3 + H_2O$$

In CVC and concrete masonry construction, this phenomenon is termed "efflorescence". The formation of this white salt tends to clog voids adjacent to the surface and thus reduce seepage through the RCC mass. Still, the formation of calcium hydroxide or ultimately calcium carbonate has produced some negative effects on several RCC projects in service. Negative effects include clogging of drain holes, increasing the pH of the seepage water, making gallery floors slippery, and possibly creating undesirable visual effects downstream the dam.

Calcium carbonate as thick as 50mm has been noticed [12.03] on the face of the gallery walls at both Willow Creek and Middle Fork dams. If this amount of calcite can be produced, it could clog internal drain holes, which generally have a 75mm diameter. At Middle Fork Dam, drain holes have required periodic cleaning or redrilling. Drain holes at Copperfield were reamed out in 1989. Holes exiting in the roof of the gallery were apparently clear of calcium carbonate beyond approximately 1m to 2m and drain holes from the foundation, full of water, were clear of calcium carbonate buildup. This confirms that carbon dioxide present in the air is required to produce the calcium carbonate precipitate.

Increasing the pH of the seepage water has its greatest negative effect when releases from the reservoir are low or nonexistent. In this case, there is not sufficient water to dilute the highly alkaline water that is being produced by calcium hydroxide and carried downstream by seepage water. Such was the case at Grindstone Canyon Dam where the calcium carbonate precipitated at the bottom of the stilling basin and streamed downstream of the dam soon after its initial filling in the spring of 1988.

The water exiting the dam was determined to have a pH greater than 11. Initially, the volume of seepage from the dam was nearly as great as the receiving waterway. As a result, rapid dilution of alkalinity did not occur. Instead, precipitation of calcium and some magnesium carbonate occurred. This mineral precipitation was aggravated by the fact that the water in the first stream downstream of the dam was already supersaturated with calcium carbonate. Water softening by pH adjustment is another way of explaining the phenomenon. While the white-colored bottoms of the streams produced an unnatural visual effect, there was no indication of either aquatic or terrestrial biological damage.

Reports on the performances of Copperfield, Craigbourne, and Middle Fork dams provide additional insight into the calcium hydroxide leaching and calcium carbonate buildup phenomenon. At Copperfield Dam, analysis of seepage water varied from a high pH value of 11.6 for a slow leak to 7.45 through a crack, with an average of 9.3 for a flow downstream of the dam of 10.3 l/s. Thus, water flowing quickly through a crack is less able to dissolve the calcium hydroxide than water slowly seeping through the RCC mass, in contact with more cemented surfaces.

A greater amount of calcium carbonate effluorescence appeared on the exposed downstream face of Craigbourne dam than at Copperfield. This was attributed primarily to a more porous RCC at this location, mainly due to a greater difficulty in compacting the external edge and to achieve a high density.

With the relatively dry no-slump mixes used for RCC, there is a possibility of partially hydrated cement to be present in the structure prior to filling. As water seeps through the mass, the cement hydrates, producing greater strength but also releasing additional calcium hydroxide for dissolution and transport downstream. If the reservoir level remains constant, the amount of leaching diminishes with time. This is due to both reduced seepage flow attributed to the natural siltation and calcification process and to the reduced amount of available calcium hydroxide. There is a fixed amount of calcium hydroxide within the structure and if some has already been carried downstream, the remaining amount is less. If the reservoir is raised to levels not previously exposed to water, the chemical phenomenon is again reproduced.

Basic concrete technology indicates that pozzolanic material will react with the calcium hydroxide produced from the cement hydration process and will make less calcium hydroxide available for dissolution and leaching.

12.3.3 Erosion Resistance

RCC erosion resistance can be best evaluated following high-velocity, high-volume flow over its surface. The most noticeable examples of RCC erosion resistance are at Tarbela dam, Kerrville Ponding dam [12.03] and Serra da Mesa cofferdam [12.04]. The 6.4-m high and entire RCC dam at Kerrville, Texas, was overtopped by as much as 4.4m and 4.9m in 1985 and 1987, with little noticeable RCC erosion except that it washed away some uncompacted material from the downstream face. As mentioned in Chapter 3, Serra da Mesa cofferdam behaved according to what was expected in the design and showed a remarkable strength against erosion.

The 40-m high upstream cofferdam at Geheyan Dam in China was overtopped in 1988 by a flow of 350m3/s for 4h without presenting any damage. During the construction of Craigbourne Dam and Bucca Weir in Australia, their cofferdams were overtopped, producing very little evidence of erosion to the recently placed RCC on the surface or downstream face. Exposed RCC has proved to have a high degree of erosion resistance due to the high percentage of aggregate in the mix. The degree of erosion resistance is directly proportional to the compressive strength of RCC, which depends on both the quality of the aggregate, the mix proportions and the degree of compaction.

At Copperfield Dam, some RCC was exposed during construction of the upstream face. After four years of exposure to reservoir water, there was an erosion of the paste at or above the waterline due to wave action, exposing some segregated RCC. The quality of the 150-mm RCC was good. It was difficult to achieve a high degree of compaction for RCC placed directly against forms, resulting in lower density and lower strength of RCC at this location.

12.4 Structural Performance

For dams which were subjected to full reservoir load, there have been no failures or unanticipated movements or deformations in the RCC structures.

There is no record of an RCC dam that has been shaken by a significant earthquake up to date, even considering seven RCC dams that have been completed in Japan and others also located in active seismic areas.

Following initial filling at Jordão dam, the strain- meters installed [12.05] at the same elevation (Figures 12.03 and 12.04) revealed deformations of the same pattern than previously admitted.

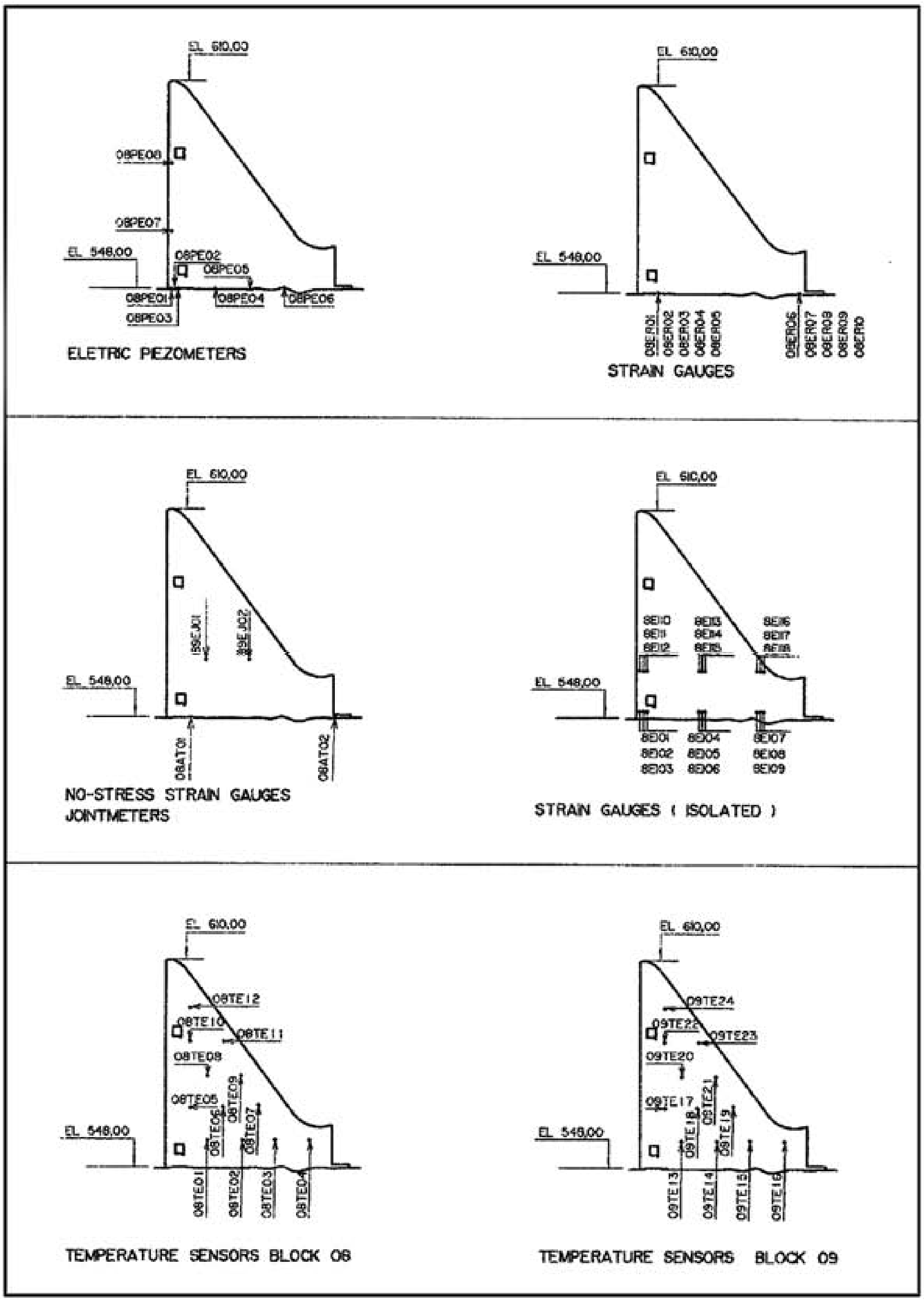


Figure 12.04 Locations of the instruments at Jordão Dam [12.05]

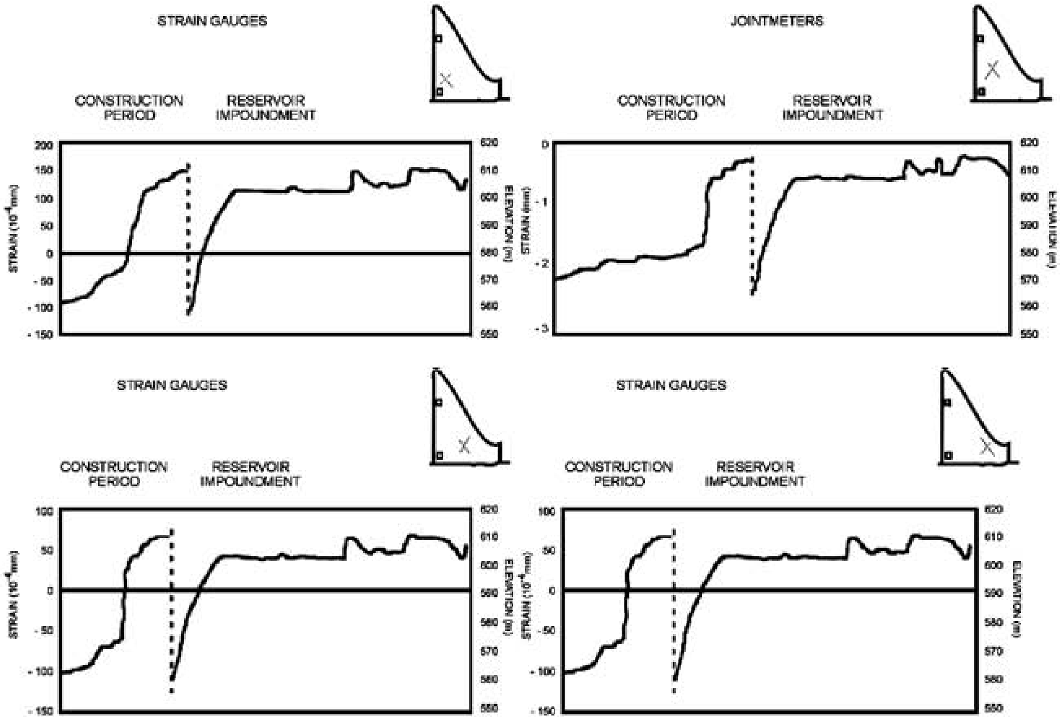


Figure 12.05 Strain measurements at a 548m elevation near the contact RCC-Rock Foundation, at Jordão dam.

12.5 Thermal Performance

Temperature in RCC dams is measured (not "controlled" because, if no post cooling is used, it is not possible to change the temperature development history of the concrete mass) by thermometer. A large number of temperature-sensors are usually planned for RCC dams.

During construction, temperature meters installed at Salto Caxias RCC dam [12.06] (Figure 12.06) indicated a temperature history as shown in Figure 12.07.

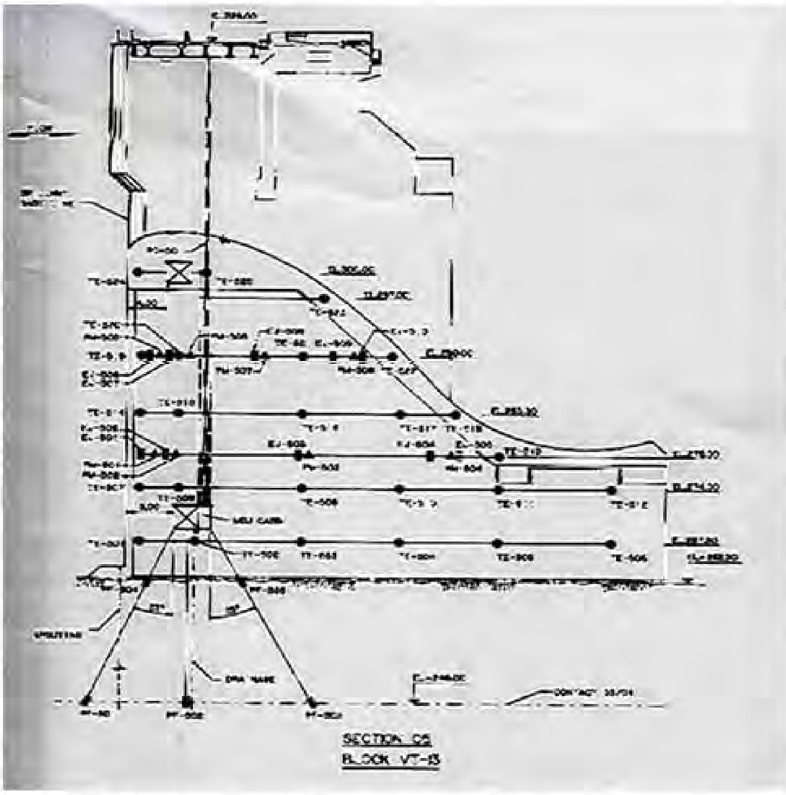


Figure 12.06a Locations of the instruments at Salto Caxias Dam.

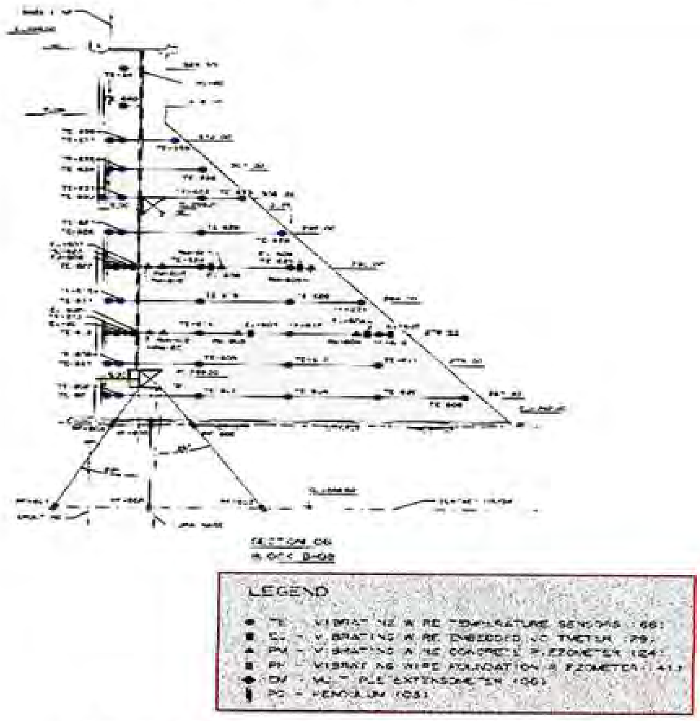


Figure 12.06b Locations of the instruments at Salto Caxias Dam [12.06].

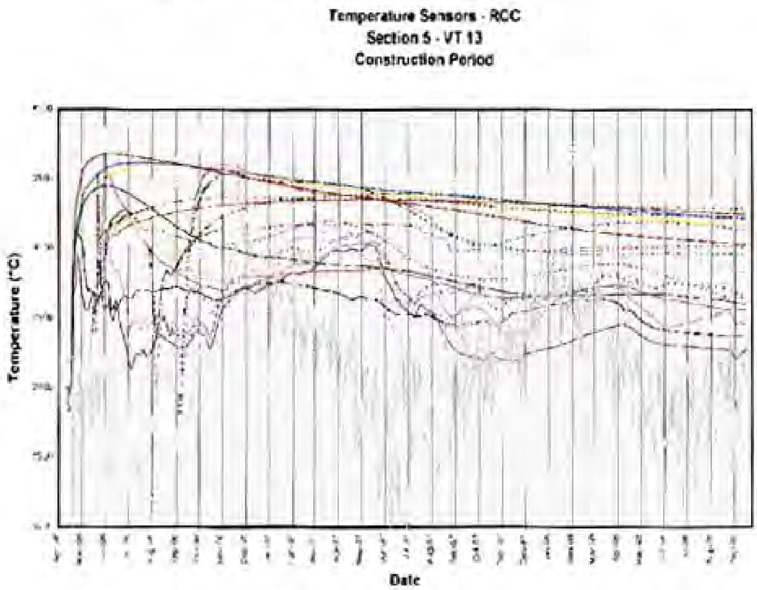


Figure 12.07 Temperature development at Salto Caxias RCC dam mass, showing measured values near theoretical data.

12.6 Cracks and Seepage

Measured seepage is an indication of how the designed seepage control system performs. Total measured seepage may consist of the following items:

a. Leakage through joints and cracks;
b. Seepage through a CVC face if used and the RCC material itself; and
c. Seepage through foundation materials

Water passing through RCC depends upon void characteristics of the mixture in addition to construction-related voids, such as those produced by segregation of the large aggregate at or near the bottom of the lift and a possibly inadequate compaction of a lift. Most seepage measurements have been from weirs located in the gallery, at the downstream gallery entrance or at some point in the waterway downstream the dam.

To compare seepage through various dams on an equal basis, size and shape of the dam's upstream face exposed to reservoir pressure should be taken into account. In order to fairly compare seepage between RCC dams and those with conventional concrete dams, a normalized seepage unit was derived. Relative unit seepage is the seepage flow divided by hydraulic height and the wetted area of the upstream face exposed to seepage. The average head is the vertical distance from the water surface to the centroid of the wetted surface area and is the height of average pressure acting upon the face. Thus, as the reservoir water surface fluctuates, both the wetted area and average head change.

The location of the average pressure is different from the location of the average force acting upon the structure. The location of the average pressure is generally between one-third to one-half the total hydraulic head at any reservoir level. The one-third factor corresponds to a triangular-shaped upstream face while one-half is for a rectangular face. For a dam with a rectangular-shaped face, the location of the resulting hydraulic force is two-thirds the head measured from the water surface.

Because there is a considerable variation in the accuracy of seepage measurements, mainly due to variations in what is being measured, relative unit seepages for each dam and reductions over time are more significant than the absolute values. Factors which overestimate the actual amount of water passing through the RCC structure are flows through foundation and abutment rock that are collected from foundation drains or drainage edits and downstream rainfall that is collected and flows through the measuring device. Water passing through the dam that evaporates at the downstream face or is not collected in a downstream weir results in underestimating actual seepage.

Low reservoir levels may produce higher unit seepages due to the increased effect of water passing through foundation rock, when compared to that acting above and seeping through the dam. The degree of seepage reduction with time for a certain dam should be helpful in predicting the future seepage performance for a recently completed dam, built with similar seepage control measures and same RCC mixtures.

Information on seepage measurements with time together with remedial action that where required are available from the following dams in service.

1- Shimajigawa Dam: Shimajigawa Dam [12.03] was completed in 1981, with a maximum height of 89m, a crest length of 240m and with 317,000m^3 of concrete. The RCC mix had 120kg/m^3 of cementitious content (70:30 Ordinary Portland Cement: Fly-Ash).

Seepage has been continuously measured and monitored since the initial reservoir filling in 1981. No seepage has been visible on the downstream face, and the amount of seepage from foundation drains has never exceeded 0.5 l/s. Leakage from the contraction joints is as small as that experienced in conventional concrete dams in Japan.

Detailed investigation of the dam, built with full-section contraction joints spaced at 16m, revealed no cracking on the upstream or the downstream face, nor the gallery has caused water leakage. Maximum opening of the joints was 5mm and the mean opening width was 2.7mm.

2- Willow Creek Dam: Willow Creek Dam [12.03; 12.07] was completed in 1983, with a maximum height of 52m, a crest length of 543m and with 331,000m^3 of concrete. The RCC mix had 66kg/m^3 of cementitious content (75:25 Ordinary Portland Cement: Fly-Ash).

When the reservoir for this dam, which is primely for flood control, was initially filled during the spring of 1983, seepage in the drainage gallery and on the downstream face was noticed within 12 h after filling.

It is very important to remember from the reference [12.08], that:

(page 4-28)

... Even with these modifications, perfect joints should not be expected. But, to repeat, they are not necessary. Some seepage could be tolerated just as is the practice on lift joints in isolated locations in essentially all conventional concrete gravity dams... ... At any rate, seepage along lift joints would be aesthetic rather than a structural problem if it did occur, and it could be remedied if later deemed necessary by drilling and grouting the affected area...

(page 4-38)

... Seepage is not expected to be a problem but even if did occur there are no materials that could pipe and threaten the integrity of the structure. Except for brief and infrequent partial fillings of the reservoir under flood conditions only a small reservoir will be maintained....

.... Cracking of the concrete mass and leakage of horizontal construction joints is expected to be minimal. ... ... In the event that leakage did become a problem, it would be of an aesthetic nature but not of structural concern... ... If the improbable condition of excessive seepage through joints and cracks did occur, it could be handled by drilling from outside to the suspected area of seepage and either grouting it or draining it to the spillway face....

The initial total seepage, including water exiting in the gallery and spillway stilling basin, was nearly 189 l/s with a water depth of 14.7m. This produced an initial unit seepage value of wetted area per head (93.5 l/s.m^3.m). Over a two-month period, the total measured seepage dropped to 150 l/s.

Narrow hairline cracks have been noticed on the exposed RCC at the crest and inside the gallery. These cracks were closely spaced and did not have sufficient width for any water to pass to the downstream face. On the gallery ceiling, however, there were evidences of greater water leakage through the cracks.

After the reservoir level was raised, the instrumentation detected an internal crack within the RCC, starting near the foundation at a transition section where the spillway meets the non-overflow section. It did not penetrate through the RCC mass because no indication of a crack could be detected at either the upstream or downstream surface in this area.

At that time, the U.S. Army Corps of Engineers decided to reduce seepage at Willow Creek dam by grouting. The reservoir level was lowered to 10.6m of water depth to prepare for grouting. An initial chemical grouting program from the upstream face did not significantly reduce the seepage. A subsequent cement grouting program from the dam crest was then performed during the second half of 1983 and early 1984. Following the completion of grouting, the water level was raised to the original water depth of 14.7m and then to 28.9m. At the lower reservoir level, total seepage was about 8.5 l/s, much less if compared to seepage prior to grouting of 150 l/s. At the higher reservoir level, the total seepage collected was 128 l/s, which accounted for the higher head and a greater wetted upstream surface area that was exposed to water for the first time. Seepage was noticeable on the downstream face of the dam. After one year with the reservoir at about the same 28.9m level, seepage decreased to 29.3 l/s. The following two years saw even further more reduction of the seepage to 21.5 l/s and then to 15.9 l/s, respectively.

With unsealed joints between the upstream precast concrete forming panels, RCC was considered to be the primary water barrier. Initial seepage was attributed to voids at the lift interface caused by coarse aggregate segregation, which in turn contributed to decreased bond between untreated successive lifts of RCC. A bedding mix placed between successive lifts above the level of the gallery was not effective because it was too narrow, about 300mm wide. Located too close to the upstream facing panels it did not ensure that RCC could be properly compacted into the bedding mix. Reduction in seepage with time was determined to be promoted by silting, calcification (production of calcium carbonate), additional maturity, as well as the grouting program.

3- Copperfield Dam: Copperfield Dam [12.03] was completed in 1984, with a maximum height of 40m, a crest length of 340m and with 156,000m³ of concrete. The RCC mix had 110kg/m³ of cementitious content (73:27 Ordinary Portland Cement: Fly-Ash).

Figure 12.08 Seepage at downstream face at Galesville Dam (Courtesy: Selmo C. Kuperman).

Initial filling of this dam, built to provide water for gold mining operations, started in late 1984. With a water depth of 21.0m, the total measured initial seepage was 24.7 l/s. Although the reservoir level was raised to 23.7m, seepage decreased to 17.8 l/s after one month. Two months later it was further reduced to 10.2 l/s. Seven months after the initial filling, a vertical transverse crack developed through the spillway which increased seepage to 16.0 l/s.

At Copperfield Dam a single transverse uncontrolled crack developed through the spillway, as a result of a temperature drop of 11°C from the peak temperature of 36°C. Leakage increased following the formation of this crack and then naturally diminished thereafter. In addition to the crack through the spillway, three transverse contraction control joints opened as intended with no significant seepage bypassing the waterstops. Crack opening width measurements made on the three joints indicated a total width of 4.5mm two months after cracking. During the following summer, joints and cracks closed fully and reopened to their initial width in the next winter.

The downstream face of the dam has shown a development of the crack. Some seepage bypassed the vertical drain holes and was draining through the spillway facing drainage system. Seepage decreased by natural autogenous healing (calcification) to a value of 5.6 l/s in late 1986 and decreased further to 2.15 l/s by mid 1989.

Figure 12.09 Leakage from the gallery at Galesville Dam (Courtesy: Selmo C. Kuperman).

4- Middle Fork: Middle Fork [12.03] was completed in 1984, with a maximum height of 38m, a crest length of 125m and with 43,000m³ of concrete. The RCC mix had 66kg/m³ of Portland Cement.

The dam was built to provide flood protection and supplementary water supply for a proposed shale oil mine and processing plant. The reservoir was filled in the fall of 1984 up to a water depth of 13.4m. At that time, an initial seepage of about 9.5 l/s was measured, which decreased to 6.9 l/s after 2.5 months.

The reservoir was raised in the spring of 1985 up to the elevation of the primary spillway, which produced a water depth of 26.2m. Total seepage then peaked to 30.0 l/s, but decreased to less than 3.0 L/s 18 months later. This was less than the 3.2 l/s to 7.9 L/s predicted during design. Seepage reduction was attributed to calcification of the RCC mass, which was most rapid during the first 3 months after the complete reservoir filling.

At the time of the maximum seepage, it was determined that 80% of total seepage was through the dam as collected from roof and floor drains that exited in the gallery or from the gallery walls. The remaining 20% was collected from drainage tunnels built in each abutment. After four years of service, the amount of seepage percolating through the RCC dam was estimated to be about the same as that passing through the rock abutments due to the decreased permeability by further calcification within the dam.

***5- Winchester Dam**:* Winchester Dam [12.03] was completed in 1985, with a maximum height of 23m, a crest length of 363m and with 27,000m³ of concrete. The RCC mix had 104kg/m³ of Portland Cement.

When the reservoir for this municipal water supply dam was initially filled in 1985, no seepage was measured or noticeable through the dam. However, leakage through the jointed limestone foundation was considered excessive. The water level was lowered and remedial cement grouting of the foundation was performed. The reservoir was filled again, and after four years there was basically no seepage through the dam, indicating effectiveness of the membrane-lined precast concrete panel that comprised upstream facing system. The very small amount of water collected downstream the dam was determined to be origined from the seepage through the foundation rock.

***6- Galesville Dam**:* Galesville Dam [12.03] was completed in 1985, with a maximum height of 50m, a crest length of 290m and with 171,000m³ of concrete. The RCC mix had 104kg/m³ of cementitious content (50:50 Portland Cement: Fly-Ash).

Initial filling of this multipurpose reservoir, which includes hydroelectric power generation, started in December 1985. By late March 1986, a hydraulic head of 33.5m had been achieved and the maximum total seepage was measured as 45 l/s. Total seepage decreased over the following 10 months to a value of 20 l/s, which was attributed to siltation and calcification during the maturation of the RCC.

A delay in starting RCC placement contributed to the formation of seven cracks which were the primary cause of leakage at Galesville. The uppermost lifts of RCC were placed during the hottest time of the year. Cracking occurred when unusually cold weather hit 60 days later and caused rapid cooling of the concrete. Delay in construction caused the peak temperature to be more than 12°C greater than originally predicted due to higher temperatures of both RCC and ambient air. Capping the crest of the dam with conventional concrete on three sides contributed to the heat rise in this area.

Cracking occurred when the differential temperature measured between the downstream face and the interior mass was of about 16°C. Cracks started at the crest and extended vertically down on both faces. The first crack noticed was located near the right abutment in such angle to the vertical that it intercepted the entrance edit to the gallery, a hollow which provided the least resistance to the thermally induced tensile stresses.

In early 1987, the reservoir was raised to about 1.5m below the spillway crest, thus producing a head of 41m. Seepage increased to a maximum of 60 l/s, not including seepage exiting on the downstream face, which could not be measured. Most of the leakage passed through seven major cracks in the dam. A coal-tar based elastomeric membrane sprayed on the upstream face in two 0.5mm thick layers did not effectively bridge the cracks, but was effective in reducing seepage through the area between the cracks.

A reduction in seepage to 49.8 l/s was attained after pelletized bentonite was dumped from a boat into the reservoir, near the widest crack, soon after recording maximum seepage. It worked well because there was sufficient velocity of water to draw the bentonite into the crack. Then, a further decrease in seepage to 32.2 l/s occurred after divers caulked the cracks to a depth from 15m to 18m below the water surface using quick-set cement. Since maximum water level was reached in early 1987, the reservoir has been steadily lowered due to less inflow. In the spring of 1988, when a head of 33.5m was reached, a seepage of 12.6 l/s was recorded. This can be compared to the 45 l/s seepage with the same head during initial filling two years earlier.

7- Craigbourne Dam: Craigbourne Dam [12.03] was completed in 1986, with a maximum height of 25m, a crest length of 247m and with 24,000m³ of concrete. The RCC mix had 130kg/m³ of cementitious content (54:46 Portland Cement: Fly-Ash).

Initial seepage measured at the downstream toe of this irrigation dam was 8.81 l/s when the hydraulic head was 18.5m following the filling that started in October 1986. Five months later, seepage decreased to 2.7 l/s. This seepage reduction was attributed to autogenous calcification healing. After two years of reservoir operation, seepage was further reduced to 1.5 l/s.

No cracking has been identified after one year. RCC temperatures peaked at 20°C to 21°C and were expected to stabilize at 12°C to 14°C. Thus, the maximum temperature drop of 9°C was not expected to cause thermal cracking.

The design for Craigbourne, unlike Copperfield by the same designer, included precast concrete panels rather than conventional unreinforced concrete on the upstream face. Both designs incorporated a 2-m partial bedding concrete between each RCC lift placed near the upstream face.

8- Grindstone Canyon Dam: Grindstone Canyon Dam [12.03] was completed in 1986, with a maximum height of 42m, a crest length of 432m and with 96,000m³ of concrete. The RCC mix had 76 kg/m³ of Portland Cement.

Although RCC for this dam was completed in July 1986, filling of the municipal water supply reservoir did not start until late March 1988. The delay in initial filling was due to a number of reasons, these included a missing outlet works valve, a dispute over water rights, and the need to seal some cracks. By the end of May, water level was 28m above the reservoir floor and total seepage, measured at a flume in the channel downstream of the dam, was of 72.3 l/s. During June, water level continued to rise and seepage exceeded flume capacity and was estimated to have reached a maximum of 88 l/s.

Calcification and siltation together with repair of one hole in RCC at the right end of the gallery, estimated to let a flow of about 6 l/s, brought total seepage down to nearly 25l/s. During the cold weather in early 1989, the RCC mass contracted and the leakage from existing cracks or joints in the conventional concrete upstream face increased to 33.6 l/s. It was then decided to empty the reservoir to allow for repair of these joints and cracks during 1989. It was reported that the original joint sealant used in the dummy joints spaced 4.9m on the center was not of the type recommended for underwater placement and that it was not applied to the specified depth.

9-Monksville Dam: Monksville Dam [12.03] was completed in 1986, with a maximum height of 48m, a crest length of 670m and with 232,000m^3 of concrete. The RCC mix contained 64kg/m^3 of Portland Cement.

Initial filling of this municipal water supply reservoir started in July 1987. Full pool producing a hydraulic head of 43m was reached in April 1988, when a maximum total seepage of about 15.8 l/s was measured in weirs located in the gallery and both abutments. Beside this amount, the measured seepage from the gallery, with an extension of only 91m across the dam and corresponding to the spillway width, was 3.8 l/s. During the next five months, total seepage had decreased to 7.6 l/s and total seepage from the gallery to 1.6 l/s. During cold winter weather, total seepage increased to 18.3 l/s in March 1989 and the flow collected apart in the gallery rose to 3.5 l/s. Three months later, total seepage was reduced to 9.5 l/s. Wet spots were noticeable on the exposed RCC downstream face of the non-overflow sections soon after filling and remained still visible two years later.

Overall low permeability of this dam was attributed to the design response to a refined thermal analysis and improvements in RCC mix design to provide reduced permeability. When it was found that a delay in construction would produce higher peak temperatures than predicted in the original design, due to warmer weather, the designers decided to increase the number of waterstopped joints for the upper 12m of the dam. Basic watertightness of RCC material was aided by a reduction in maximum size aggregate from the usual 75mm to 50mm and by using a 40% sand fraction in the mix. Both mix design factors favored a decreasing segregation potential and minimizing voids for an RCC dam which had a low cement content of 63kg/m^3.

10- Arabie Dam: Arabie Dam [12.03] was completed in 1987, with a maximum height of 36m, a crest length of 455m and with 142,000m^3 of concrete. The RCC mix had 110kg/m^3 of cementitious content (33:67 Ordinary Portland Cement: Blast Furnace Slag).

Reservoir filling started in early 1987 and measured total seepage did not exceed 1 l/s. Low amount of seepage has been attributed to the design of an improved seepage control system and to the fact that the dam was located in a warm area, in Lebowa. There was a low-temperature drop from the peak of RCC temperature in the mass to the annual average ambient temperature, thus minimizing potential for thermal-induced cracking.

Seepage control system included waterstops installed downstream of formed grooves in the upstream conventional face concrete spaced at 12m between centers. Bedding concrete was placed atop each RCC lift for a horizontal distance back from the upstream face equal to one-fourth of the dam height at that elevation. Segregation of coarse aggregate remained a problem, but increasing sand content of the RCC mix to 40 percent was of help to reduce permeability of the RCC mass.

11- Upper Stillwater Dam: Upper Stillwater Dam [12.03; 12.09; 12.10] was completed in 1987 with a maximum height of 91m, a crest length of 815m and with 1,281,000m^3 of concrete. The RCC mix had 252kg/m^3 of cementitious content (31:69 Ordinary Portland Cement: Blast Furnace Slag).

The primary function of the dam is to store the spring runoff from Rock Creek for diversion into the Stillwater Tunnel. It is the start of the Strawberry Aqueduct which conveys water to populated areas in the west of the Wasatch Mountains. Approximately 74x10^6m^3 must be diverted annually for municipal, industrial and agricultural uses on the Central Utah Project. Usual reservoir operation includes filling the reservoir in the spring, keeping it full during summertime for recreation, then drawing down the reservoir to near the minimum pool elevation during the winter.

RCC construction was selected to shorten construction period and to minimize total project cost. Shortening construction period was important to anable to complete construction during the non-freezing month, a window available each year. The dam volume was minimized by using a 0.6:1.0 downstream face slope and high strength RCC. Features, which could have interfered with the efficient hauling and placing of RCC by large earth moving equipment, were eliminated or redesigned. This required locating the outlet works on the foundation, designing a long

Figure 12.10 Downstream view of Upper Stillwater Dam.

uncontrolled spillway on the dam crest, and eliminating *in situ* concrete cooling systems and contraction joints. Galleries were designed to be built horizontally and to avoid forms installed parallel to abutment slopes. Horizontal slipforming replaced conventional facing concrete placed against supported forms, completely eliminating the need to form dam faces.

To ensure bonding development on lift surface, RCC was designed to be enriched with paste and to provide tensile strength to resist water pressure, seismic and thermally induced tensile stresses. This resulted in a higher compressive strength than typically used for concrete gravity dams.

As the dam was being built with horizontal slip-formed elements of conventional non-reinforced concrete on both upstream and downstream faces, narrow vertical cracks, spaced 6m to 9m apart, were noticed on the concrete surface within two days after placement. These shrinkage-related cracks were limited to the facing elements and did not extend into the RCC mass.

The dam was topped out in August 1987. By December, 13 cracks had developed along the dam and spillway crest. All started at the joints in the parapet or spillway crest where the steel reinforcement had been stopped. Parapet contraction joints were produced by handtooling a 50-mm groove at 12.1m centers spacing on both sides of the 1.4-m slip-formed parapet wall. These cracks, which started at the crest and continued down the faces, had an average spacing of 49m. As the weather warmed up, crack-width instrumentation showed close up of the cracks and little or no leakage passing through.

In the original design, cracking was predicted. However, higher temperatures than the anticipated peak near the top of the dam produced a deeper cracking into the mass than expected.

Figure 12.11 Hairline crack at Saco de Nova Olinda Dam, during construction.

Spacing between cracks was greater than anticipated, resulting in fewer but wider cracks in the 815-m long structure.

While the reservoir was being filled, a single major crack occurred. The reportedly crack was noticed first at the base of the dam and then propagated upward to the crest. The external temperature restraint condition is what best explains the formation of this crack. However, it might have been triggered by a slight downstream movement in the foundation. All cracks at Upper Stillwater Dam are vertical and transverse to the dam axis and have already started to heal naturally.

Two cracks, at a point approximately one-third of the dam length, may be related to foundation movement previously discussed. The largest crack opened 6.4mm wide on the gallery wall. An attempt was made to reduce the water flow from this crack into the gallery and on the downstream face by injection of polyurethane resin grout. It greatly reduced the flow into the gallery and was partially successful in reducing flow on the downstream face.

Both foundation drains and cracks contributed to the uncontrolled flow of water through the dam. Foundation drains were drilled along the gallery into the foundation. Gallery gutters collected water from the foundation drains and also water entering directly into the gallery from cracks. In 1991, the maximum flow collected in the gallery occurred on July 14, five days after filling the reservoir. This flow was 52 l/s directly from cracks into the gallery and 103 l/s from foundation drains. It decreased about 10% as the weather warmed up during the summer. With a full reservoir, an estimated flow of 57, 18 and 16 l/s flowed through three cracks, respectively. About 16 l/s flowed through all the other cracks together.

RCC dams that are being currently reviewed or designed by the U.S. Bureau of Reclamation, are provided with contraction joints to alleviate problems associated with water flowing from contraction joints without waterstops and from cracks. Contraction joint spacing is being evaluated on a specific site basis. Based on the Upper Stillwater experience, spacing of joints should be no greater than 15m to completely control formation of cracks. Geologic and foundation shape should also be considered for locating contraction joints.

After three years of RCC construction, filling of the reservoir started in early December 1987, at an average rate of 90mm/day. By early June 1988, the water surface had risen to an elevation of 2,482m, 50m above the tailgater elevation. The streambed is at an elevation of 2,436m. At that time, total leakage measured from weirs within the gallery and both abutments was slightly greater than 44 l/s. It produced an initial unit seepage value of 0.40 $l/s.m^2.m$. Most of the seepage measured in the gallery, whose invert is at the same elevation as the streambed, came up from the foundation drains, indicating that the greatest volume of seepage was passing the grout curtain rather than percolating through RCC.

A major transverse crack was then formed on the right side of the 183-m spillway, which was located near the central portion of the dam. With a full reservoir (water at an elevation of 2,491m) the flow through this single crack, which reached a maximum width of 6mm, overflowed the gutters in the gallery. Leakage was estimated to be about 100 l/s into the gallery plus another 140 l/s exiting from the crack on the downstream slope.

Even though the crack was formed and was producing leakage, it was determined that it would not affect the structural safety of the dam. The reservoir was lowered to the inactive storage pool elevation of 2,447m in order to cap some fine red sand piles in the reservoir that had discolored the water. With the reservoir lowered, the crack repair work with the use of polyurethane resin was accomplished during the winter of 1988-1989 and the reservoir was filled again in the spring of 1989.

With a full reservoir, the estimated leakage was now 57 l/s from the crack on the downstream face. Leakage into the gallery from the crack had been stopped by the repair program. Some additional repairs in the vicinity of the crack were planned for 1990.

12- Zaaihoek Dam: Zaaihoek Dam [12.11] was completed in 1987, with a maximum height of 47m, a crest length of 527m and with 134,000m^3 of concrete. The RCC mix had 120kg/m^3 of cementitious content (70:30 Ordinary Portland Cement: Blast Furnace Slag). On July 31, 1991, at wintertime (South Africa), the leakage into the gallery from the left flank reached a total of 15 l/s, of which 9 l/s were coming from a single crack, and other 6 l/s from two other cracks.

13- Saco de Nova Olinda Dam: Saco de Nova Olinda Dam was completed in 1987, with a maximum height of 56m, a crest length of 230m and with 143,000m^3 of concrete. The RCC mix had 70kg/m^3 of cementitious content (80:20 Ordinary Portland Cement: Pozzolanic Material). During construction, hairline cracks were observed and considered to have a shrinkage origin [12.12]. After more than a decade in use, the owner considers that the dam has a satisfactory behavior.

14- Urugua-i Dam: Urugua-i Dam was completed in 1989, with a maximum height of 77m, a crest length of 687m and with 626,000m^3 of concrete. The RCC mix had 60kg/m^3 of Ordinary Portland Cement. Imperviousness was trusted to the combined action of a 2-mm PVC membrane and a CVC face of 0.90m to 0.50m thick [12.13; 12.14; 12.15]. The CVC face was poured simultaneously with RCC and has 200kg/m^3 of Ordinary Portland Cement. Permeability of RCC was reduced to some extent by the addition of powder fines to the mix.

Total seepage can be described as [12.14]:

Seepage Source	**Flow (l/s)**	**%**
PVC membrane drain	38.3	45
Rock contact	11.7	14
Diversion conduits	9.2	11
Contraction joint drains	9.2	11
RCC inside the gallery	6.3	8
Downstream drains	4.3	5
Shear key	3.7	4
Gallery foundation drains	1.9	2
Total	**84.6**	**100**

On the non-overflow crest, the major crack that occurred had a maximum opening of about 5mm.

15- Knellpoort Dam: Knellpoort Dam [12.11] was completed in 1989, with a maximum height of 50m, a crest length of 200m, and with 59,000m^3 of concrete. The RCC mix had 203kg/m^3 of cementitious content (30:70 Ordinary Portland Cement: Pulverised Fuel Fly-Ash). In the lower part of the dam, cracks were less than 0.2mm and partly closed. In the middle section of the dam, cracks were less than 0.1mm and in parts were still closed. In the upper section of the dam, cracks were less than 0.2mm and in parts were still closed. There were some induced cracks-joints showing larger openings.

16- Wolwedans Dam: Wolwedans Dam [12.11] was completed in 1990, with a maximum height of 70m, a crest length of 268m and with 210,000m^3 of concrete. The RCC mix had 194kg/m^3 of cementitious content (30:70 Ordinary Portland Cement: Pulverised Fuel Fly-Ash). In the lower part of the dam, cracks were less than 1mm and in parts closed. In the middle and upper parts of the dam, joints were closed for most parts and the maximum crack width was 1mm and in parts was still closed. In the upper section of the dam the cracks were less than 0.2mm and in parts were still closed. There were some induced cracks-joints showing larger openings.

17- Arriaran Dam: Arriaran Dam [12.16] was completed in 1993, with a maximum height of 58m, a crest length of 206m and with 113,000m^3 of concrete. The RCC mix had 220kg/m^3 of cementitious content (40:60 Portland Cement: Fuel Fly-Ash)

On November 1992, two vertical cracks [12.16] that cut across the dam body were detected. One year later, another one was detected in the middle of the left-hand block. The cracks with 0.5mm width were filled with epoxy resin.

18- Jordão Dam: Jordão Dam [12.05] was completed in 1996, with a maximum height of 95m, a crest length of 550m and with 650,000m^3 of concrete. The RCC mix had 75kg/m^3 of Pozzolanic Portland Cement.

On April 24, 1996, the sluiceway gates were closed [12.05] with a discharge of 104.6 m^3/s. During wintertime (June 1995), some hairline cracks were observed on the upstream face (CVC face). Prior impoundment, cracks on the upstream face were repaired (sealed and/or grouted). Cracks wider than 0.3mm were grouted with epoxy resin and the remaining ones, thinner than 0.3mm, were sealed with elastic epoxy seal.

During impoundment, a large inspection scheme was planned and put into operation to check seepage. It was observed that contraction joint drains had a large contribution to it. A reparation plan was implemented and seepage was drastically reduced, as it can be seen in Figure 12.10.

Figure 12.12 Downstream view of Arriaran Dam.

12.7 Lessons Learned from Cracking, Seepage and Seepage-Related Phenomena

One can learn much from the performance of RCC dams in service,. Most of following lessons are self-evident.

With regard to structural behavior of dams submitted to a full reservoir load, neither failures nor unforeseen movements or deformations have been observed. As for percolation, the main conclusions obtained from observations carried out may be listed as follows:

I. It is possible to build RCC dams with seepage of the same order of magnitude as those for concrete dams built with traditional methods;

II. RCC dams with CVC faces and joints having waterstops (including dams built with the Japanese method), as well as those with faces formed by prefabricated concrete panels lined with an impermeable membrane have shown a high degree of watertightness;

III. Seepage considerably reduces with time, due to a series of external effects, such as filling of voids and a natural process of internal "welding" due to the formation of additional concrete gel and its calcification through contact with the passing water;

IV. In those cases in which the volume of leakage has increased considerably, it was usually due to formation of a new crack or fissure;

V. The secondary effects of seepage, such as appearance of humidity stains or effluorescence have, in general, created more concern than the flow itself through the dam and its foundation;

VI. As it would be expected, seepage is greater the higher is the water head and the wetted surface. Also it increases during cold weather spells, in which shrinkage of the compacted concrete mass increases the opening of the cracks;

VII. The seepage from cracks can be corrected in a more efficient way than the flow percolating through the mass of RCC;

VIII. The impermeability of RCC can improve by increasing the the fine material content, and by employing constructive methods that minimize the voids in the mass of the material once compacted;

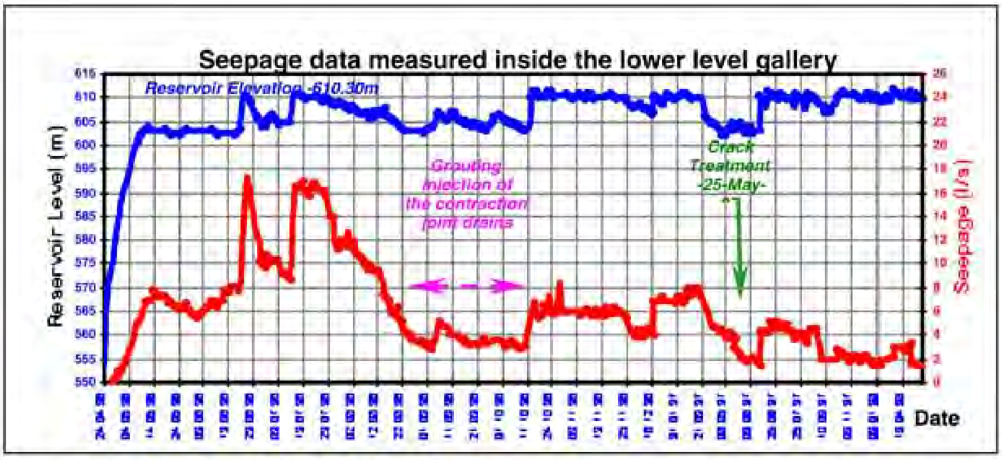


Figure 12.13 Seepage Control at Jordão Dam.

IX. The contact between the dam and its foundation and its abutments are, as in any other type of dam, a potential source of seepage, and care should be taken to assure that these contacts have a high degree of watertightness;

X. With regard to its behavior in relation to cracks, the following points can be emphasized:

- **a.** RCC is less likely to crack than CVC due to lower contraction potential of the RCC mass combined with generally lower elastic modulus and higher creep rates. Less amount of shrinkage is due to lower water and cementitious contents in the RCC mixtures as compared to CVC placed concrete;
- **b.** Most cracking in RCC dams can be attributed to thermally induced stresses. Cracking occurs when the thermal stress exceeds the tensile capacity of the concrete. Cracks can occur with a temperature drop as little as 11°C from the peak temperature for lean weaker RCC mixes up to as much as 20°C for stronger mixes. Cracks in CVC concrete faces are also influenced by drying shrinkage stresses;
- **c.** Increased crack spacing induces greater individual crack width as the total volume reduction must be accommodated in fewer cracks or joints. Obviously, wider cracks have a greater leakage potential;
- **d.** Full-section transverse contraction joints with upstream waterstops and drain holes are an effective means of controlling cracking through the entire RCC dam. When the spacing between joints is too great, cracking will occur between the joints. Crack width of uncontrolled cracks between joints is smaller than the width of the induced cracks in transverse joints;
- **e.** Cracks invariably will occur in intentionally planned transverse contraction joints or at a point of reduced dam section where the overall tensile resistance of the section is less. This crack position can be at a reentrant angle in the foundation rock, which induces a stress concentration; it may occur through a central spillway section, at a transverse entrance edit, or at a planned groove in the conventional concrete face;
- **f.** Cracks in RCC dams are generally vertical, transverse to the dam axis, and pose no problem to the structure stability of a gravity section. The preceding conclusions provide an insight into the potential spacing and location of transverse contraction joints through all or rather a portion of an RCC dam, as desired;
- **g.** Initial cracking can usually be attributed to the internal temperature restraint condition where the temperature at the center of the concrete mass is greater than at the exposed faces of the dam;
- **h.** Greater cracking than initially predicted by thermal analysis has occurred due to delays in the construction schedule, forcing placement during warmer weather, and thus producing higher peak temperatures in the concrete than anticipated. Moreover, the thermal analysis currently used does not seem to properly account for radiant heat effects on exposed RCC surfaces;
- **i.** Cracking in CVC concrete faces can be effectively controlled by either joints or crack inducers formed in the concrete;

Durability of roller compacted concrete dams is logically related to the properties of the materials of the faces, either being of CVC or RCC concrete. In both cases, a greater strength of the mix and a greater quality of the aggregates provides a greater durability.

The surfaces of RCC submitted, on occasions of overflowing, to great volumes of water flowing at high speed have shown an adequate resistance to erosion.

The evaluation of actual and anticipated performance of the RCC that has been incorporated into a dam presents issues and problems that are similar as well as dissimilar to those posed by an evaluation of concrete placed by traditional methods. The premise is that proper planning, materials selection, mixture proportioning, and construction practices were all followed as set in the contract documents, duly referenced in the preceding chapters. Performance evaluation involves the verification that quality control operations and quality assurance programs were effective so that the concrete in the finished structure has the appropriate properties.

The design of seepage control systems for RCC dams should be based on a safe operation and economic requirements of the project.

To date, RCC dams do not necessarily exhibit more seepage than conventional concrete dams and have been able to satisfactorily fulfill project goals. However, RCC dams that depend primarily on the RCC itself for seepage control do result in higher unit rates of seepage that conventional concrete dams. This fact may impact project economics.

As experience is gained with RCC mixes and placement techniques, the ability of the RCC mass itself to resist seepage will increase. For the near future, however, designers will probably rely on upstream reduction measures to limit seepage.

Systems have been designed and built to reduce or eliminate seepage in RCC dams. As the next generation of dams are designed, new systems will be developed and the present systems will be improved.

Embedment of instruments to monitor structural behavior can be handled similarly to that employed in other types of concrete dams. However, the necessity to minimize impediments to rapid construction should be considered.

The thermal regime of RCC dams during construction and impounding water is of particular interest to engineers, on the aim of preventing structural cracks. The temperature cycle in several sections of the mass should be recorded from readings of embedded thermocouples installed during construction.

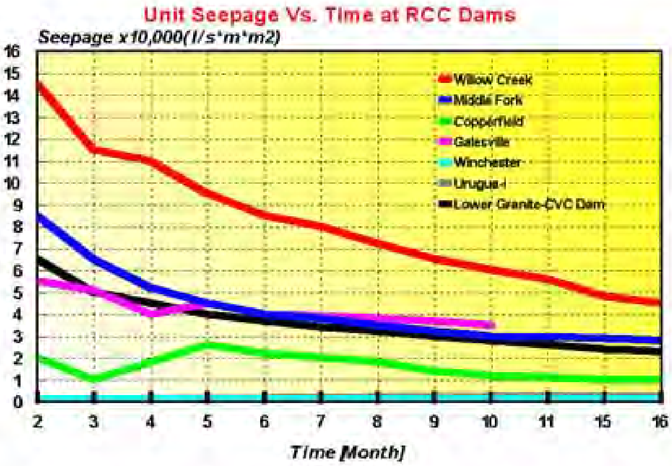


Figure 12.14 Seepage reducing with time.

12.8 Additional Comments

It is very important to consider the comments made by F. Lempérière [12.17] :

"Overtopping caused by river floods is the greatest risk to dam safety-

- *From around 100 dam failures since 1950, 40 were caused by overtopping...*

This failure record can be analyzed with a view to improving the safety of existing as well as future dams,...

Since 1950, there have been 14 failures of embankment dams under construction.

This risk may be substantially reduced in the following ways:

- *By designing the diversion tunnels of high dams for the 1000-year flood instead of for the 50 or 100-year flood....*
- *By protecting the downstream face of the dam with reinforced rockfill (see ICOLD Bulletins 48a and 89) or roller compacted concrete (RCC).*
- *By using RCC for high cofferdams.*

There are no reported failures by overtopping among the 1200 gravity dams more than 30m high built in the last 100 years, but there have been 22 failures out of the 3000 embankment dams more than 30m high.

Risks can be considered reduced at future dams, but it cannot feasibly be reduced to zero for embankment dams. It may be preferable to select a type of dam capable of withstanding major overtopping without collapse. While foundations are not always suitable for an arch or arched gravity dam, most sites will accommodate, for example, a symmetrical faced RCC gravity dam. This type (described in ICOLD Bulletin 83, p89), is often very competitive in overall cost and should have a great future in terms of safety considerations, in that, it is remarkably effective in withstanding very severe overtopping, as well as earthquake, uplift, poor foundations, toe scour, and so on Ithat is, all natural contingencies and human error)"

12.9 REFERENCES

12.01 MOLER, W. A. and MOORE, J. F. "Design of Seepage Control Systems for RCC Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. New York: ASCE, March 1988.

12.02 MEHTA, P. Kumar. "Concrete –Structure, Properties and Materials". New Jersey, 1986.

12.03 HANSEN, Kenneth D.; REINHARDT, William G. *Roller Compacted Concrete Dams*. McGraw Hill, 1991.

12.04 GUERRA, Elcio Antonio; OLIVEIRA, João Carlos F. de ; GRAÇA, Newton Goulart; ANDRADE, Walton P.de. "Análise do Desempenho das Ensecadeiras Galgáveis em CCR de Serra da Mesa Após Cinco Períodos de Galgamento", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April/1995.

12.05 COPEL – Report. "Derivação do Rio Jordão - Board Meeting XVIII". October, 1996.

12.06 COPEL – Report. VOCV-CX-RT- 001/98. Relatório Resumido do Controle de Qualidade da Barragem UHE Salto Caxias. Dezembro /1997 - Janeiro/1998.

12.07 SCHRADER, E. K. "Watertightness and Seepage Control in Roller Compacted Concrete Dams", in: Rolled Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

12.08 "General Design Memorandum nº 2 for Willow Creek Lake- Oregon". US Army Engineer District, Walla Walla, June 1979.

12.09 RICHARDSON, A. T. "Performance of Upper Stillwater Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November, 1991.

12.10 RICHARDSON, A. T. "Performance of Upper Stillwater Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. New York: ASCE, February 1992.

12.11 HOLLINGWORTH, F. and GERINGER, J. J. "Cracking and Leaking in RCC Dams", in: International Water Power & Dam Construction. United Kingdom, vol. 44, nº 2, February 1992.

12.12 DUMONT, N. A.; VAZ, L. E.; REZENDE, S.; QUIN, J. T. "Análise de Fissuração do Paramento de Montante do Maciço da Barragem Saco Nova Olinda-PB-SRH", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August/1987.

12.13 LORENZO, A. C. and. CALIVARI, S. S. "Behavior of Urugua-I Dam", in: Proceedings, Symposium on RCC Dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

12.14 LORENZO, A. C. and CALIVARI, S. S. "Behavior of Urugua-I Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference San Diego, California. New York: ASCE, February 1992.

12.15 GOLIK, M. A.; ANDRIOLO, F. R. "Desempenho da Membrana de PVC da Barragem de Uruguai", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November/1992.

12.16 AGUIRRE, E. and VILLARROEL, J. M. "Thermal analysis and behavior of the Arriaran dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October/1995.

12.17 LEMPÉRIÈRE, F. "Dams that Have Failed by Flooding : An Analysis of 70 Failures", Water power & Dam Construction. September/October 1993.

13

The Author's Comments on RCC as a Construction Material

13.1 General

Regarding the structural behavior of RCC, the main conclusions drove from the use and observations carried out for years, follow:

1- It is possible to construct dams of RCC with the same watertightness as that of concrete dams built with traditional methods;

2- RCC dams with CVC faces, or a special RCC proportion mix, and joints having water-stops (including among these the dams constructed with the Japanese method), as those with faces formed by prefabricated concrete panels, lined with an impermeable membrane, have shown a high degree of watertightness;

3- The impermeability of RCC can be improved by increasing its fines content;

4- RCC dams present less danger of cracking than those of conventional concrete, due to their lower shrinkage, combined in general with a reduced modulus of elasticity and higher creep. The lower shrinkage of roller compacted concrete originates from its lower water and cement contents, in comparison with those of a vibrated concrete;

5- The majority of the cracks in RCC dams can be attributed to stresses of thermal origin in most of the richer mixes;

6- The transverse contraction joints, having water-stops upstream and drainage holes, are an efficient system for cracking control. When distance between joints is too large, intermediate cracks are produced. Their width is smaller though than that of the joints;

7- Cracks are always produced in transverse joints where transverse sections has been deliberately reduced, as well as in other points with smaller transverse section, as a consequence of a lower total tensile strength. Examples of these latter points could be a protrusion of rock foundation, giving rise to a stress concentration; a central spillway, or a joint on a face of conventional concrete;

8- Cracks of RCC dams are in general vertical, perpendicular to the axis of the dam, and do not affect its structural stability;

9- Initial cracking can be attributed in general to stresses induced by restraining the deformations of thermal origin, due to the greater temperature of the inner concrete of the dam and that of the external faces;

Durability of RCC dams is logically related to the properties of the face materials, either being of CVC or RCC. In both cases, a greater strength of the mix and a better quality of the aggregates are required to provide a greater durability. In the case of CVC concrete, the inclusion of air improves significantly frost resistance and watertightness. RCC surfaces submitted on occasions to overtopping, with great flows running at high speed, have shown an adequate resistance to erosion, except in some badly compacted zones, such as those observed in faces built directly against formwork. The resistance to freezing-thawing cycles has also been very good.

Evaluation of actual and anticipated performance of RCC incorporated into the dam poses issues and problems either similar as dissimilar to those posed by CVC placed by traditional methods. The premise is that proper planning, material selection, mixture proportioning, and construction practices were all followed as set in the contract documents and pointed in preceding chapters. Performance evaluation involves the verification that quality control operations and quality assurance programs were effective so that the concrete in the finished structure has appropriate properties. For example, if sulfate-resisting cement was needed, it is assumed that it was specified, obtained, delivered, and used, and that it is the product intended by the specification.

13.2 Structural and Materials Properties

The comparison of important physical properties of RCC and CVC (as mentioned in Chapter 7) indicates that modern RCC is ***"a concrete"*** and that high and large RCC dams, of the same quality as existing major CVC dams, can be designed and built, provided strict quality control is practiced in material selection, design of RCC mixes, and during construction.

All materials used in a high RCC dam including cement, pozzolanic material, filler and fine and coarse aggregates, should be of similar quality as those considered suitable for comparable CVC dam or pavement. Particularly important are the physical properties related to specific gravity, susceptibility to alkali-aggregate reaction or excessive thermal expansion.

RCC mix should be designed with the lowest necessary cementing content to obtain the desired consistency and specified compression and shear strength at prescribed ages, and with the lowest rise in temperature possible.

Experience accumulated in design and construction of RCC dams indicates that RCC can be successfully employed to build high dams of the same quality as comparable CVC dams and pavements which have been in satisfactory service for several years. The acceptance standards of quality and safety for RCC dams should be the same as those currently internationally accepted for comparable CVC dams and pavements. However, the performance of several completed RCC dams has demonstrated the need to improve certain shortcomings regarding selection of materials for RCC, foundation treatment, structural monolithicity, crack and leakage prevention, when compared to the standards for CVC dams.

Adequate bond, uniformly distributed over the entire surface of each construction joint, is essential to obtain the necessary degree of elastic monolithicity in a high RCC gravity dam. Without such adequate bond, there may occur higher shear stresses than admissible and an unacceptable risk of shearing at a weak construction joint. Adequate bond at the construction joints can be obtained with a correct treatment.

The scope of exploration, analysing and rock foundations treatment of a high RCC gravity dam should be the same as required for a comparable CVC dam. The impact of foundation treatment on costs and construction schedule of the dam should not be underestimated at the time of type and layout selection of the dam. The foundation should be shaped smooth since irregularities may cause stress concentration and cracking of the dam.

Prevention of structural cracks in a high RCC dam should be a mandatory goal. Transverse contraction joints for the full section of the dam, provided at intervals not exceeding 20m to 25m and along the entire length of the dam, are effective in preventing transverse cracking.

13.3 Cost

The cost of RCC is less than CVC for unit volume.

The cost of RCC dam can be less than other type of dam. A large number of factors and conditions, especially site conditions, can affect cost and construction time.

Past standards to chose one or other type of dam need to be reviewed considering all factors, conditions, time scheduled, and costs.

"…O homem se humilha, se castra o seu sonho,
Seu sonho é sua vida,
E a vida é trabalho,
E sem o seu trabalho o homem não tem Honra,
E sem sua Honra, se morre, se mata,
Não dá p'ra ser feliz, não dá p'ra ser feliz…"

Gonzaguinha, da música "Um homem também chora (Guerreiro Menino)"

14

References

In this Chapter a list of the main publications concerning RCC-Roller Compacted Concrete is grouped by year of publication.

The references listed are based on the "Annotated Bibliography on Roller-Compacted Concrete Dams" prepared by USCOLD Committee on Concrete - United States Committee on Large Dams - June 1994, and were complemented by the author that included the Brazilian publications and updating of seminars, congresses and publications relative to RCC.

The Sixties and Earlier

41.01 HADLEY, H.M. "Discussion: Masonry Dams - A Symposium", in: *Transactions*. New York: ASCE, 1941, vol.106.

62.01 LOWE, J. III. "Discussion: Utilization of Soil-Cement as Slope Protection for Earth Dams" by W. G. HOLTZ and F. C. WALKER, in: First ASCE Water Resources Engineering Conference. Omaha, Nebraska, May 1962. (No proceedings of this conference were published.)

63.01 POLIVKA, MILOS, PIRTZ, DAVID, AND ADAMS, Robert F. "Studies of Creep in Mass Concrete", in: Symposium on Mass Concrete, SP-6, ACI. Detroit, 1963.

64.01 ENGINEERING NEWS – RECORD. "Concrete gravity dam built like earthfill". New York, December 1964. vol.173, nº 26.

64.02 GENTILE, G. "Study, Preparation and Placement of Low Cement Concrete with Special Regards to Its Use in Solid Gravity Dams", in: Transactions, Eighth International Congress on Large Dams. Q30. Edinburgh, May 1964. vol. 111.

65.01 NASH, J.K.T.L., F.M. JARDINE and J.D. HUMPHREYS. "Economics and Physical Feasibility of Soil - Cement Dams", in: Proceedings of the Sixth International Conference on Soil Mechanics and Foundation Engineering. Canada, 1965. vol. II.

68.01 THOMAS, D. A. "Artificial Bedrock for Outlet Structure", in: Rocky Mountain Construction. Denver, 16 July 1968.

68.02 POWERS, T. C. *The Properties of Fresh Concrete*. New York: John Wiley & Sons, Inc., 1968.

69.01 HOUK Jr., Ivan E.; BORGE, Orville E.; HOUGHTON, Donald L. "Studies of Autogenous Volume Change in Concrete for Dworshak Dam", in: ACI Journal *Proceedings*. July 1969. vol. 66, nº 7.

1970

70.01 CARLSON, R. W. "Concrete Dams Built Without Contraction Joints", in: Rapid Construction of Concrete Dams. Proceedings, Engineering Foundation Research Conference, Pacific Grove, ASCE. California, March 1970.

70.02 DAVIS, R. F. "Discussion: Optimum Gravity Dam " in: Rapid Construction of Concrete Dams. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California: ASCE, March 1970.

70.03 GENTILE, G. "Notes on the Construction of the Alpe Gera Dam", in: Rapid Construction of Concrete Dams. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California: ASCE, March 1970.

70.04 KOLLER, E. R., and P. J. NUSSBAUM. "Developing Technology in Soil-Cement Dams", in: Transactions, Tenth International Congress on Large Dams. Montreal, June1970. vol. V.

70.05 PATON, J. "Discussion: Recent Development in the Design and Construction of Concrete Dams", in: Transactions, Tenth International Congress on Large Dams Q39. Montreal, June 1970. vol. VI.

70.06 RAPHAEL, J. M. "The Optimum Gravity Dam", in: Rapid Construction of Concrete Dams. Proceedings, Engineering Foundation Research Conference, Pacific Grove. California: ASCE, March 1970.

70.07 TERRACINI, C. "Behavior of Alpe Gera Gravity Dam in Its Early Stages", in: Transactions, Tenth International Congress on Large Dams Q39. Montreal, June 1970. vol. VI.

70.08 WALLINGFORD, V. M. "Proposed new Techniques for Construction of Concrete Gravity Dams", in: Transactions, Tenth International Congress on Large Dams Q39. Montreal, June 1970. vol. VI.

70.09 HOUK Jr., IVAN E.; PAXTON, James A.; HOUGHTON, Donald L. "Prediction of Thermal Stress and Strain Capacity of Concrete by Tests of Small Beams", in: ACI Journal, Proceeding. March 1970. vol. 67, nº 3.

1971

71.01 NUSSBAUM, P. J., and B. E. COLLEY. "Dam Construction and Facing with Soil -Cement", in: Research and Development Bulletin, Publication nº RD 010.01W, Portland Cement Association. Denver,1971.

71.02 PATON, J. "Discussion on Concrete Dams - Methods for Rapid Construction and Economies", in: BNCOLD Journal nº10. London: Institution of Civil Engineers, 1971.

71.03 ROBERTS, C. M. "Discussion on Concrete Dams - Methods to Be Employed for Rapid Construction and to Effect Economies", in: BNCOLD Journal nº10. London: Institution of Civil Engineers, 1971.

71.04 "Soil - Cement Slope Protection for Earth: Planning and Design", in: W. Portland Cement Association. Denver, 1971. Publication nº IS173.01

1972

72.01 CANNON, R. W. *Concrete Dam Construction Using Earth Compaction Methods*", *Economical Construction of Concrete Dams.* Proceedings, Engineering Foundation Research Conference. Pacific Grove, California: ASCE, May 1972.

72.02 RAPHAEL, J. M. *Construction Methods for Soil-Cement Dam, Economical Construction of Concrete Dams.* Proceedings. Engineering Foundation Research Conference. Pacific Grove, California: ASCE, May 1972.

1973

73.01 BASGEN, D. H. "New Ideas for More Rapid and Economical Construction of Concrete Dams", in: Transactions, Eleventh International Congress on Large Dams Q43. Madrid, June1973. vol. III.

73.02 CERVENI, C. "Discussion: Behavior of Alpe Gera Gravity Dam in Its Early Stages", in: Transactions, Eleventh International Congress on Large Dams Q43. Madrid, June 1973. vol. V.

73.03 "Fact Sheet on Sly Creek Dam" in: Portland Cement Association. Denver, July 1973.

73.04 MOFFAT, A. I. B. "A study of Dry Lean Concrete Applied to the Construction of Gravity Dams", in: Transactions, Eleventh International Congress on Large Dams Q43. Madrid, June 1973. vol. III.

73.05 MOFFAT, A. I. B. "Discussion: New ideas for more rapid and economic construction of concrete dams", in: Transactions, Eleventh International Congress on Large Dams Q43. Madrid, June 1973. vol. V.

73.06 TYNES, W. O. "Feasibility Study of No-Slump Concrete for Mass Concrete Construction", in: Miscellaneous Paper C-73-10. Vicksburg, Mississippi: US Army Corps of Engineers, Waterways Experiment Station, October 1973.

1974

74.01 CANNON, R. W. "Compaction of Mass Concrete with Vibratory Roller", in: ACI Journal, Proceedings, Title nº 71-34. Detroit, October 1974. vol. 71, nº10.

74.02 HALL, D. J., and HOUGHTON, D. L. *Roller Compacted Concrete Studies at Lost Creek Dam Report*. Portland District, Oregon: US Army Corps of Engineers, June 1974.

74.03 "Repairs at Tarbela dam race spring snowmelt", in: Engineering News. New York: Record, October 31,1974. vol.193, nº19.

74.04 US Bureau of Reclamation. "Design Criteria for Concrete Arch and Gravity Dams", in: Engineering Monograph. Denver, Colorado, 1974; nº 19.

1975

75.01 "General Construction Specification nº G 48 for Roller Compacted Concrete", in: Tennessee Valley Authority. Knoxville, Tennessee, August 1975.

75.02 MARSHALL, T. "Tarbela rescue: 380,000 m^3 plug beats the flood", in: New Civil Engineer, Institution of Civil Engineers. London, 27 April 1975.

75.03 "Repair and Reconstruction of the Tunnels at Tarbela", in: Water Power & Dam Construction. United Kingdom, June-July 1975.

1976

76.01 SIVLEY, W. F. "Discussions: Zintel Canyon Optimum Gravity Dam", in: Transactions, Twelfth Congress on large Dams Q44. Mexico City, April 1976. vol. V.

76.02 HOUGHTON, D. L. "Determining Tensile Strain Capacity of Mass Concrete", in: ACI Journal, Proceedings. December 1976, vol. 73.

76.03 *Design Of Gravity Dams*. Denver, Colorado: US Bureau of Reclamation, 1976.

76.04 "Atividades da Divisão em Junho/76", in: REPORT C-09/76 Divisão de Controle de Concreto- Itaipu Binacional. Foz de Iguaçu, Brazil, June/1976.

1977

77.01 "Another crash repair program begins at Tarbela dam", in: *Engineering News*. New York: Record, October 6, 1977. vol. 199, nº14.

77.02 CANNON, R. W. "Bellefonte Nuclear Plant - Roller Compacted Concrete – Summary of Concrete Placement and Evaluation of Core Recovery", in: Report nº CEB- 76-38, Tennessee Valley Authority. Knoxville, Tennessee, 1977.

77.03 DUNSTAN, M. R. H. "Trial of Lean Rolled Concrete at the Tamar Treatment Works", in: Report to the South West Water Authority. England, June 1977.

77.04 "Major erosion hits Tarbela Dam again", in: Engineering News. New York: Record, 22 September 1977. vol.199, nº12.

77.05 MOFFAT, A. I. B., and PRICE, A. C. "New Materials: Dry Lean Concrete Applied to Fill Construction of Dams", in: BNCOLD Journal nº18. BNCOLD meeting held in London, December 1976. Journal published London, 1977.

77.06 PRICE, A. C. *The Engineering characteristics of Dry Lean Concrete* as *Applied to the Construction of Gravity Dams*. Newcastle, England: University of Newcastle upon-Tyne, 1977. (Ph. D. thesis.)

77.07 SCHRADER, E. K. "Roller-Compacted Concrete", in: The Military Engineer, The Society of Military Engineers. Washington, D. C., vol. 69 (451), September-October 1977. (Reprinted by Portland Cement Association, Skokie, Illinois, 1978.)

1978

78.01 AVERA, J. K., and HANSEN, K. D. "Dams that never end", in: Water Power & Dam Construction. United Kingdom, March 1978. vol. 30, nº 3.

78.02 DUNSTAN, M. R. H. "Rolled Concrete with particular reference to its use as a hearting material in concrete dams", in: Draft Report of the Concrete Society. London, March 1978.

78.03 HAYWARD, D. "Indus River Contractors win race to protect Tarbela's eroded plunge pool", in: New Civil Engineer, Institution of Civil Engineers. London, March 1978.

78.04 MOFFAT, A. I. B., and PRICE, A. C. "Rolled Dry Lean Concrete Applied to Fill Construction of Dams", in: Materials of Construction for Developing Countries. International Conference. Bangkok, Thailand, August 1978.

78.05 MOFFAT, A. I. B and PRICE, A. C. "The rolled dry lean concrete gravity dam", in: International Water Power & Dam Construction. United Kingdom, July 1978. vol. 30, nº7.

78.06 RICHARDSON, P. "A First in Alaska... Roller - Compacted Concrete", in: Alaska Construction & Oil.. Seattle: Vernon Publications, Inc., November 1978. vol.19, nº11.

78.07 "Rollcrete Helps Beat Erosion Repair Deadline", in: New Civil Engineer, Institution of Civil Engineers. London, June 9,1978.

78.08 SCHRADER, F. K. "Roller Compacted Concrete", in: The Military Engineer, The Society of Military Engineers. Washington, D.C. vol. 69 (451), September-October 1977. (Reprinted by Portland Cement Association, Skokie, Illinois, 1978.)

78.09 SHIMIZU, S. and TAKEMURA, K. "Test Fill of RCD at the Upstream Cofferdam of Ohkawa Dam", in: Concrete Journal. Japan: Concrete Institute, April 1978.

78.10 "Technical Report- RT-03/78" in: Divisão de Controle de Concreto- Itaipu Binacional. Foz de Iguaçu, Brazil, February/1978.

1979

79.01 DAWSON, E. S., and DUNSTAN, M. R. H. "Trials for a Prototype Concrete Dam", in: Transactions, Thirteenth International Congress on Large Dams Q48. New Delhi, November 1979. vol. I.

79.02 DUNSTAN, M. R. H. "A new dam construction method", in: Consulting Engineer. London, May 1979. vol. 43, nº 5.

79.03 DRUYTS, F. H. W. M. "Concrete placing Tests at Elandspruit Dam", in: Water, House Journal of the Department of Water Affairs. South Africa, December 1979.

79.04 HANSEN, K. D. *Roller Compacted Concrete, Water Control Applications in U.S. and Canada*. Denver: Portland Cement Association, July 1979.

79.05 JOHNSON, H. A., and CHAO, P. C. "Rollcrete Usage at Tarbela Dam", in: Concrete International, ACI. Detroit, Michigan, November 1979. vol.1, nº 11.

79.06 "Tarbela spillway pool erosion prompts $100 million repair job", in: Engineering News. New York: Record, January 4, 1979. vol. 202, nº1.

79.07 SHIMIZU, S. and TAKEMURA, K. "Design and Construction of a Concrete Gravity Dam on a Weak Bedrock", in: Transactions, Thirteenth International Congress on Large Dams Q48. New Delhi, November 1979. vol. I.

79.08 WALLINGFORD, V. M. "Proposed New Technique for Construction of Concrete Gravity Dams", in: Xth ICOLD Congress, International Commission on Large Dams. Montreal, 1979, vol. 4.

1980

80.01 CHAO, P. C. "Tarbela Dam - Problems Solved By Novel Concrete", in: Civil Engineering, ASCE. New York, December 1980. vol. 50, nº12.

80.02 HIROSE, T., S. SHIMIZU and TAKEMURA, K. "Studies on Construction of Dams by the RCD Method", in: Transactions of the Japan Society of Civil Engineers. Tokyo, 1980. nº303

80.03 JONES, J. C., and MASS, G. R. "Use of Roller Compacted Concrete in Dam Construction", in: Proceedings of Symposium on Problems and Practices on Dam Engineering in Asia. Bangkok, Thailand: Asian Institute of Technology, December 1980.

80.04 "News: Unusual cofferdam protects against catastrophic failure", in: Civil Engineering, ASCE. New York, July 1980. vol. 50, nº 7.

80.05 "Rolled concrete dam slated", in: Engineering News. New York: Record, February 28, 1980. vol. 204, nº 9.

80.06 "Rolled Lean Concrete Debut on Devon Dam", in: New Civil Engineer, Institution of Civil Engineers. London, September 1980.

80.07 "Roller Compacted Concrete", in: ACI Journal, Committee Report nº ACI 207. 5R-80, Title nº 77-25. Detroit, July-August 1980.

80.08 HIROSE, T.; SHIMIZU, S.; TAKEMURA, K. "Research of the Construction by Roller Compacted Concrete Dam (RCD) Concrete", in: Proceedings. Japan Society of Civil Engineers, November, 1980. nº 303.

80.09 NAGAYAMA, I.; YAZAWA, K. "Thermal Stress Analysis for Concrete Dams", in: Civil Engineering Journal. Japan Society of Civil Engineers, 1980.

80.10 SUZUKI, N.; TANAKA, M.; IWATA, Y. "Construction of the Shimajigawa Dam Rationalized by Using RCD Concrete", in: Civil Engineering Journal, The Society Of Civil Engineers, November 1980.

80.11 ANDRIOLO, F. R.; BETIOLI, I.; SCANDIUZZI, L. "Concreto Adensado com Rolo Vibratório", in: Proceedings of the XIII Seminário nacional de Grandes Barragens. Rio de Janeiro, Brazil, April/1980.

1981

81.01 ADDYMAN, O. T. "Discussion: Other experiences with rolled concrete for dams", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.02 BLAKE, L. S. "Discussion: CIRIA laboratory investigation of material", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.03 BUSH, E. G. W. "Rollcrete in Revelstoke Cofferdam", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.04 CANNON, R. W. "Laboratory Investigations and Full Scale Trials by the Tennessee Valley Authority", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.05 MINISTRY OF CONSTRUCTION. *Construction of Shimajigawa Dam with Roller Compacted Dam Concrete.* Japan: Chugoku Regional Construction Bureau, 1981.

81.06 DAWSON, E. S. "Design of Rolled Concrete Dam for Milton Brook", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.07 MINISTRY OF CONSTRUCTION. *Design and Construction Manual for RCD Concrete.* Tokyo: Technology Center for Land Development, 1981.

81.08 DUNSTAN, M. R. H. "Relationship between properties generated by cement and by flyash", in: Rolled Concrete or Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.09 DUNSTAN, M. R. H. "Rolled Concrete for Dams - A Laboratory Study of the Properties of High Fly Ash Content Concrete", in: CIRIA Technical Note 105. London, May 1981.

81.10 DUNSTAN, M. R. H. "Rolled Concrete for Dams: a resume of laboratory and site studies of high flyash content concrete", in: CIRIA Report 90. London, May 1981.

81.11 DUNSTAN, M. R. H. "Rolled Concrete for Dams - Construction Trials Using High-Flyash-Content Concrete", in: CIRIA Technical Note 106. London, May 1981.

81.12 DUNSTAN, M. R. H. "Properties of concrete found during CIRIA laboratory Investigation", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.13 DUNSTAN, M. R. H. "Upper Stillwater Dam Trial Section", in: Report to the U.S. Bureau of Reclamation. Devon, United Kingdom: Malcolm Dunstan & Associates, December 1981.

81.14 "Editorial: Cheaper way to build dams", in: Engineering News. New York: Record, November 19, 1981. vol. 201, nº 21.

81.15 "Flyash and rolled concrete for cheaper dam construction", in: International Water Power & Dam Construction. United Kingdom, August 1981.

81.16 GORDON, E. C. "Discussion: CIRIA full scale trials and dam design", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.17 HIROSE, T., and YANAGIDA, T. "Some Experiences Gained in Construction of Shimajigawa and Ohkawa Dams", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.18 KENNARD, M. F. "Introduction to rolled concrete dams", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.19 KRAUCH, H. W. "Rolled Lean Concrete at Itaipu Dam", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.20 LAVILLA, G.-C. "The Technique of Placing Rollcrete as Experienced at Tarbela Dam During 1978 - 1981 for the Construction of Additional Works at the Spillway", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.21 LIEWELLIN, J. D. "Final Summing up of Conference", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.22 LOWE, J. III. "Use of Rollcrete in Earth Dams", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.23 MAYNARD, D. P. "Fullscale Trial at Wimbleball", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.24 MAYNARD, D. P. "Properties of Cores from Full-Scale Trials", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.25 MONTGOMERY, D. G., and DUNSTAN, M. R. H. "A particular use of flyash in Concrete - Rolled concrete in dams", in: Civil Engineering Transactions, Institution of Engineers. Crows Nest, New South Wales, Australia, 1981.

81.26 MURPHY, W. E. "Discussion: Other laboratory investigations and full - scale trials of rolled concrete (outside the U K)", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.27 RICHARDSON, A. "Status report on the Upper Stillwater Dam and test section", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.28 "Rollcrete repair is quick", in: Engineering News. New York: Record, March 1981. vol. 206, nº 12.

81.29 SAUCIER, K. L. "Investigation of No-Slump Roller Compacted Concrete (RCC) for use in Mass Concrete Construction", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.30 SCHRADER, E. K. "Willow Creek Dam - An Optimum Gravity RCC Dam with Vertical Upstream Face", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.31 STORM, R. W. "Corps of Engineers Lines Spillway Channel with Roller Compacted Concrete", in: USCOLD Newsletter. Denver, November 1981, nº 66.

81.32 "Studies on RCD Concrete", in: Abstracts of the Japan Society of Civil Engineers 36th Annual Academic Presentation Meeting. October 1981. (Reprint in English by Shimizu Construction Co., Ltd. Tokyo.)

81.33 "Technical Guide to RCD Construction Method", in: Research Committee On Rationalized Execution of Concrete Dam Construction. Tokyo: Technology Center for National Land Development, August 1981.

81.34 WEEKS, K. A. "Relining of an oxidation ditch at Bishop's Stortford, using high pfa content slipformed and rolled concrete", in: Rolled Concrete for Dams, Proceedings of the International CIRIA Conference. London, June 1981.

81.35 "Willow Creek Design Memorandum, Supplement to GDM 2 - Phase 2, Main Dam, Spillway, and Outlet Works", in: U.S. Army Engineer District. Walla Walla, Washington, December 1981.

81.36 SATOU, K.; MINAMI, S. "Concrete Dam Construction by The RCD Method-Stilling Basin at Shin-Nakano Dam", in: The Dam Digest. The Japan Dam Foundation, June 1981. nº 440.

81.37 " Studies on RCD Concrete " in: Shimizu Construction Co., Ltd.. Japan Society Of Civil Engineers, October, 1981.

1982

82.01 CANNON, R. W. "Proportioning No-Slump Concrete for Expanded Applications", in: Concrete International, ACI. Detroit, August 1982. vol. 4, nº 8.

82.02 CHOUDRY, T.; BOGDOVITZ, W. and CHAVARRI, G. "Construction of Cofferdam at Guri with Rollcrete", in: Transactions, Fourteenth International Congress on Large Dams Q55. Rio de Janeiro, May 1982. vol. IV.

82.03 DINCHAK, W., G. and HANSEN, K. D. "Consider Roller-Compacted Concrete for Hydro Power Facilities", in: Proceedings, Fifth Miami International Conference on Alternative Energy Sources. Florida, December 1982. (Published by PCA, Skokie, Illinois: nº TA 044.01W.)

82.04 HIROSE, T. "Research and Practice Concerning RCD Method", in: Transactions, Fourteenth International Congress on Large Dams. Rio de Janeiro, May 1982. vol. III.

82.05 KLOPENSTEIN, D.; and KIOPENSTEIN, I. "Rollcrete Dam - More Strength, Less Price", in: Pacific Builder & Engineer. Seattle, July 1982. vol. 88, nº 13.

82.06 "Rollcrete Dam Near to Completion", in: New Civil Engineer. London: Institution of Civil Engineers, February 1982.

82.07 "Rolled concrete triumphs", Engineering News. New York: Record, October 1982. vol. 209, nº 17.

82.08 SCHRADER, E. K., and THAYER, H. J. "Willow Creek Dam A Roller Compacted Concrete Fill", in: Transactions, Fourteenth International Congress on Large Dams Q55. Rio de Janeiro, May 1982. vol. IV.

82.09 SCHRADER, E. K. "The First Concrete Gravity Dam Designed and Built for Roller-Compacted Construction Methods", in: Concrete International, ACI. Detroit, October 1982. vol. 4, nº 10.

82.10 SCHRADER, E. K. "World's First All-Rollcrete Dam", in: Civil Engineering – ASCE. New York, April 1982. vol. 52, nº4.

82.11 "Utah Dam Faces Slipformed", in: Concrete Construction Magazine. Illinois: Concrete Construction Publications, Inc. Addison, September 1982.

82.12 "What is Roller Compacted Concrete?", in: Concrete Construction Magazine. Illinois: Concrete Construction Publications, Inc. Addison, September 1982.

82.13 CRCB. *Record of Shimajigawa Dam Construction*. Chugoku Regional Construction Bureau, March 1982.

82.14 KURITA, Y.; OKUMURA, T.; NEGAMI, Y. "Research of Roller Compaction Properties of RCD Concrete", in: Proceedings, Annual Conference Of The Japan Society of 37th Civil Engineers, 1982. Part 5.

82.15 MIZUNO, M.; NAGAYAMA, I.; YAZAWA, K. "Thermal and Mechanical Properties of Early Aged Concrete", in: Civil Engineering Journal. Japan: Society of Civil Engineers, 1982.

82.16 JAPPANESE NATIONAL COMMITTEE ON LARGE DAMS. *Dams in Japan*.1982, nº 9.

1983

83.12 TIDA, K, et al. "Vibrating Compaction Properties of Double Mixed Roller Compacted Concrete", in: Transactions of the Japan Concrete Institute. Tokyo, 1983.

83.13 "Willow Creek joints leak", in: Engineering News. New York: Record, May 19 1983. vol. 210, nº 20.

83.14 SHIMOMURA, S.; YANAGAWA, J. "Test Fill Works of RCD at Tamag Dam", in: Engineering For Dams. Japan: Dam Engineering Center, 1983. vol. 1, nº 2.

83.15 YANAGAWA, J.; INADA, S. "Temperature Control at Tamagawa Dam" in: Engineering Dams. Japan: Dam Engineering Center, 1983. vol. 1. nº 4.

83.16 MIURA, Y.; KODERA, Y. *First-Stage Cofferdam Construction by RCD Method*. Japan: Dam Engineering Center, 1983. vol. 1, nº 4.

83.17 MURATA T.; FURUYA, M.; MINAMI, K. "Designing and Construction of Raising Dam-Construction of Shin-Nakano Dam", in: Journal of Japan Society of Civil Engineers, June, 1983.

83.18 TANAKA, M.; SUZUKI, A.; SAKAMOTO, M.; YUDASAKA, M. "The Dynamic Behavior of Double-Mixed Fresh Lean Mortar", in: Transactions Of The Japan Concrete Institute, 1983.

83.19 "Concrete Report - Willow Creek Dam, World's First All Roller Compacted Concrete Dam", in: US Army Corps of Engineers. Walla Walla District, Walla Walla, Washington, July 1983.

83.20 CAMPITELLI, L. "Aproveitamento Hidrelétrico de Tucuruí"; "Aterro de Cascalho não Coesivo"; "Proteção de Talude com Cascalho; Proteção de Talude com Solo-Cimento", in: Proceedings of the XV Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, November 1983.

83.21 ONO, S.; COSTA, A. F. "UHE Tucuruí: Estuudos de Utilização de Solo-Cimento para Proteção de Talude da Barragem", in: Proceedings of the XV Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, November 1983.

83.22 SANTOS, M. G.; FONCEA, C.; FRANÇOSO, N. C. T. "Análise Comparativa entre Solo-Cimento e Laje de Concreto para Proteção do Talude de Montante da Barragem de Porto Primavera", in: Proceedings of the XV Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, November 1983.

83.23 SANTOS, M. G.; FONCEA, C.; FRANÇOSO, N. C. T. "Análise Crítica dos Métodos de dosagem de Solo-Cimento para Proteção de Taludes de Barragens de Terra", in: XV Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, November 1983.

83.24 HIROSHE, T.; YANAGIDA, T. "Construction of Dams with Roller Compacted Concrete in Japan", in: Symposium on Roller Compacted Concrete ACI 207. Los Angeles, California, March 1983.

1984

84.01 ANDERSON, F. A. "RCC Does More", in: Concrete International, ACI. Detroit, May 1984. vol. 6, nº5.

84.02 ANDRIOLO, F. R.; VASCONCELES, G. R. L. de and GAMA, H. R. "Use of Roller Compacted Concrete in Brazil", in: Concrete International, ACI. Detroit, May 1984. vol. 6, nº 5.

84.03 "BuRec debuts first rollcrete dam", in: Engineering News. New York: Record, March 29, 1984. vol. 212, nº13.

84.04 CAMPBELL, D. B., and JOHNSON, P. C. "RCC Dam Incorporates Innovative Hydraulic Features", in: Proceedings, Water for Resource Development. Coeur d'Alene, Idaho, Hydraulics Division, ASCE. New York, August 1984.

84.05 CARRUTH, B. "A Study of Construction Related Problems Encountered During the Production and Placement of Roller-Compacted Concrete", in: Masters Research Report. Colorado State University: Fort Collins Fall, 1984.

84.06 "Concrete Report, Willow Creek Dam", in: U.S. Army Corps of Engineers. Walla Walla District, Washington, August 1984. vols. I-II.

84.07 CROW, R. D., et al. "Mix Design Investigation Roller Compacted Concrete Construction - Upper Stillwater Dam, Utah", in: Research Report REC-ERC-84-15 Bureau of Reclamation. Denver, Colorado, June 1984.

84.08 "Design and Analysis of Upper Stillwater Roller Compacted Concrete Dam", in: U. S. Bureau of Reclamation, Technical Memorandum nº US 02-221-AGD-84. Denver, April 1984.

84.09 "Development in Japan of Concrete Dam Construction by the RCD Method 1984", in: River Development Division, Ministry of Construction, 2-13, Kasumigaseki, Chiyoda - ku. Tokyo, 1984.

84.10 "ENR Unit Prices: NJ. dam draws 10 bidders", in: *Engineering News – Record.* New York, vol. 212, nº19, May 1984.

84.11 HIROSE, T., and T. YANAGIDA. "Dam Construction in Japan - Burst of Growth Demands Speed, Economy", in: *Concrete International,* ACI. Detroit, vol. 6, nº 5, May 1984.

84.12 KOKUBU, M. "Development in Japan of Concrete Dam Construction by the RCD Method", in: *Technical Lecture, 52nd ICOLD Executive Meeting.* Tokyo, June 1984.

84.13 OLIVERSON, J. E., and A. T. RICHARDSON. "Upper Stillwater Dam: Design and Construction Concepts", in: Concrete International, ACI. Detroit, May 1984. vol. 6, nº 5.

84.14 PRICE, W. A., and MOLER, W. A. "Oil Shale as Aggregate for Roller Compacted Concrete", in: Construction Conference on Materials for Dams 84. Conference organized at Monte Carlo by International Water Power & Dam Construction. United Kingdom, December 1984.

84.15 "Rollcrete cuts concrete placing costs on DWA project", in: South African Construction World: Phase Four (Pty) Ltd. Sandton, March 1984. vol. 3. nº 2.

84.16 "Rollcrete: the dam-building technique of the future", in: South African Construction World· Phase Four (Pty) Ltd. Sandton, November 1984. vol. 3, nº 10.

84.17 "Roller Compacted Concrete", in: An ACI Forum, Concrete International: Design and Construction. Detroit, May 1984. vol. 6, nº 5.

84.18 SAUCIER, K. L. "No-Slump Roller Compacted Concrete (RCC) for Use in Mass Concrete Construction", in: US Army Corps of Engineers, Technical Report SL-84- 17, Waterways Experiment Station. Vicksburg, Mississippi, October 1984.

84.19 Schrader, E. K., and R. McKinnon. "Construction of Willow Creek Dam", in: Concrete International, ACI. Detroit, May 1984. vol. 6, nº 5.

84.20 SCOTT, G. A. "Foundation Studies for a Roller-Compacted Concrete Gravity Dam", in: Proceedings, Twenty-Fifth Symposium on Rock Mechanics. ASCE. New York, June 25, 1984.

84.21 SMYTH, M. "New construction method used on dam", in: Engineers Australia. St Leonards, New South Wales, October 1984. vol. 56, nº 20.

84.22 MINISTRY OF CONSTRUCTION. "Tamagawa Dam - Omono River System", in: Tamagawa Dam Construction Office. Tazawako Town, Senboku District, Akita Prefecture, Japan: Tohoku Regional Construction Bureau, March 1984.

84.23 TATRO, S. "Willow Creek Dam, To Be or Not To Be", in: Proceedings, Water for Resource Development. Coeur d'Alene, Idaho: Hydraulics Division, ASCE. New York, August 1984.

84.24 TUCKER, G. "Elk Creek Dam: Roller-Compacted Concrete Mixing and Placing Study Report to Corps of Engineers", in: Tucker Associates Inc. Portland District, 1984.

84.25 "Willow Creek Dam Concrete Report", in: U.S. Army Corps Engineers. Walla Walla, Washington, October 1984. vols. 1-2.

84.26 "With rollcrete, dam builders outrun winter", in: Engineering News. New York: Record, December 1984. vol. 213, nº 24.

84.27 HARADA, J.; SHIMADA, Y. "Design and Construction of Tamagawa Dam", in: Journal of Jancold. March 1984. nº 107.

84.28 AOYAGI, I.; SUGAWARA, K.; KURITA, Y.; KANAMORI, Y. "Research of Flyash Application to Roller Compacted Concrete", in: Proceedings. Annual Conference of The Japan Society of Concrete Engineers, 1984. Part 6.

84.29 JINBO, A.; KOMATSU, A. "The Experimental Concrete Placement by RCD Method in Pirika Dam", in: Concrete Journal. Japan: Japan Concrete Institute, 1984. vol. 2 1, nº 8.

84.30 MINISTRY OF CONSTRUCTION. "Multipurpose Dams in Japan", in: River Development Division. River Bureau, May 1984.

1985

85.01 "Another Auburn redesign?", in: Engineering News. New York: Record, December 1985. vol. 215, nº 22.

85.02 BOGGS, H. L., and RICHARDSON, A. T. "USBR Design Considerations for Roller Compacted Concrete Dams", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.03 BOGGS, H. L. "Cracking in Concrete Dams - USBR Case Histories", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.04 CANNON, R. W. "Design Considerations for Roller Compacted Concrete and Rollcrete Dams", in: Concrete International, ACI. Detroit, December 1985. vol. 7, nº 12.

85.05 "Cement and Concrete Terminology", in: ACI 116R-85, ACI Committee 116. Detroit, 1985.

85.06 "Dam Pioneers Concrete Variant", in: Civil Engineering – ASCE. New York, July 1985. vol. 55, nº 7.

85.07 DOLEN, T. P. "Use of Fly Ash Concrete for Upper Stillwater Dam Roller Compacted Concrete", in: Proceedings, Seventh International Ash Utilization Symposium and Exposition, Orlando, Florida, DOE/MCTC - 85/6018. Washington, D. C., March 1985. vol. 2.

85.08 DUNSTAN, M. R. H. "A Method of Design for the Mix Proportions of Roller - Compacted Concrete To Be Used in Dams", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.09 DVORACEK, J.; HOBST, L. and PRIBYL, F. "Investigation of Gravity Dams by Rolling in High Layers", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.10 ELIAS, G. C.; CAMPBELL, D. B. and SCHRADER, E. K. "Monksville Dam - A Roller Compacted Concrete Water Supply Structure", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q 57, June 1985. vol. II.

85.11 FORBES, B. A., and DELANEY, M. G. "Design and Construction of Copperfield River Gorge Dam", in: ANCOLD Bulletin nº71. Melbourne, Australia, August 1985.

85.12 FORBES, B. A. "Roller Compacted Concrete: Design, Construction and Performance of Copperfield Dam", in: Queensland Division Technical Papers, Institution of Engineers. Brisbane, Australia, September-October 1985. vol. 26, nº31.

85.13 FUJISAWA, T., and NAGAYAMA, I. "Cause and Control of Cracks by Thermal Stress in Concrete Dams", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.14 GILBROUGH, N. "Roller Compacted Concrete and Tunnel Boring Machines - Two Tools for Designers and Planners", in: Water Power '85: Proceedings of an International Conference on Hydropower, ASCE. Las Vegas, September 1985. vol. II.

85.15 GIIG, B., Chm. "Discussions: A New Technology: Rolled Concrete (Rollcrete)", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. V.

85.16 GOMEZ LAA, G. "Rollcrete in the Erizana Dam", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.17 HALE, T. C. "Roller Compacted Concrete", in: Construction Digest. Indianapolis, Indiana, August 1985.

85.18 HANSEN, K. D. "Roller Compacted Concrete Procedings at the Symposium", in: ASCE Convention. Denver, May 1985.

85.19 HOLLINGWORTH, F., and DRUYTS, F. H. W. M. "Experimental Use of Rollcrete on Sections of a Concrete Gravity Dam", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.20 HOPMAN, D. R.; KEIFER Jr., O.; and ANDERSON, F. "Current Concepts of Roller Compacted Concrete in Dams", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.21 "Japan goes for rollcrete dams", in: *Engineering News*. New York: Record, February 1985. vol. 214, nº 9.

85.22 KARL, R. W. "Upper Stillwater Dam Construction Program", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, 1985.

85.23 KOKUBU, M.; SHIMIZU, S.; JOJIMA, S. "Present State and Problems of Rationalized Construction of Concrete Dams in Japan", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams, June 1985. vol. II.

85.24 KOKUBU, M. "Development in Japan of Concrete Dam Construction by the RCD Method", in: Technical Lecture Given at 52nd ICOLD Executive Meeting. Tokyo, June 1984 and published in Engineering for Dams, Japan Dam Engineering Center, Special Issue. Tokyo, 1985. vol. 3.

85.25 KOLLGAARD, E. B.; JACKSON, H. E. and COLLINS, P. J. "Design of Galesville Dam", in: Presented at the Southern Idaho Section, Roller-Compacted Concrete Seminar, ASCE. Boise, Idaho, April 1985.

85.26 KOLLGAARD, E. B., and JACKSON, H. E. "Design Innovations for Roller-Compacted Concrete Dams", in: *Transactions*. Lausanne: Fifteenth International Congress on Large Dams Q57, June 1985. vol. II.

85.27 LAWRENCE, D. J. "Operations Guide and Modification Analysis for Use of the CE Concrete Quality Monitor on Roller-Compacted Concrete and Soil-Cement", in: U.S. Army Corps of Engineers Construction. Champaign, Illinois: Engineering Research Laboratory Technical Report M-854/06, July 1985.

85.28 "Leakage No problem at New RCC Dam", in: Highway & Heavy Construction. New York: Cahners Publishing Co., July 1985.

85.29 LOGIE, C. V. "Economic Considerations in Selection of a Roller Compacted Concrete Dam", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.30 LOGIE, C. V. "Rollcrete Wins Over Pamo Dam Designers", in: World Water. London, June 1985.

85.31 MATSUMURA, G. M.; SCHRADER, E. K.; and MCKINNON, R. "Discussion: Construction of Willow Creek Dam", in: Concrete International, ACI. Detroit, March 1985.

85.32 MCDOWELL, T. E. "Grouting of Willow Creek Dam and Foundation", in: USCOLD Newsletter nº78. Boston, November 1985.

85.33 "Membrane-lined Panels Face New RCC Dam", in: Highway & Heavy Construction. New York: Cahners Publishing Co., February 1985.

85.34 "Middle Fork RCC Dam", in: Civil Engineering - ASCE. New York, July 1985.

85.35 MORSMAN, D. E.; LAWLER, L. E. and SEIMEARS, J. R. "Construction of Two Spillways Using Roller Compacted Concrete", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.36 NAGATAKI, S.; YANAGIDA, T. and OKUMURA, T. "Construction of Recent RCD Concrete Dam Projects in Japan", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.37 "New Materials and Methods Help Seal Second RCC Dam", in: Highway & Heavy Construction. New York: Cahners Publishing Co., January 1985.

85.38 NOSE, M. "General Paper: Japanese National Committee on Large Dams", in: Transactions, Fifteenth International Congress on Large Dams Q57. Lausanne, June 1985. vol. II.

85.39 OBERHOLTZER, G. L. "Galesville Project Materials Engineering for Roller compacted Concrete", in: Presented at the Southern Idaho Section ASCE Roller-Compacted Concrete Seminar, ASCE. Boise, Idaho, April 1985.

85.40 PARENT, W. F.; MOLER, W. A. and SOUTHARD, R. W. "Construction of Middle Fork Dam", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.41 PIGGOTT, R. W.; NAAS, O. "Roller Compacted Concrete Pavements in British Columbia, Canada", in: Roller Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.42 PHILLEO, R. E. "General Report Question 57, A New Technology: Rolled Concrete (Rollcrete)", in: Transactions, Fifteenth International Congress on large Dams GR Q57. Lausanne, June 1985. vol. II.

85.43 PRICE, W. A. "Middle Fork Dam in Colorado", in: Presented at the Southern Idaho Section, ASCE Roller-Compacted Concrete Seminar, ASCE. Boise, Idaho, April 1985.

85.44 "Quebec gives rollcrete Dam a run on remote power job", Engineering News. New York: Record, May 1985. vol. 214. nº 22.

85.45 "RCC - Concrete Dams and Pavements That Are Built Faster and Cost Less", in: RCC Newsletter; PCA. Skokie, Illinois, July 1985. nº 1.

85.46 "RCC dam changes U.S. ways", in: *Engineering News - Record.* New York, vol. 215, nº 21, November 1985.

85.47 "RCC dam key to potable water project", in: *Civil Engineering – ASCE.* New York, vol. 55, nº5, May 1985.

85.48 REEVES, G. N., and YATES Jr., L. B. "Simplified Design and Construction Control for Roller Compacted Concrete", in: *Roller Compacted Concrete,* Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.49 REEVES, G. N. "Planned Overtopping of Embankments Using Roller Compacted Concrete", in: *Proceedings, ASCE Hydraulics Division Specialty Conference.* Lake Buena Vista, Florida, August 1985.

85.50 "Reservoir Will Add Seven Billion Gallons of Storage", in: *Public Works,* Journal Corp. Ridgewood, New Jersey, August 1985.

85.51 RICHARDSON, A. T. "Upper Stillwater Dam Roller Compacted Concrete Design and Construction Concepts", in: Transactions, Fifteenth International Congress on Large Dams Q57. Lausanne, May 1985. vol. II.

85.52 "Roller Compacted Concrete", in: Proceedings of an Interagency Forum, Engineering and Research Center, Department of the Interior, Bureau of Reclamation. Lakewood, Colorado, April 1985.

85.53 "Roller-Compacted Concrete", in: Engineering and Design, EM 1110-2-2006, U.S. Army Corps of Engineers. Washington, D.C., August 1985.

85.54 RUSSO, R.; RICHARDSON, J. K. and ALLEN, P.H. "Design of Burdekin Falls Dam", in: Civil Engineering Transactions, Institution of Engineers CE77. Crows Nest, New South Wales, Australia, October 1985. nº 16.

85.55 SAINZ PEREZ, M. A., and SANZ CLEMENTE, J. M. "Rolled concrete in the Spill Dam of Daule-Peripa (Jaime Roldos Project - Ecuador)", in: Transactions, Fifteenth International Congress on Large Dams C16. Lausanne, June 1985. vol. II.

85.56 SCHRADER, E. K. "Watertightness and Seepage Control in Roller Compacted Concrete Dams", in: Rolled Compacted Concrete, Proceedings of the Symposium at the ASCE Convention. Denver, May 1985.

85.57 SORENSEN, R. M. "Stepped spillway hydraulic model investigation", in: Journal of Hydraulic Engineering, ASCE. New York, December 1985. vol. III. nº12.

85.58 "Spreader box aids RCC placement", in: Engineering News. New York: Record, July 1985. vol. 215. nº 3.

85.59 SPRINGENSCHMID, R., and SONNEWALD, P. "Permeability, Frost Resistance and Crack Prevention of Roller Compacted Concrete (RCC)", in: Transactions, Fifteenth International Congress on Large Dams Q57. Lausanne, May 1985. vol. II

85.60 SUDAKOV, V. B., et al. "Erection techniques for rolled gravity dam of the Tashkumyrskaya hydropower plant", in: Proceedings, Russian Research Institute for Hydraulic Structures, Izvestia VNIIG. St. Petersburg, 1985. vol. 177.

85.61 TATRO, S. B., and SCHRADER, E. K. "Thermal Considerations for Roller-Compacted Concrete", in: Journal of the American Concrete Institute, ACI. Detroit, March-April 1985. vol. 82, nº 2.

85.62 "Texas Detention Dams Built of RCC", in: *Highway & Heavy Construction*. New York: Cahners Publishing Co., March 1985.

85.63 "Roller Compacted Concrete", in: U.S. Army Corps of Engineers EM 1110-2-2006. August/1985.

85.64 VENKATESHA, C. R. "A Review on Application of Roller Compacted Construction Methods for Concrete Dams", in: Irrigation and Power, Control Board of Irrigation and Power. New Delhi, 1985.

85.65 WILLIAMSON, J. V, et al. "General Paper: United States National Committee On Large Dams", in: Transactions, Fifteenth International Congress on Large Dams Q57. Lausanne, June 1985. vol. II.

85.66 YAMAUCHI, T., et al. "Construction of Tamagawa Dam by the RCD Method", in: Transactions, Fifteenth International Congress on Large Dams Q57. Lausanne, June1985. vol. II.

85.67 ADACHI, T., USUI, K. " Construction of Tamagawa Dam by The RCD Method With a Lift Thickness of 1 m", in: Engineering For Dams, Japan Dam Engineering Center, 1985. vol. 3. nº 4.

85.68 HARADA, J., SHIMADA, S. "Measuring of Concrete Temperature at Tamagawa Dam", in: Engineering For Dams, Japan Dam Engineering Center. 1985. vol. 3. nº 2.

85.69 HARADA, J.; TAKAHASHI, F., and YAMADA, K. "Incline Facilities at Tamagawa *Dam", in*: Engineering For Dams, Japan Dam Engineering Center. 1985. vol. 3.

85.70 SIMAKOV, G. K. "Shear Characteristics of Horizontal Joints in Rolled Concrete Dams", in: Izvestia Vniig Imeni B. E. Vedeneeva. Sbornik Nauchnykh Trudov, 1985, vol. 177.

85.71 TAKAHATA, H. "Automatic Concrete Conveyance System at Mano Dam", in: *Engineering For Dams*. Japan Dam Engineering Center, 1985. vol. 3, nº 4.

85.72 CARVALHO, L. H.; REZENDE, S.; HOLANDA, F.G. "Barragem do Acauã- Otimização do Projeto com o Emprego do Concreto Compactado-CCR", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.73 ANDRIOLO, F.R. "Comparações de Características e Propriedades de Concreto Rolado, Aplicado no Brasil e em outros Países", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.74 ANDRIOLO, F.R. "Concreto Adensado com Rolo Vibratório: Sugestões para Projeto e Construção", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.75 ANDRIOLO, F.; CUNHA, J. C.; PEDRONI, R. M.; KUPERMAN, S. C.; DAL FABRO, J. C. "Concreto Rolado, uma opção para a Futura UH Barra Grande", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.76 CARVALHO, L. H.; REZENDE, S.; HOLANDA, F. G. "Proposta de Aterro Experimental de Concreto Compactado – Barragem de Acauã-DNOCS", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.77 PIMENTEL, A. C.; VASCONCELOS, G. R. L.; GAMA, H. R.; SILVEIRA, J. A. "Utilização de Concreto Rolado na Usina Hidrelétrica Tucuruí", in: Proceedings of the XVI Seminário Nacional de Grandes Barragens. Belo Horizonte, Brazil, November 1985.

85.78 "RCC (Roller Compacted Concrete) Succeeds with ABG", in: ABG Publication. 1985.

1986

86.01 ANDERSON, R. "Roller-Compacted Concrete Increases Worldwide", in: Baumashine Und Bautechnik. Germany, September 1986. vol. 33, nº 9.

86.02 BRETT, D. M. "Craigbourne Dam Design and Construction", in: ANCOLD Bulletin nº74. Melbourne, Australia, August 1986.

86.03 CAMPBELL, P. A. "Readers Write: RCC Firsts", in: Civil Engineering – ASCE. New York, January 1986. vol. 56, nº1.

86.04 "Crack on Oregon RCC dam tied to thermal conditions", Engineering News. New York: Record, April 1986. vol. 216, nº15.

86.05 MINISTRY OF CONSTRUCTION. "Development in Japan of Concrete Dam Construction by the RCD Method 1986", in: River Development Division, 2-13, Kasumigaseki, Chiyoda - ku. Tokyo, 1986.

86.06 DOYLE, J. "Rollcreting in full swing on R20-m Arabie Dam project", in: South African Construction World, Phase Four (Pty) Ltd. Sandton. September 1986. vol. 5, nº 8.

86.07 DUNSTAN,G. "Continuous Volumetric Metering of Concrete Ingredients; The ARAN Equipment Approach to Accuracy-How and why it Works". Brisbane, Australia, October 1986.

86.08 DUNSTAN, M. R. H. "Design considerations for roller-compacted concrete dams", In: International Water Power & Dam Construction. United Kingdom, January 1986. vol. 38, nº 1.

86.09 "Editorial: The Japanese Strike Again", Engineering News. New York: Record, January 1986. vol. 216. nº 4.

86.10 HANSEN, K. D., and J. W. FRANCE. "RCC: A Dam Rehab Solution Unearthed", Civil Engineering ASCE. New York, September 1986. vol. 56, nº 9.

86.11 HANSEN, K. D. "Roller compacted concrete developments in the USA", in: International Water Power & Dam Construction. United Kingdom, January 1986. vol. 38, nº 1.

86.12 HANSEN, K. D. "Soil Cement for Embankment Dams", in: *ICOLD Bulletin*. Paris, 1986, nº 54.

86.13 HOLLINGWORTH, F., and F. H. W. M. DRUYTS. "Rollcrete: some applications to dams in South Africa", in: International Water Power & Dam Construction. United Kingdom, January 1986. vol. 38, nº 1.

86.14 JACKSON, H. E. "Roller-Compacted Concrete for Dams", in: Electric Power Research Institute Report AP4715. Palo Alto, California, September 1986.

86.15 JACKSON, H. "Construction of the Middle Fork and Galesville RCC dams", in: International Water Power & Dam Construction. United Kingdom, January 1986. vol. 38, nº1.

86.16 "Japanese nab Corps dam", in: *Engineering News*. New York: Record, January 1986. vol. 216, nº 4.

86.17 LAUNAY, J. "Soil-Cement and Roller-Compacted Concrete: Rollcrete", in: Conference at LPPE. Casablanca, Morocco, October 1986.

86.18 "Material Handling – the Key in RCC Dam Construction", in: *Highway & Heavy Construction*. New York: Cahners Publishing Co., December 1986. vol. 129, nº12.

86.19 MCKEON, T. J., and L. GROSS. "Roller Compacted Concrete: Taking on the Big Jobs", in: *The Construction Specifier*. Alexandria, Virginia: Construction Specification Institute, December 1986. vol. 39, nº 12.

86.20 NAGAYAMA, I., and T. YAMANAKA. "Watertightness of the RCD Dam - Monitoring Shimajigawa Dam", in: Engineering for Dams. Tokyo: Japan Dam Engineering Center, 1986. vol. 4, nº1.

86.21 "RCC Applications, Research and Technology Transfer Continues to Expand", in: RCC Newsletter, PCA. Skokie, Illinois, October 1986. nº 3.

86.22 "RCC dam placed faster yet", In: *Engineering News*. New York: Record, August 1986. vol. 217, nº 6.

86.23 "RCC dams rise in the south", in: *Engineering News*. New York: Record, June 1986. vol. 216, nº 23.

86.24 "RCC pace slow at big dam", in: *Engineering News*. New York: Record, June 1986. vol. 216, nº 26.

86.25 REINHARDT, W. G. "RCC dam rising 'like a weed' for N.J. water - Monkville hitting 800 cu yd a day", in: Engineering News. New York: Record, June 19, 1986. vol. 216, nº 25.

86.26 REINHARDT, W. G. "Rollcrete dam design evolution - Corps Elk Creek RCC dam includes lessons from Willow Creek", in: *Engineering News*. New York: Record, July 1986. vol. 217, nº 2.

86.27 REINHARDT, W. G. "Slip formed faces pace rapid pours for RCC dam", in: *Engineering News*. New York: Record, December 1986. vol. 217, nº 23.

86.28 SCHEXNAYDER, C. J., and R. F. STEWART. "Construction Technique for Roller-Compacted Concrete", in: Transportation Research Record 1062, Transportation Research Board National Council. Washington, D.C., 1986.

86.29 SCHRADER, E. K. "Compaction of Roller-Compacted Concrete", in: Proceedings of the American Concrete Institute Symposium on Consolidation of Concrete. San Francisco, ACI/ Detroit, March 1986.

86.30 SCHRADER, E. K. Discussion of the article "Design Considerations for Roller Compacted Concrete and Rollcrete Dams, by R. CANNON *(1985)*", in: Concrete International, ACI. Detroit, October 1986.

86.31 SCOTT, G. A. "Concrete and Grout Damage Control for Blasting at Upper Stillwater Dam", in: ASCE National Convention in Massachusetts, 1986.

86.32 SHIMIZU, S.; YANAGIDA, T. and JOJIMA, S. "The Development of the r.c.d. method in Japan", in: International Water Power & Dam Construction. United Kingdom, January 1986. vol. 38, nº 1.

86.33 SMITH, L. "RCC dam survives Texas flood: 30-day-old Kerrville Dam overtopped with no damage", Engineering News. New York: Record. April 1986. vol. 216, nº17.

86.34 TASSEL, A. "DWA uses a PFA mix on its third rollcrete project", in: South African Construction World, Phase Four (Pty) Ltd. Sandton, September 1986. vol. 5, nº 8.

86.35 TASSEL, A. "First full-scale application of Rollcrete at Zaaihoek", in: South African Construction World, Phase Four (Pty) Ltd. Sandton, April 1986. vol. 5, nº 3.

86.36 "The First Generation of RCC Dams - Success Breeds Success", in: RCC Newsletter, PCA. Skokie, Illinois, April 1986.

86.37 "Three Bid Seattle Dams Low", in: *Engineering News*. New York: Record, November 1986. vol. 217, nº 20.

86.38 "Two RCC Dams are First For South America", In: Civil Engineering – ASCE. New York, August 1986. vol. 56, nº 8.

86.39 WELLS, W. L. "Readers Write", in: Civil Engineering - ASCE. New York, March 1986. vol. 56, nº 3.

86.40 HUKUOKA, T., YAMASHITA, K., KOMATSU, A. "Design and Construction of Pirika Dam" in: The Dam Digest, The Japan Dam Foundation, 1986. nº 50.

86.41 RAGAN, Steven A. "Evaluation of Frost Resistance Or Roller-Compacted Concrete Pavements", in: 65th Annual Meeting, Transportation Research Board. Session 90, 1986.

86.42 NAKAYAMA, I., and YAMANAKA, T. "Diaphram of the RCD Dam - Shimajigawa Dam's Records", in: Engineering For Dams- Japan Dam Engineering Center, 1986. vol. 4, nº 1.

86.43 OKADA, K. "Research of Super-Stiff Concrete in Lean Mix Proportion Blast-Furnace Slag and Blast-Furnace Cement", in: The Society of Materials Science. Japan, March 1986.

86.44 WHITE, Thomas D. "Mix Design, Thickness Design, and Construction of Roller Compacted Concrete Pavement", in: Transportation Research Record 1062. Roller Compacted Concrete Pavements and Concrete Construction. Washington, DC, 1986.

86.45 PIGGOTT, Robert W. "Roller Compacted Concrete for Heavy-Duty Pavements: Past Performance, Recent Projects and Recommended Construction Methods", in: Transportation Research Record 1062. Roller Compacted Concrete Pavements and Concrete Construction. Washington, DC, 1986.

86.46 PITTMAN, David W. "Construction of Roller-Compacted Concrete Pavements", in: Transportation Research Record 1062. Roller Compacted Concrete Pavements and Concrete Construction. Washington, DC, 1986.

86.47 ABRAMS, Jory M.; LACKSHA, Jerry L.; NORTON, Robert L.; IRVINE, David J. "Roller Compacted Concrete Pavement at Portland International Airport", in: Transportation Research Record 1062. Roller Compacted Concrete Pavements and Concrete Construction. Washington DC, 1986.

86.48 STEWART, Rita F.; SCHEXNAYDER, Cliff J. "Construction Technique for Roller Compacted Concrete", in: Transportation Research Record 1062. Roller Compacted Concrete Pavements and Concrete Construction. Washington, DC, 1986.

1987

87.01 ADASKA, W. S. "Earthfill or Concrete? RCC Combines the Benefits of Both", in: *Hydro Review*. Kansas City, Missouri, February 1987. vol. VI, nº1.

87.02 "All-purpose reservoir well worth the wait", in: *Engineering News*. New York: Record, September 1987. vol. 219, nº 12.

87.03 "Bonding Roller Compacted Concrete Layers", in: Concrete Information, PCA. Skokie, Illinois, 1987.

87.04 "Claims filed on RCC dams", in: *Engineering News*. New York: Record, February 1987. vol. 218, nº 9.

87.05 "Court challenge stops records at Elk Creek", In: *Engineering News*. New York: Record, December 1987. vol. 219, nº 26.

87.06 "Dam will protect river from acid", in: *Engineering News*. New York: Record, September 10, 1987. vol. 219, nº 11.

87.07 DOLEN, T. P. "Performance of Fly Ash in Roller Compacted Concrete at Upper Stillwater Dam", in: Proceedings of the 8th International Ash Utilization Symposium, Washington, D. C.,. ERPI CS-5362. Palo Alto, California, October 1987. vol. 2.

87.08 DRAHUSHAK-CROW, R. "Microcomputer Application for Roller Compacted Concrete Quality Assurance", in: Special Publication, SP-98, ACI. Detroit, 1987.

87.09 DRUYTS, F. H. W. M., and F. HOLLINGWORTH. "Ash and Rollcrete Dams", in: Transactions, International conference on "Ash - a valuable resource", CSIR Conference Centre. Pretoria, South Africa, February 1987.

87.10 DRUYTS, F. H. W. M., and L. S. TROMP. "The Use of Cement Blends in Mass Concrete and Rollcrete", in: Transactions, Practical guidelines for the use of Portland Cements, milled slag, fly ash and silica fumes in concrete, PCI Symposium. Johannesburg, South Africa, September 1987.

87.11 DUNSTAN, M. R. H "Use of Fly Ash in Roller-Compacted Concrete", in: Transactions, International conference on "Ash - a valuable resource", CSIR Conference Centre. Pretoria, South Africa, February 1987. vol. 2.

87.12 "Elk Creek troubles", in: Engineering News. New York: Record, October 1987. vol. 219, nº18.

87.13 FORBES, B. A., and POTTS, J. K. C. "Construction of Bucca Weir: Combined Use of RCC and Compacted Earthfill", in: ANCOLD Bulletin nº 78. Melbourne, Australia, December 1987.

87.14 FRANCE, J. W., and WHITESIDE, S. L. "Design of Overtopping Protection for Small Dams", in: Hydraulic Engineering. Proceedings of the National Conference. Williamsburg, Virginia, August 1987.

87.15 FREITAS, W. L., and SATO, R. S. "Cedar Falls Project - Major Rehabilitation", in: Waterpower '87. Proceedings of the International Conference on Hydropower. Portland, Oregon, August 1987.

87.16 "Guide for Consolidation of Concrete", in: ACI Committee Report 309, ACI. Detroit,1987.

87.17 "Guidelines for Designing and Constructing Roller-Concrete Dams", in: ACER Technical Memorandum. U.S. Bureau of Reclamation. Denver, June 1987. nº 8.

87.18 HANSEN, K. D. "Roller compacted dams worldwide", in: Handbook 87, International Water Power & Dam Construction. United Kingdom, 1987.

87.19 HILF, J. W. "Rolled Concrete Dams Using Gap-Graded Aggregate", in: Journal of Construction Engineering and Management, ASCE. New York, March 1987. vol. 113, nº 1.

87.20 HOUSTON, K. L. "Stepped Spillway Design with a RCC Dam", in: Hydraulic Engineering, Proceedings of the National Conference. Williamsburg, Virginia, August 1987.

87.21 HOUSTON, K. "Hydraulic Model Studies of Upper Stillwater Dam Stepped Spillway and Outlet Works", in: REC-ERC Research Report 87-6, U.S. Bureau of Reclamation. Denver, 1987.

87.22 JACKSON, H. E. "Roller-Compacted Concrete for Dams", in: Waterpower '87 Proceedings of the International Conference on Hydropower. Portland, Oregon, August 1987.

87.23 LOGIE, C. V., and RAJE, J. H. "Hydraulic Design of Pamo Dam Spillway", in: Hydraulic Engineering, Proceedings of the National Conference. Williamsburg, Virginia, August 1987.

87.24 MOLER, W. A. "Spring Creek Dam Is Ready for the PMF: A Case History", in: Hydraulic Engineering. Proceedings of the National Conference. Williamsburg, Virginia, August 1987.

87.25 "New RCC use on a California dam", Engineering News. New York: Record, April 1987. vol. 218, nº 17.

87.26 "One Major RCC Dam Complete - Another Begins", in: RCC Newsletter, PCA. Skokie, Illinois, October 1987, nº 5.

87.27 "RCC Dam Features Many Cold Joints", in: *Highway and Heavy Construction.* New York: Cahners Publishing Co., August 1987. vol. 130, nº 8.

87.28 "Record-Breaking RCC Dam Sets New Production Marks", in: *Highway and Heavy Construction.* New York: Cahners Publishing Co., January 1987. vol. 130, nº 1.

87.29 REINHARDT, W. G. "Speed and grit beat problems on BuRec dam", in: Engineering News. New York: Record, October 1987. vol. 219, nº18.

87.30 SCHRADER, E. K. "Compaction of Roller Compacted Concrete", in: Special Publication, SP-96 ACI. Detroit, 1987.

87.31 SCHRADER, E. K. "Design for Strength Variability: Testing and Effects on Cracking in RCC and Conventional Concretes", in: Lewis H. Tuthill Symposium., SP-104, ACI. Detroit, 1987.

87.32 "Spring Creek Dam", in: RCC Newsletter, PCA. Skokie, Illinois, October 1987. nº 5.

87.33 TAYAABJI, S. D., and P. A. OKAMOTO. "Bonding of Successive Layers of Roller Compacted Concrete. Report to U.S. Bureau of Reclamation", in: Construction Technology Laboratories. Skokie, Illinois, March 1987.

87.34 VERIGIN, W. M., and BENSON, S. A. "Cedar Falls Project - Rehabilitation with RCC", in: Waterpower '87. Proceedings of the International Conference on Hydropower. Portland, Oregon, August 1987.

87.35 "Mass Concrete for Dams and Other Massive Structures", in: ACI Comimittee 207.

87.36 SGARBOZA, B. C.; MENDES, L. C.; MÉLLIO, A. "Proteção do talude de Montante da Barragem de Terra do Aproveitamento Hidrelétrico de Rosana com Solo-Cimento – Aspectos Construtivos", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.37 HELLVIG, A.; AGUIAR, R. "Dosagem de Solo-Cimento para Aplicação em Proteção de Taludes da Barragens de Terra das Hidrelétricas Porto Primavera e Rosana", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.38 CARVALHO, P. A.; HELLVIG, A.; AGUIAR, R. "Controle de Qualidade do solo-Cimento Aplicado como Proteção de Talude na Barragem de Terra do Aproveitamento Hidrelétrico de Rosana", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.39 DUMONT, N. A.; VAZ, L. E.; REZENDE, S.; QUIN, J. T. "Análise de Fissuração do Paramento de Montante do Maciço da Barragem Saco Nova Olinda-PB-SRH", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.40 DUMONT, N. A.; VAZ, L. E.; REZENDE, S.; RUOSCH, J. R. A. "Análise de Tensões Durante a Fase Construtiva do Maciço da Barragem Saco de Nova Olinda-PB-SRH", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.41 DUMONT, N. A.; VAZ, L. E.; REZENDE, S.; RUOSCH, J. R. A. "Análise Térmica do Maciço da Barragem Saco de Nova Olinda-PB-SRH", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.42 ANDRIOLO, F. R.; GOTTARDO, G.; PEÑA D. F. "Uruguai : Uma Barragem em Concreto Rolado", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.43 ANDRADE, W. P.; Fontoura, J. T. F.; BITTENCOURT, R. M.; GUERRA, E. A. "Estudos de Laboratório para Concreto Compactado com Rolo Vibratório, com Alto Teor de Pozolana", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.44 MOREIRA, J. E. "General Report- TEMA IV", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.45 DANTAS, J. E. E.; HOLANDA, F. G. "CCR Uma Realidade Nacional - Açude público Saco de Nova Olinda- Paraíba-PB", in: Proceedings of the XVII Seminário Nacional de Grandes Barragens. Brasília, Brazil, August 1987.

87.46 PIGGOT, Robert W. "Ten Years of Heavy-Duty Pavement in Western Canada", in: RCC Pavements, Concrete International. ACI Compilation. February 1987. nº 8.

87.47 HUTCHINSON, R. L.; RAGAN, S. A.; PITTMAN, D. W. "Heavy-Duty Pavements- Roller Compacted Concrete Paving", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.48 LARSON, J. L. "Design Practics at the Port of Tacoma- Roller Compacted Concrtete-Project and Equipment", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.49 "Mixing of Roller Compacted Concrete", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.50 "Placing Roller Compacted Concrete Pavement", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.51 HANSEN, Kenneth D. "A Pavement for Today and Tomorrow- Roller Compacted Concrete", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.52 ANDERSSON, Ronny. "Swedish Experiences with RCC", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.53 PALMER, William D. "One Tough Pavement", in: Concrete International, ACI Compilation. February 1987. nº 8.

87.54 ABRAMS, Jory M. and LACKSHA, Jerry L. "An Airport Apron and a County Road", in: Concrete international- ACI Compilation nº8, February/1987.

87.55 LOGIE, Charles V.; OLIVERSON, James E. "Burlington Nothern Railroad Intermodal Hub Facility", in: Concrete international, ACI Compilation. February 1987. nº 8.

1988

88.01 ARJOUAN, M.; CHRAIBI, A. F. and EJJAOUANI, H. "Roller Compacted Concrete Used for the Construction of Small Dams: the Rwedat Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.02 "Auburn dam studied again", in: Engineering News. New York: Record, July 7, 1988. vol. 221, nº 1.

88.03 "A 'world first' at Knellpoort Dam", in: South African Construction World, Phase Four (Pty) Ltd. Sandton. October 1988. vol. 7, nº 9.

88.04 BAYAN, B. J. "Execution and Control of the Castiblanco de los Arroyos Dam with Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.05 BENCHEIKH, L. et al. "Ain al Koreima Dam: A Roller Compacted Concrete mixed with random alluvium - Design and concrete mix proportions", in: Transactions, Sixteenth International Congress on Large Dams Q6. San Francisco, June 1988. vol. III.

88.06 BENSON, S. A., and HOKENSON, R. A. "Small RCC Dam Plays Major Role in Rehabilitation Project", in: International Water Power & Dam Construction. United Kingdom, February 1988. vol. 40, nº 2.

88.07 BENSON, S. A.; VERIGIN, W. M. and CARNEY, M. J. "Cedar Falls Roller Compacted Concrete Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference, San Diego, California, ASCE. New York, March 1988.

88.08 BESSIÈRE, C. et al. "New designs of buttress dams or multiple arch dams: standardization of similar work, use of new developments in formwork and roller compacted techniques", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.09 BISHCHOFF, J. A. et al. "An Innovative Approach to the Strengthening and Raising of Gibraltar Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.10 BLOOMBERG, R. "Dam is designed to trap sediment", in: Engineering News. New York: Record, January 7, 1988. vol. 220, nº 1.

88.11 BOGGS, H. L.; JANSEN, R. B. and TARBOX, G. S. "Arch Dam Design and Analysis Construction Using Roller-Compacted Concrete (RCC)", in: Advance Dam Engineering for Design, Construction and Rehabilitation, Van Nostrand Reinhold. New York, 1988.

88.12 BOUYGE, B.; LANGOIS, A. P. and MARTIN, J. P. "Quality of Works in RCC in France: A Contractor's Solution", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.13 BOUYGE, B, et al. "Roller Compacted Concrete Dam Construction and Work Supervision: a Team Job", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.14 "Burdekin Falls Dam", in: Constructional Review North Sydney. New South Wales, Australia, August 1988. vol. 61, nº 3.

88.15 CACCIALANZA, L., et al. "Economic Assessments and New Plant Developments in Construction Methods of Concrete Gravity Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.16 CASIAS, T. J.; GOLDSMITH, V. D. and BENAVIDEZ, A. A. "Soil Laboratory Compaction Methods Applied to RCC", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.17 "China boosts its hydroelectric plans", in: Engineering News. New York: Record, May 1988. vol. 220, nº 18.

88.18 "Comments on Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams, Universidad de Cantabria Working Group Q62. San Francisco, June 1988. vol. III.

88.19 COOKE, J. B. "Discussions: RCC Use With the CFRD Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. V.

88.20 CORNS, C. F.; SCHRADER, E. K. and TARBOX, G. S. "Gravity Dam Design and Analysis", in: Advance Dam Engineering for Design, Construction and Rehabilitation, Van Nostrand Reinhold. New York, 1988.

88.21 DELANEY, M. "Discussions: Comparative Costs of RCC and Conventional Concrete", in: Transactions, Sixteenth International Congress on Large Dams San Francisco Q62. June 1988. vol. V.

88.22 "Design of Stacy Dam", in: USCOLD Newsletter nº 87. Denver, November 1988.

88.23 DITCHY, F. J. and SCHRADER, F. K. "Monksville Dam Temperature Studies", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.24 DOLEN, T. P. and RICHARDSON, A. T. "Slipformed Concrete Facing for Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.25 DOLEN, T. P. and TAYABJI, S. D. "Bond Strength of Roller Compacted Concrete", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California ASCE. New York, March 1988.

88.26 DOLEN, T. P.; RICHARDSON, A. T. and WHITE, W. R. "Quality Control/Inspection - Upper Stillwater Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.27 DOLEN, T. P. "Materials and Mixture Proportioning Concepts for Roller Compacted Concrete Dams", in: Advance Dam Engineering for Design, Construction and Rehabilitation, Van Nostrand Reinhold. New York, 1988.

88.28 DRAHUSHAK-CROW, R. and DOLEN, T. P. "Evaluation of Cores >From Two RCC Gravity Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.29 DUNSTAN, M. R. H. "Design and Construction Considerations for Roller Compacted Concrete Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.30 DUNSTAN, M. R. H. "Discussions: A Multitude of Choices", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. V.

88.31 DUNSTAN, M. R. H. "The growing acceptance of RCC dam construction", in: Reservoir Renovation, BNCOLD. United Kingdom, September 1988.

88.32 DUNSTAN, M. R. H. "Whither Roller Compacted Concrete for Dam Construction", in: Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.33 FORBES, B. A. "RCC in Dams in Australia", in: Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.34 FORBES, B. A. "The Development and Testing of Roller-Compacted Concrete for Dams in Australia", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.35 GARDINER, A. "120 MW Urugua-i - Scheme Incorporates Argentina's first RCC dam", in: International Water Power & Dam Construction. United Kingdom, April 1988. vol. 40, nº 4.

88.36 GOURDIN, R.; JENSEN, A. and BOUYGE, B. "Les Olivettes Dam on the River Peyne (Hérault)", in: Travaux, Science et Industrie. Paris, July 8, 1988. nº 634.

88.37 GUZINA, B. J.; UZELAC, S. and SARIC, M. "Application of Roller Compacted Concrete at Appurtenant Hydraulic Structures of a Large Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.38 HANSEN, K. D. and GUICE, L. K. (eds.). *Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego.* California, ASCE. New York, March 1988.

88.39 HANSEN, K. D. "RCC '88 will review recent developments", in: International Water Power & Dam Construction. United Kingdom, February 1988.

88.40 HIROSE, T. et al. "A Study of Control of Temperature Cracks in Large Roller Compacted Concrete Dams", in: Transaction, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.41 HOLLINGWORTH, F.; DRUYTS, F. H. W. M. and MAARTENS, W. W. "Some South African Experiences in the Design and Construction of Rollcrete Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.42 HOLLINGWORTH, F. "Discussions: RCC Arched Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.43 HOPMAN, D. R. and CHAMBERS, D. R. "Construction of Elk Creek Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California ASCE. New York, March 1988.

88.44 IMAMURA, M.; TORII, K. and HARADA, J. "Embedded Facilities Within the RCD Dam Bodies", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.45 JACKSON, H. E. "Discussions: Thermal Cracking in Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. V.

88.46 JANSEN, R. B. (Editor). *Advanced Dam Engineering for Design, Construction and Rehabilitation.* New York: Van Nostrand Reinhold, 1988.

88.47 KATO, O. "Study on the Application of Roller-Compacted Concrete Method to the Electric-Power Related Mass Concrete Structures, Part 4 - Examination of Compactibility of RCC by vibrating Table. Report nº CRIE-U-87075", in: Central Research Institute of Electric Power Industry. Tokyo, June 1988.

88.48 KURITA, M. "Compaction Characteristics of Roller Compacted Concrete", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.49 KUZMIN, K. K. et al. "Concrete Dam Construction in the USSR", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.50 LAMA, J. L.; PEREZ I. de Juan and BENET, J. "The Santa Eugenia Dam: Use of Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.51 LAMPÉRIÈRE, F. "Discussions: Cost Comparisons Between Conventional and Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco. June 1988. vol. III.

88.52 LEMONS, R. M. "A Combined RCC and Reinforced Concrete Spillway", in: Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.53 LEMONS, R. M. "Leak proofing an RCC dam", Civil Engineering ASCE. New York October 1988. vol. 58, nº 10.

88.54 LODIGIANI, G. (Chm.). "Discussions: New Development in the Construction of Concrete Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco. June 1988. vol. V.

88.55 LOGIE, C. V. and OLIVERSON, J. F. "Roller Compacted Concrete Mix Design for Pamo Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.56 LONDE, P. "Discussions: Réflexions sur le Béton Compacté au Rouleau", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco. June 1988. vol. V.

88.57 LOWE, J. III "Roller Compacted Concrete Dams - An Overview", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California ASCE. New York, March 1988.

88.58 MARCELLO, A. et al. "Some Aspects of Thermal Behaviour of Concrete in Dam Construction", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.59 MCLEAN, F. G. and PIERCE, J. S. "Comparison of Joint Shear Strengths for Conventional and Roller Compacted Concrete", in: Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.60 MCTAVISH, R. F. "Construction of Upper Stillwater Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.61 MOFFAT, A. I. and PRICE, A. C. "The rolled dry lean concrete gravity dam", in: International Water Power & Dam Construction. United Kingdom, July 1988. vol. 40, nº 7.

88.62 MOLER, W. A. and MOORE, J. F. "Design of Seepage Control Systems for RCC Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.63 OBERHOLTZER, G. L.; LORENZO, A. and SHRADER, E. K. "Roller Compacted Concrete Design for Urugua-I Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.64 ANDRADE, Pacelli de, W. "Discussions; Brazilian Experiences in Roller Compacted Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.65 "Progress in the design, construction and performance of RCC dams", in: International Water Power & Dam Construction. United Kingdom, August 1988. vol. 40, nº 8.

88.66 "Projects spur RCC innovation", in: Engineering News. New York: Record., September 8, 1988 vol. 221, nº 10.

88.67 QUIN, J. T.; REZENDS, S. P. and SCHRADER, E. K. "Saco Dam - South America's First RCC Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.68 "RCC Proves Economical and Speedier Alternative", in: Indian Concrete Journal New Delhi. May 1988. vol. 62, nº 5.

88.69 RICHARDSON, A. T. "Upper Stillwater Dam - Design, Construction and Performance", in: US. Army Corps of Engineers Structural Conference. St Louis, Missouri, June 1988.

88.70 "Roller Compacted Mass Concrete ACI Materials Journal", in: Committee Report nº ACI 207.5R-88, ACI. Detroit, September-October 1988.

88.71 SCHRADER, E. K.,and NAMIKAS, D. "Performance of Roller Compacted Concrete Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.72 SCHRADER, E. K.; and SWIGER, W. F. "Concrete Dam Construction and Foundation Treatment", in: *Advance Dam Engineering for Design, Construction and Rehabilitation*. New York: Van Nostrand Reinhold, 1988.

88.73 SCHRADER, E. K. "Behavior of Completed RCC Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.74 SCHRADER, E. K. "Materials - Comparative Limits and Advantages of RCC", in: Advance Dam Engineering for Design, Construction and Rehabilitation. Van Nostrand Reinhold. New York, 1988.

88.75 SCHRADER, F. K. "Spillway Design and Construction – Construction Considerations", in: Advance Dam Engineering for Design, Construction and Rehabilitation, Van Nostrand Reinhold. New York, 1988.

88.76 SERAFIN, J. L. "General Report Question 62 - New Developments in the Construction of Concrete Dams", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.77 SHEN, C. "Discussions: RCC dams in China", in: Transactions, Sixteenth Congress on Large Dams Q62. San Francisco, June 1988. vol. V.

88.78 SNIDER, S. H. and SCHRADER, E. K. "Monksville Dam: Design Evolution and Construction", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.79 "Structure built in 37 days", in: Engineering News. New York: Record., August 1988. vol. 221, nº 7.

88.80 SUDAKOV, V. B. et al. "Shear characteristics of horizontal joints in an RCC block", in: Proceedings, Russian Research Institute for Hydraulic Structures, Izvestia VNIIG. St Petersburg, 1988. vol. 206.

88.81 TARBOX, G. S. and HANSEN, K. D. "Planning, Design and Cost Estimates for RCC Dams", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.82 TROMP, L. S. *Guidelines for the Use of Rollcrete for the Construction of Concrete Dam Structures.* South Africa: Faculty of Engineering, University of Pretoria, 1988. (thesis)

88.83 "Unsafe Earth Dams Rehabilitated with RCC", in: RCC Newsletter PCA. Skokie, Illinois, April 1988.

88.84 URLICH, D. M. et al. "Design and Construction of Lower Chase Creek Dam", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.85 VIELMO, I. "Continuous Placement Concrete Dams: Possible Developments for Secondary Technologies", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.86 WANG, S. "Kengkou Roller Compacted Concrete Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 689, 1988. vol. III.

88.87 WITHROW, H. "Compaction Parameters of Roller compacted Concrete", in: Roller Compacted Concrete II Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.88 "Wolwedans - Owners express concern", in: *Water*, House Journal of the Department of Water Affairs. Pretoria, South Africa, March 1988.

88.89 WONG, N. C.; ORDUZ, F. and RIPLEY, B. D. "Strengthening of Gibraltar dam with roller compacted concrete", in: International Water Power & Dam construction. United Kingdom, February 1988. vol. 40, nº 2.

88.90 WONG, N. C.; BISCHOFF, J. A. and JOHNSON, D. H. "Strengthening and Rising Gibraltar Dam with RCC", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.91 "World News: construction of Elk Creek RCC dam halted", in: International Water Power & Dam Construction. United Kingdom, July 1988. vol. 40, nº 7.

88.92 "World News: Geheyan cofferdam withstands overtopping", in: International Water Power & Dam Construction. United Kingdom, July 1988. vol. 40, nº 7.

88.93 YAMAGUCHI, J. et al. "Construction Work and Quality and Temperature Control for Tamagawa RCD Dam", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.94 YONEZAWA, T. et al. "Measurement and Analysis of Cracks Caused by Thermal Stress in Mass Concrete", in: Transactions, Sixteenth International Congress on Large Dams Q62. San Francisco, June 1988. vol. III.

88.95 BRETT, D. M. "RCC Pavements in Tasmania, Australia", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.96 RAGAN, S.A. "Proportioning RCC Pavement Mixtures", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.97 HESS, J. R. "RCC Storage Pads at Tooele Army Depot, Utah", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.98 DELVA, K. L. "Rennick Yard RCC Pavement Design and Construction", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California, ASCE. New York, March 1988.

88.99 RABA, G. W.; SCHWEIZER, E. "Roller Compacted Concrete with Marginal Aggregates", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.100 KEIFER, O. J. "Corps of Engineers Experience with RCC Pavements", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.101 PITTMAN, D. W. "RCC Pavement Construction and Quality Control", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.102 ROLLINGS, R. S. "Design of Roller Compacted Concrete Pavements", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.103 JOFRE, C.; FERNANDEZ, R.; JOSA, A.; MOLINA, F. "Spanish Experience with RCC Pavements", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, March 1988.

88.104"Dams in Japan", in: Japanese national Committee on Large Dams, 1988, nº 11

88.105 "Dam Professionals in FRANCE", in: French Committee on Large Dams, 1988.

88.106 "Concrete Plant Does Double Duty- Stacy Dam", in: Hygway & Heavy Construction. September 1988.

88.107 LESCANO, R. "Hormigón Compactado con Rodillo-Concepto y Tendencias", in: Jornadas de Extension Universitaria, Hormigon Compactado a Rodillo para Presas y Otras Estructuras. Cordoba, Argentina, September 1988.

88.108 ZARAZAGA, C. "Hormigon Compactado a Rodillo. Algunos Temas Controvertidos", in: Jornadas de Extension Universitaria, Hormigon Compactado a Rodillo para Presas y Otras Estructuras. Cordoba, Argentina, September 1988.

88.109 GOLIK, Miguel A. "Urugua-i en HCR.-Aplicación de Una Tecnologia en Expansión", in: Jornadas de Extension Universitaria, Hormigon Compactado a Rodillo para Presas y Otras Estructuras. Cordoba, Argentina, September 1988.

88.110 SEGARRA, F.; LORENZO, A.; VELEDA, C. A. "Proyecto Hidroeléctrico Urugua-i – Presa Principal de HCR", in: Jornadas de Extension Universitaria- Hormigon Compactado a Rodillo para Presas y Otras Estructuras. Cordoba, Argentina, September 1988.

88.111 VELEDA, C. A.; LORENZO, A.; DECI, J. "Proyecto Hidroeléctrico Urugua-i –Presa Principal de HCR- Consideraciones Sobre la Seguridad Ante el Deslizamiento", in: Jornadas de Extension Universitaria- Hormigon Compactado a Rodillo para Presas y Otras Estructuras. Cordoba, Argentina, September 1988.

1989

89.01 BOUYGE, B. "Cracking of Roller-Compacted Concrete Dams - Example of the Les Olivettes Dam", in: Bulletin de Liaison des Laboratoires des Ponts et Chaussées. Paris, July-August 1989. nº 162.

89.02 BOUYGE, B. et al. "New Dam Building Techniques: RCC (Roller Compacted Concrete)", in: *Revue de l'Energie*. Paris, March-April, 1989. vol. 40, nº 410.

89.03 "Business News - Design contract awarded for RCC dam in Greece", in: International Water Power & Dam Construction. United Kingdom, April 1989. vol. 41, nº 4.

89.04 "Dissolving RCC Dam Begins Self Recovery", in: Civil Engineering - ASCE. New York, June 1989. vol. 59, nº 6.

89.05 DUNSTAN, M. R. H. "Recent developments in roller compacted concrete dam construction", in: Handbook 1989, International Water Power & Dam Construction. United Kingdom, 1989.

89.06 "Editorial: Good things in a small package", Engineering News. New York: Record. October 12, 1989. vol. 223, nº 15.

89.07 HANSEN, K. D. "Performance of Roller-Compacted Concrete Dam Rehabilitations", in: Proceedings, Sixth ASDSO Annual Conference. Albuquerque, 1989. Association of State Dam Safety Officials. Lexington, Kentucky, 1989.

89.08 HOLLINGWORTH, F.; HOOPER, D. J. and GERINGER, J. J. "Roller compacted concrete arched dams", in: International Water Power & Dam Construction. United Kingdom, November 1989. vol. 41, nº 11.

89.09 JOHNSON, D. L. "Stagecoach Dam", in: USCOLD Newsletter nº 88 Denver, March 1989.

89.10 KOLONIAS, E. et al. "Design of Platanovryssi, Europe's highest rcc dam", in: International Water Power & Dam Construction. United Kingdom, November 1989. vol. 41, nº 11.

89.11 "Low cost concrete finds a new use", in: Engineering News. New York: Record., October 1989. vol. 223, nº 15.

89.12 "New program finances dam", in: Engineering News. New York: Record, March 1989. vol. 222, nº 13.

89.13 "Roller Compacted Concrete for Gravity Dams - State-of-the-Art Bulletin 75", in: International Commission on Large Dams (ICOLD). Paris, 1989.

89.14 MINISTRY OF ELECTRIC POWER INDUSTRY PRC. "RCC Arch Dam- Highest in World First in China- Puding Hydroelectric Project", in: Guiyang Hydroelectric Investigation Design & Research Institute, 1989.

89.15 SOLLO, J. P. "Geological problems at Urugua-i RCC dam", in: International Water Power & Dam Construction. United Kingdom, December 1989. vol. 41, nº 12.

89.16 SUZUKI, N. and SHIMIZU, S. "Characteristics of the RCD Construction method and the RCC Construction method", in: Proceedings of the Japan Society of Civil Engineers. Tokyo, March 1989. nº 403.

89.17 TASSELI, A. "Rollcrete allows high-speed construction at Wolvedans", in: South African Construction World, Phase Four (Pty) Ltd. Sandton, September 1989.

89.18 "The Zaaihoek Dam – New developments in Rollcrete construction", in: The Civil Engineer in South Africa, South African Institute of Civil Engineers. Johannesburg, September 1989. vol. 31, nº 9.

89.19 "World First For Water Affairs", in: Water, House Journal of the Department of Water Affairs. Pretoria, South Africa, June 1989.

89.20 "World News - Wolwedans RCC dam under way", in: International Water Power & Dam Construction. United Kingdom, March 1989. vol. 41, nº 3.

89.21 ZANELLA, Mario Raul; BRAGA, José Augusto; ROSARIO, Luiz Cesar; AYALA, Adalberto G. Chenu; ANDRIOLO, Francisco R.; GOLIK, Miguel. "Concreto Rolado – Ensaios Especiais", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.22 GOLIK, Miguel A.; ANDRIOLO, Francisco R. "Urugua-i (C.C.R.) - Controle de Qualidade do Concreto Lançado no Tramo Principal da Barragem", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.23 BARROS, Paulo Antonio de; ANDRADE, Walton Pacelli de; MOURA, Francisco Itamar. "Ensecadeiras Galgáveis em Concreto Compactado a Rolo - Aproveitamento Hidroelétrico de São Félix – Usina Serra Da Mesa", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.24 QUEVEDO, Carlos A.; ESPAÑA, Manuel; NESPRAL, Cesar D. " Aprovechamiento Hidroelectrico Urugua-I (República Argentina) - Tecnologia del H.C.R", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.25 MODÉ, Antônio Carlos Mazzucco; DIAS, Eduardo Guimarães; CARMO, João Bosco Moreira do; NASCIMENTO, José Francisco Farage do; FONTOURA, José Tomaz França; SILVA, José Vítor da; GRAÇA, Newton Goulart; ANDRADE, Walton Pacelli de. "Construção e Controle do Concreto Compactado a Rolo Para as Ensecadeiras Galgáveis da Usina Serra da Mesa Aproveitamento Hidroelétrico de São Félix", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.26 BIRINDELLI, Lucy Inês Olivan; FERREIRA, Omar Vilela; INOUE, George; MIYAJI, Yssamu; SCANDIUZZI, Lutércio. "Estudo Térmico das Condições de Lançamento e de Definição do Espaçamento de Juntas de Contração em Barragens de C.C.R", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.27 VELEDA, Carlos A.; LORENZO, Andrés; DADI, Jorge L. "Proyecto Hidroeléctrico Urugua-i - Presa Principal de HCR - Consideraciones Sobre la Seguridad Ante el Deslizamiento", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.28 CANHOLI, Aluísio Pardo; JENSEN, Pedro Diego; KUPERMANN, Selmo. "Alguns Aspectos de Projeto para Barragens em C.C.R", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.29 SEGARRA, José F.; VELEDA, Carlos A. LORENZO, Andrés. "Proyecto Hidroeléctrico Urugua-i - Presa Principal de HCR - Descripcion General", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.30 BALLESTRERO, Lucio A.; GARRONE, Juan R. "Utilizacion Del H.C.R. en el Aprovechamiento Hidroeléctrico del Arroyo Urugua-i", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.31 ZALESKI, Juarez Moraes; SEIFART S. Leopoldo A.; BRAGA, José Augusto; ROSARIO, Luiz Cesar. "Concreto Adensado Com Rolo Vibratório - Dados Sobre Uso na Itaipu Binacional com Aproximadamente 10 Anos de Idade", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.32 BRAGA, José Augusto; ROSARIO, Luiz Cesar; DUARTE, José D. Carreras; LACERDA, Saulo Silva. "Utilização de Finos - Subproduto de Britagem nos Concretos Rolado e Convencional", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.33 AVILA, Nathanael Vilela de. "Algumas Considerações a Respeito da Estabilidade das Barragens de Concreto Compactado A Rolo", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.34 GAMBALE, Eduardo de Aquino; GUERRA, Élcio Antônio; FONTOURA, José Tomaz França; SANTOS, Marcia Campos dos; GÓZ, Rogério Sales; BITTENCOURT, Rubens Machado; ANDRADE, Walton Pacelli de. "Pesquisa Com Cimento De Escória de Alto Forno", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.40 GUERRA, Élcio Antônio; OLIVEIRA, João Carlos Faig de; FONTOURA, José Tomaz França; SANTOS, Marcia Campos dos; BITTENCOURT, Rubens Machado; ANDRADE, Walton Pacelli de. "Influência da Finura da Escória de Alto Forno Moída nas Propriedades do Concreto Compactado a Rolo", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.41 DIAS, Eduardo Guimarães; GUERRA Élcio Antônio; LEROY, Guilherme; OLIVEIRA Joao Carlos Faig de; FONTOURA, José Tomaz França; GÓZ Rogério Sales; BITTENCOURT, Rubens Machado; ANDRADE, Walton Pacelli de. "Estudo de Dosagens para Concreto Compactado a Rolo - Obras de Desvio da Usina Serra da Mesa", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.42 GUERRA, Élcio Antônio; NASCIMENTO, José Francisco Farage do; FONTOURA, José Tomaz França; GÓZ, Rogério Sales; BITTENCOURT, Rubens Machado; ANDRADE, Walton Pacelli de. "Procedimento de Controle de Qualidade do Concreto Compactado a Rolo das Ensecadeiras Galgáveis para o Aproveitamento Hidroelétrico de São Fé1ix Usina Serra da Mesa", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.43 KUPERMAN, Selmo Chapira; VIEIRA JUNIOR, Luiz Prado; INOUE, George; FERREIRA, Omar Vilela; MULATINHO, João B. "Análise Térmica de Estruturas de Concreto Compactado a Rolo", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.44 CARVALHO, Luiz Hernani de; QUIN, Jin Tien; REZENDE FILHO, Severino de Pereira. "Projeto do Maciço da Barragem Saco de Nova Olinda – PB", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.45 REZENDE FILHO, Severino De Pereira; CARVALHO, Luiz Hernani de; QUIN, Jin Tien. "Inspeção e Controle da Construção da Barragem Saco de Nova Olinda – PB" in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.46 VIVAN, Milton E. "Estudo Comparativo Entre Dois Critérios de Projeto de Barragens de Concreto Compactado a Rolo", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.47 SEGARRA, José F.; VELEDA, Carlos A.; LORENZO, Andrés; DADI, Jorge. "Proyecto Hidroeléctrico Urugua-i - Presa Principal De HCR - Criterios De Diseño", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.48 CARVALHO, Jorge Luiz Vieira. "Evolução do Concreto Compactado a Rolo em Barragens de Gravidade", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.49 GONÇALVES, Fábio Félix; FERREIRA, Maria Cecília N. F.; COSTA, Gilceu de Oliveira. "Emprego de Escória de Alto Forno, nos Estudos de Concreto Compactado a Rolo, Rico em Pasta, para a Barragem da UHE de Bocaina", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.50 QUIN, Jin Tien; CARVALHO, Luiz Hernani de; REZENDE Filho, Severino de Pereira. "Construção da Barragem Saco de Nova Olinda – PB", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.51 PICCOLI, Geraldo Moritz. "Subsídios para Implantação de Controle da Qualidade do CCR", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.52 "Roller Compacted Concrete", in: ACI Committee 207.5R/89.

89.53 ANDRIOLO, F. R. "General Report - TEMA I", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

89.54 ELETRONORTE. Centrais Elétricas do Norte do Brasil. *Concreto Compactado a Rolo - Estado Atual do Conhecimento*. Brasilia, Brazil: Departamento de Projetos e Construção, January 1989.

89.55 REZENDE, Paulo Fernando Vieira Souto. "Concreto Compactado a Rolo, Altenativa de Projeto Viável ou Não?", in: Proceedings of the XVIII Seminário Nacional de Grandes Barragens. Foz do Iguaçu, Brazil, April 1989.

1990

90.01 ARNOLD, T. and JOHNSON, D. "Monitoring and Instrumentation - Stagecoach RCC Dam", in: Proceedings, Seventh ASDSO Annual Conference, New Orleans. Lexington, Kentucky: Association of State Dam Safety Officials, October 1990.

90.02 "Big dam and tunneling job planned", in: Engineering News. New York: Record, March 1990. vol. 224, nº 12.

90.03 BINGHAM, W. B. and SCHWEIGER, P. G. "Rehabilitation of Saltlick Dam - A Case Study in Dam Rehabilitation", in: Proceedings, Seventh ASDSO Annual Conference, New Orleans. Lexington, Kentucky: Association of State Dam Safety Officials, October 1990.

90.04 BURKE, N. A. and WATT, D. H. P. "Beaulieu Dam - Spillway failure and repairs", in: Proceedings, Symposium on Dam Safety, "Four Years On", CSIR Conference Centre. Pretoria, South Africa, September 1990.

90.05 "California First", in: RCC Newsletter, PCA. Skokie, Illinois, Fall-Winter 1990.

90.06 CAMPBELL, D. B. "Stepped Spillways", in: RCC Newsletter, PCA. Skokie, Illinois, Fall-Winter 1990.

90.07 "Cement and Concrete Terminology", in: ACI 116 R - 90, Publication SP (90), ACI Committee 116, ACI. Detroit, 1990.

90.08 DUNSTAN, M. R. H. "RCC Dams", in: *Handbook 1990*. United Kingdom: International Water Power & Dam Construction, 1990.

90.09 DUNSTAN, M. R. H. "Review of Roller Compacted Concrete Dams in the 1980's", in: International Water Power & Dam Construction. United Kingdom, May 1990. vol. 42, nº 5.

90.10 "Failed dike replaced by RCC", in: *Engineering News*. New York: Record. February 8, 1990. vol. 224, nº 6.

90.11 FORREST, M. P. et al. "Quail Creek South Dam Cutoff", in: USCOLD Newsletter nº 91. Denver, March 1990.

90.12 GEHRING, D. "Quail Creek RCC Dam", in: Concrete International, ACI. Detroit, October 1990. vol. 12, nº 10.

90.13 HOLDERBAUM, T. W. and BINGHAM, W. P. "RCC for Pennsylvania Dam Rehab", in: RCC Newsletter. PCA. Skokie, Illinois, Fall-Winter 1990.

90.14 HOLLINGWORTH, F. and DRUYTS, F. H. W. M. "The Development of Rollcrete in South Africa", in: Proceedings, Concrete Society of Southern Africa: National Report to the 11th International Congress of the Federation Internationale de Ia Précontrainte (FIP). Hamburg, June 1990.

90.15 HOLLINGWORTH, F. "Rollcrete and dam safety. "*Proceedings*, Symposium on Dam Safety, "Four Years On", in: CSIR Conference Centre. Pretoria, South Africa, September 1990.

90.16 HOLLINGWORTH, F. "Rollcrete Dams", in: Proceedings, First National Symposium South African Ash Association, CSIR Conference Center. Pretoria, South Africa, May 1990.

90.17 HOLLINGWORTH, F. "South African Experience on Roller Compacted Dams", in: Proceedings, Course on roller compacted concrete dams. Santander, Spain: Instituto Español del Cemento y sus Applicaciones, May 1990.

90.18 JACKSON, H. E.; FORREST, M. P. and HANSEN, K. D. "Rebuilding Quail Creek Dike with RCC", in: Proceedings, Seventh ASDSO Annual Conference, New Orleans. Lexington, Kentucky: Association of State Dam Safety Officials, October 1990.

90.19 KURAKINA, E. V.; SUDAKOV, V. B. and SHANGIN, V. S. "Design and Construction of the Tashkumyr RCC Dam, USSR", in: International Water Power & Dam Construction. United Kingdom, May 1990. vol. 42, nº 5.

90.20 LEMONS, R. M.; KING, J. R. and RUTLEDGE, J. R. "Rehabilitation of Dams for Planned Overtopping", in: Proceedings, Seventh ASDSO Annual Conference, New Orleans. Lexington, Kentucky: Association of State Dam Safety Officials, October 1990.

90.21 MANSON, H. A.; NEWELL, V. A. and WAGNER, C. D. "Dam Safety Rehabilitation of Nickajack Dam", in: USCOLD Newsletter nº 93. Denver, November 1990.

90.22 MASS, G. R. "Computers and Concrete Produce a Fine Mix", in: Concrete International, ACI. Detroit, February 1990. vol. 12, nº 2.

90.23 "Project Updates", in: *Handbook 1990.* United Kingdom: International Water Power & Dam Construction, 1990.

90.24 ROBERTSON, J. O. et al. Discussion on "Knellpoort Dam: The World's first Rollcrete Arch/Gravity Dam", in: The Civil Engineer in South Africa. Johannesburg: South African Institute of Civil Engineers, September 1990. vol. 32, nº 9.

90.25 "Rollcrete dam on schedule for September handover", in: South African Construction World, Phase Four (Pty)Ltd. Sandton, April 1990.

90.26 "Roller Compacted Concrete Above and Below", in: RCC Newsletter, PCA. Skokie, Illinois, Spring/Summer 1990.

90.27 SAUCIER, K. L. "Placing Specialized Concrete", in: Concrete International, ACI. Detroit, June 1990. vol.12, nº 6.

90.28 SCOTT, G. A. "Deformation of Rock Foundations Under Dams", in: Dam Foundation Engineering, Tenth Annual USCOLD Lecture, U.S. New Orleans: Committee on Large Dams, March 1990.

90.29 SHAW, Q. H. W. "Quality control standards for the construction of Rollcrete dams", in: Proceedings, Symposium on Dam Safety, "Four Years On", CSIR Conference Centre. Pretoria, South Africa, September 1990.

90.30 SHAW, Q. H. W. "The quality control of rollcrete placed at the Wolvedans arch-gravity dam", in: The Civil Engineer in South Africa, South African Institute of Civil Engineers. Johannesburg, September 1990. vol. 32, nº 9.

90.31 "Upper Michigan Dam Rehabilitated with RCC", in: RCC Newsletter, PCA. Skokie, Illinois, Spring/Summer 1990.

90.32 "Willow Creek Dam, Seepage Investigations and Dam Safety Review", in: Special Report, U.S. Army Corps of Engineers. Portland District, February 1990.

90.33 "World News - Capanda RCC Dam may be stopped", in: International Water Power & Dam Construction. United Kingdom, January 1990. vol. 42, nº 1.

90.34 VASKOV, Sam. "Rehabilitating Santa Cruz Dam", in: Rocky Mountain Construction. May 1990.

1991

91.01 AOYAGI, Y. and ENDO, T. "Laboratory and Field Tests on Roller Compacted Concrete Materials with Particular Reference to Increased Use of Fly Ash", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.02 BACCINI, S. et al. "Roller Compacted Concrete Dam of Conception, Honduras", in: IDRO TECNICA -L'Acqua Nell' Agricoltura, Nell' Igiene, Nell' Industria. Consiglio Nazionale delle Ricerche. Milano, Italy, March-April 1991. nº 2.

91.03 BAKANOVICHUS, S. A. et al. "Important Strength Deformation and Shear Characteristics of Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.04 BINGHAM, W. B. "Roller Compacted Concrete for Dam Rehabilitation", in: Proceedings, Eigth ASDSO Annual Conference, San Diego. Association of State Dam Safety Officials. Lexington, Kentucky, 1991.

91.05 BOUYGE, B. and MARTIN, J. P. "Economy and Quality in RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.06 BUCHAS, J. and BUCHAS, F. "Applications of Roller Compacted Concrete Dams in Argentina", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.07 BUCHAS, J. and BUCHAS, F. "Argentina plans second generation of rcc dams", in: International Water Power & Dam Construction. United Kingdom, April 1991. vol. 43, nº 4.

91.08 CATANACH, R. B. et al. "Quail Creek Dike Failure, Failure Mechanisms, Redesign and Construction", in: Transactions, Seventeenth International Congress on Large Dams Q66. Vienna, June 1991. vol. III.

91.09 CHRAIBI, A. F. and BZIOUI, M. "Moroccan Experience in RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.10 CHRAIBI, A. F. and STERENBERG, J. "Design and construction of Morocco's Aoulouz rcc dam", in: International Water Power & Dam Construction. United Kingdom, March 1991. vol. 43, nº 3.

91.11 "Comments on Concrete Durability", in: Transactions, Seventeenth International Congress on Large Dams Q67. Vienna, June 1991. vol. W C18.

91.12 "Dances with wolves", in: *Water,* House Journal of the Department of Water Affairs. Pretoria, South Africa, October 1991.

91.13 DENIS, B. et al. "French Approach to Thermo-Mechanics in RCC Dams Experimental Application to the Riou Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.14 DIEZ-CASCON, J. et al. "Studies on the hydraulic behavior of stepped Spillways", in: International Water Power & Dam Construction United Kingdom, September 1991. vol. 43, nº 9.

91.15 DOLEN, T. P. and FAY, K. F. von. "The Development of Roller Compacted Concrete Mixtures for the Bureau of Reclamation Mass Concrete Construction", in: Robert Philleo Symposium. Dallas, Texas: American Concrete Institute Fall Convention, November 1991.

91.16 DOLEN, T. P. "Freezing and Thawing Durability of Roller Compacted Concrete", in: Second CANMET/ACI International Conference on the Durability of Concrete. Montreal, August 1991.

91.17 DOLEN, T. P. "Mixture Proportioning Concepts and Quality Control for RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.18 DONG, Fupin. et al. "Elasto - Creeping Thermal Stress Analysis of Roller Compacted Concrete Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.19 DUNSTAN, M. R. H. "RCC Dams", in: *Handbook 1991*. International Water Power & Dam Construction. United Kingdom, 1991.

91.20 DUNSTAN, M. R. H.; WARK, R. J. and MANN, G. B. "New Victoria Dam – Western Australia", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.21 DUNSTAN, M. R. H. "The 1980's - The Decade During Which the Roller Compacted Dams Came of Age", in: 1990 Conference on Dams in Perth, ANCOLD Bulletin nº 87. Melbourne, Australia, April 1991.

91.22 EZZAT, H. M. and CRISWELL, M. E. "Roller Compacted Concrete Behavior and Seepage Control Characteristics", in: Proceedings, Eighth ASDSO Annual Conference, San Diego. Association of State Dam Safety Officials. Lexington, Kentucky, 1991.

91.23 KUNHE, Fang and LI, Zeng. "An Investigation in Fly Ash Content of Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.24 KUNHE, Fang. "The Judgement of the Setting State for Fresh Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.25 FASSO, C. A.; SIVIERO, A. and VITALIANI, R. "Thermal Analysis of RCC Dams - A Comparison of Two Numerical Methods", in: IDRO TECNICA -L'Acqua Nell' Agricoltura, Nell' Igiene, Nell' Industria. Consiglio Nazionale delle Ricerche. Milano, Italy, March-April 1991. nº 2.

91.26 DABIN, Feng. "The RCC Cofferdam for Yantan Hydroelectric Project", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.27 FORBES, B. A.; GILLON, B. R. and DUNSTAN, T. G. "Cooling of RCC and Construction Techniques Adopted for Victoria Dam, Australia", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.28 FROEHLICH, D. R. and NIGUS, L. A. "Ashton Hydroelectric Project Rehabilitation", in: Proceedings of Water Power '91, the International Conference on Hydropower, ASCE. New York, July 1991. vol. 3.

91.29 GEHRING, D. "Dam - something new!", in: Southwest Contractor. McGraw-Hill. Phoenix, Arizona, September 1991. vol. 54, nº 2.

91.30 GINZBURG, S. M. et al. "Selection of Temperature Control Parameters for Roller Compacted Concrete Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.31 GIOVAGNOLI, M.; SCHRADER, E. and ERCOLI, F. "Design and Construction of Concepcion Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.32 GUIZHEN, Guan and HONGPENG, Zhang. "Research on Adjustment of Sand Fineness with Powdered Tailings", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.33 GUPTA, P. N. and LE MOIGNE, G. "Developments in Roller Compacted Concrete Dams - Some Relevant Questions and Other Items for General Acceptability", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.34 HANSEN, K. D. and REINHARDT, W. C. "Roller Compacted Concrete. McGraw-Hill". New York, 1991.

91.35 HANSEN, K. D. "Advantages of Roller Compacted Concrete Dams", in: RCC Newsletter, PCA. Skokie, Illinois, Spring-Summer 1991. vol. 7, nº 1.

91.36 HINKS, J. L.; COPLEY, A. F. and DUNSTAN, M. H. R. "Thermal Modeling for RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.37 SHUPING, Huang and BAOYING, Ding. "A Study of Thermal Creep Stress Between RCC Lifts", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.38 XUTONG, Huang and HONGWEI, Yang. "On Interlayer Bond and Construction Quality Monitoring Method of Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering Beijing. China, November 1991.

91.39 XUTONG, Huang. "Investigation on Physical and Mechanical Properties of Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.40 IIDA, R. "Comment: Development of RCD construction method in Japan", in: International Water Power & Dam Construction. United Kingdom, November 1991. vol. 43, nº 11.

91.41 IISAKA, T.; SUSUKI, N. and WEIGANG, Wu. "On the Material Injected in Cracking of Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.42 JANSEN, A.; FROUIN, A. and BOUYGE, B. "Adapting an RCC Dam to Site Conditions: La Borie Dam Project", in: Transactions, Seventeenth International Congress on Large Dams. Vienna, June 1991. vol. IV, C12.

91.43 FUTIAN, Jiang. "Relationship Between the Properties of RCC and Vibratory Characteristics of Vibrating", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering Beijing, China, November 1991.

91.44 "Job halted, but not debated", in: Engineering News. New York: Record, February 1991. vol. 226, nº 5.

91.45 "Kakamas is nie meer 'n eedjie nie", in: *Water,* House Journal of the Department of Water Affairs. Pretoria, South Africa, April 1991.

91.46 KOGAN, E. A. and SIKACHEV, K. G. "The Elasticity and Creep Characteristics of Roller Compacted Concrete for the Katun Hydropower Station Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.47 KOLLGAARD, E. B. and JACKSON, H. E. "Design and Construction of Quail Creek South Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.48 LANDAU, Yu. A. and MGALOBELOV, Yu. B. "Structural Decisions and Peculiarities of Static Work of RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.49 CHENGQUIAN, Li and CHUSHENG, Cao. "A Small Naked Freeze-Resistance RCC Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.50 DONGSHENG, Li; FENGGE, Sun and YANWEN, Yun. "The Structural Design and Tests for the RCC Dam of Linjiang Hydropower Station", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.51 EDING, Li. "Comment: New development in rcc dams to be discussed at Beijing symposium", in: International Water Power & Dam Construction. United Kingdom, November 1991. vol. 43, nº 11.

91.52 GUOREN, Li. "On the temperature Control for High RCC Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.53 XIQI, Li. "Development of Nuclear Density Gauge and Sand Moisture Compensation System and Their Application", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.54 YOUCHANG, Lin; JIALI, Huang and YANJI, Huang. "The Technique on RCC Dam Construction of Yantan Project", in: Proceedings Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.55 LIU, T. C. "Performance of Roller-Compacted Concrete - Corps of Engineers' Experience", in: Proceedings, Second International Conference on Durability of Concrete, ACI SP-126. Detroit, 1991.

91.56 XIAOYAN, Liu and QIZUO, Dai. "Mix Design and Properties of the Finest-Sand RCC of Mahui Hydropower Station", in: Proceedings, Symposium on RCC Dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.57 LORENZO, A. C. and CALIVARI, S. S. "Behavior of Urugua-I Dam", in: Proceedings, Symposium on RCC Dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.58 MINGKUAN, Mao and YUNXIN, Zhu. "Research on Placing RCC with Vacuum Flume Chute Combination System", in: Proceedings, Symposium on RCC Dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.59 MINGKUAN, Mao. "Study of Mechanism of RCC Vibration Compaction", in: Proceedings, Symposium on RCC Dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.60 MCINTYRE, W. "Dam in a desert completed", in: Rocky Mountain Construction. Denver, November 4,1991. vol. 72, nº 2.

91.61 "Miyagase Dam to employ innovative RCD methods", in: International Water Power & Dam Construction. United Kingdom, November 1991. vol. 43, nº II.

91.62 MONARI, F. and SCUERO, A. M. "Aging of concrete dams: the use of geocomposites for repair and future protection", in: Transactions, Seventeenth International Congress on Large Dams Q 65. Vienna, June 1991. vol. II.

91.63 OOSTHUIZEN, C. "The use of field instrumentation as an aid to determine the behaviour of roller compacted concrete in an arch gravity dam", in: Proceedings, Third International Symposium on Field Measurements in Geomechanics. Oslo, Norway, September 1991.

91.64 *Engineering News*. New York: Record, September 1991. vol. 227, nº 9.

91.65 ZHUGUANG, Ou and Jiang Futian. "Study on the Vibro-Compacted Mechanism of RCC. ", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.66 PAK, A. P.; TRAPEZNIKOV, L. P. and YUDELEVICH, A. M. "Determination of Tensile Strength of Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.67 RICHARDSON, A. T. "Performance of Upper Stillwater Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.68 "Ryumon composite dam uses lifting bridges for RCD placement", in: International Water Power & Dam Construction. United Kingdom, November 1991. vol. 43, nº 11.

91.69 SANCHEZ, R. "Gibraltar Dam - Roller Compacted Concrete Buttress Construction", in: Proceedings, Eight ASDSO Annual Conference, San Diego. Association of State Dam Safety Officials, Lexington, Kentucky, 1991.

91.70 CHONGGANG, Shen and DUNSTAN, M. R. H. "The Development of RCC Dams throughout the World", in: Proceedings, Symposium on RCC dam sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.71 CHONGGANG, Shen. "Roller compacted concrete dams in China", in: International Water Power & Dam Construction. United Kingdom, November 1991. vol. 43, nº 11.

91.72 SMOAK, W. G. "Crack Repairs to Upper Stillwater Dam", in: Concrete International, ACI. Detroit, February 1991. vol. 13, nº 2.

91.73 STEFANAKOS, J. et al. "Plantanovryssi HEP - Design Considerations", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.74 STEPHENSON, D. "Energy dissipation down stepped spillways", in: International Water Power & Dam Construction. United Kingdom, September 1991. vol. 43, nº 9.

91.75 STERENBERG, J. "Reflections on the Use of RCC for Gravity Dams", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.76 SUDAKOV, V. B. et al. "RCC Method for the Tashkumyr Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.77 SUZUKI, N.; LISAKA, T. and WEIGANG, Wu. "On Characteristics of the RCD Construction Method", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.78 SHUNRU, Tang. "Testing Lateral Pressure on Form of RCC", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.79 MINISTRY OF CONSTRUCTION. *The RCD Construction Method in Japan 1991*. Kasumigaseki, Chiyoda – ku, Tokyo, March 1991.

91.80 TOYODA, T. et al. "The Latest Situation of Rationalized Construction Methods for Concrete Dams in Japan", in: Transactions, Seventeenth International Congress on Large Dams. Vienna, June 1991. vol. IV, C9.

91.81 TOYODA, T.; SAKANISHI, T. and KOBAYASHI, Y. "A study of Labor-Saving Form Erection Method for Concrete Dam Construction", in: Transactions, Seventeenth International Congress on Large Dams. Vienna, June 1991. vol. IV, C2.

91.82 TRAPEZNIKOV, L. P.; RUKAVISHNIKOVA, T. N. and LEONOVA T. A. "Investigations of Thermal Stress State and Thermal Crack Resistance in RCC Dam Construction", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.83 "Upper Stillwater cracking no threat, says BuRec", in: Engineering News. New York: Record, September 1991. vol. 227, nº 10.

91.84 BAILE, Wang et al. "Structure Design of the Puding RCC Arch Dam and Its Temperature Control", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.85 HONGSHUO, Wang. "On the Types and Their Applicable Conditions of RCCD", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.86 SHENGPEI, Wang. "Development of Dam Construction Using Rollcrete Technology in China", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.87 ZUXIAN, Wang; YICHING, Shen and YONGJIE, Liu. "Design and Test of the RCC Mix Applied in the Cold-Climate Region", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.88 WARK, R. J.; KERBY, N. E. and MANN, G. B. "New Victoria Dam Project", in: Presented at the 1990 Conference on Dams in Perth, ANCOLD Bulletin nº 88. Melbourne, Australia, August 1991.

91.89 DAZHI, Wei et al. "RCC Dam Construction of Tongjiezi Hydroelectric Project", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.90 "World News - workers killed at Capanda Dam", in: International Water Power & Dam Construction United Kingdom, June 1991. vol. 43, nº 6.

91.91 SHENGGUANG, Wu. "Calculations on the shear Resistance Between RCC layers", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.92 GAOMEN, Xiao and XIAOXIAN, Zeng. "RCC Mix Design and Application to the Shuikou Project Diversion Wall", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.93 DEJIN, Xie and LINSEN, Wu. "Design of Roller Compacted Concrete (RCC) Cofferdams and Part of Main Dam for Yantan Hydroelectric Station", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.94 DONGLIN, Xie. "Properties of Tuff Roller Compacted Concrete", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.95 CHENGQIU, Yang. "Studies of the Properties of Roller Compacted Concrete with Full Aggregates", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.96 KANGNING, Yang and RUN, Liang. "Design Unit Weight and Construction Quality Control of RCCD", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society Hydroelectric Engineering. Beijing, China, November 1991.

91.97 QUANMIN, Yang; ZHENTIAN, Sun and PURONG, Ding. "Impervious elements of RCCD", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society Hydroelectric Engineering. Beijing, China, November 1991.

91.98 YUMING, Yan. "Construction and Operation of Two RCC Dams in Fujian", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society Hydroelectric Engineering. Beijing, China, November 1991.

91.99 YUNXIANG, Yang. "RCC Construction of Re-Regulation Dam of Lower Reservoir on Panjiakou Pumped-Storage Station", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.100 YUNXIANG, Yang. "RCC Construction on Wan'an Hydropower Station", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society Hydroelectric Engineering. Beijing, China, November 1991.

91.101 YUNXIANG, Yang. "RCC Construction Practice on Tianshengqiao-II Hydropower Station Main Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.102 XIANKANG, Zeng. "The Application & Development of Solid RCC Dam Technology in Fujian Province of the P.R.C", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering Beijing, China, November 1991.

91.103 GUOXIN, Zhang and GUANGTING, Liu. "Fracture Problem of Multiple Crack Body Under Harmonic Thermal Load and the Stability of Cracks in RCAD", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.104 MINGXIAN, Zhang. "A Construction of RCC Arch Gravity Cofferdam for Yantan Hydroelectric Project", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.105 ZHONGQING, Zhang. "Shape Design and Stress Analysis of RCC Arch Dam", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectrical Engineering. Beijing, China, November 1991.

91.106 ZHI, Zhang; RONSHUA, Lin and Liu FUMING,. "Seepage Prevention Structures at Two RCC Dams in China", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.107 MEIJUAN, Zhao; RONGMIN, Wu and JIANGSHU, Zhang. "Design and Construction of RCC Diversion Wall for Shuikou Project", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.108 SHOUXIAN, Zhou; YALI, Kwang and ZHENSHUN, Xiao. "Study on High Mixture RCC", in: Proceedings, Symposium on RCC dams sponsored by the Chinese Society of Hydroelectric Engineering. Beijing, China, November 1991.

91.109 BRAGA, J. A.; ROSARIO, L. C.; ANDRIOLO, F. R. "Efeito da Revibração nos Concretes Massa e Rolado", in: Proceedings of the XIX Seminário Nacional de Grandes de Barragens. Aracaju, Brazil, March 1991.

91.110 BRAGA, J. A.; ZANELLA, M. R.; ZALESKI, J. M.; ANDRIOLO, F. R. "Uso do Concreto Rolado - Projeto Capanda (Angola) - Ensaios Especiais", in: Proceedings of the XIX Seminário Nacional de Grandes de Barragens. Aracaju, Brazil, March 1991.

91.111 ANDRIOLO, F. R "Desenvolvimento de mantas de P.V.C. - Opção Técnica e Econômica para Impermeabilização de barragens", in: Proceedings of the XIX Seminário Nacional de Grandes de Barragens. Aracaju, Brazil, March 1991.

91.112 "Recommended Practice for Selecting Proportions for No-Slump Concrete", in: ACI Committee 211.1/91.

91.113 "Dams in Japan", in: Japanese National Committee on Large Dams. 1991, nº 12.

91.114 GEHRING, Don. "Conveyor System Speeds RCC Dam Construction", in: Concrete Construction. November 1991.

91.115 MCINTYRE, Wade. "Dam in a Desert Completed", in: Rocky Mountain Construction. November 1991.

91.116 BACCINI, Saverio; CARCAMO, Julio; ERCOLI, Franco; GIOVANOI, Mauro. "Roller Compacted Concrete Dam of Concepcion- Honduras", in: Projects and Works. Idrotecnica, March/April 1991.

91.117 SNYDER, Guy. "Roller Compacted Concrete Aids Reconstruction of Victoria Dam", in: Michigan Contractor and Builder. November 1991.

91.118 "ETL nº 1110-2-343", in: Roller Compacted Concrete- Corps of Engineers US Army District. Portland, Oregon.

1992

92.01 ALLEN, J. C. "RCC Dam Construction - A Contractor's View", in: Roller Compacted Concrete II. Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

92.02 FRANCO, Alonso M. and COROVA, J. Yägue. "The development of dam construction in Spain", in: International Water Power & Dam Construction. United Kingdom, September 1992. vol. 44, nº 9.

92.03 ANDRIOLO, F. R. and SCHMIDT, M. T. "The Capanda RCC dam in Angola", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.04 ARNOLD, T. E.; FELDSHER, T. B. and HANSEN, K. D. "RCC Test Specimen Preparation - Developments Toward a Standard Method", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.05 ARNOLD, T. E. and JOHNSON, D. R. "RCC Dam Design Concepts versus Construction Conditions for Stagecoach Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.06 BARRET, P. R. et al. "Thermal-Structural Analysis Methods for RCC Dams", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.07 BUCHAS, J. and BUCHAS, F. "Construction of Urugua-I RCC Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference San Diego, California. ASCE. New York, February, 1992.

92.08 "Conference Report: International Symposium on RCC dams", in: International Water Power & Dam Construction United Kingdom, February 1992. vol. 44, nº 2.

92.09 "Directory of Computer Programs in Use for Dam Engineering in the United States", in: United States Committee on Large Dams (USCOLD). Denver, Colorado, July 1992.

92.10 DITCHEY, E. J. "Rehabilitating Small Earth Embankments with RCC", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.11 DUNSTAN, M. R. H. "A Review of Design Criteria for High RCC Dams", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.12 DUNSTAN, M. R. H. "RCC Dams", in: *Handbook 1992*. International Water Power & Dam Construction. United Kingdom, 1992.

92.13 DUNSTAN, M. R. H. "Use of Pozzolans in RCC Dams", in: Advances in Concrete Technology Proceedings of the Conference in Athens, Greece. CANMET, Energy, Mines and Resources, Ottawa, May 1992.

92.14 DUSSART, J.; DESCHARD, B. and PENEL, F. "Petit Saut: an RCC Dam in a wet tropical climate", in: International Water Power & Dam Construction United Kingdom, February 1992. vol. 44, nº 2.

92.15 FORBES, B. A.; CROQUEVIELLE, D. and ZABALETA, H. "Design and Proposed Construction Techniques for Panque Dam", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference, San Diego, California. ASCE, New York, February 1992.

92.16 FRIZELL, K. H. "Hydraulics of Stepped Spillways for RCC Dams and Dam Rehabilitations", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.17 GAEKEL, L. and SCHRADER, E. "RCC Mixes and Properties Using Poor Material - Concepcion Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.18 GERINGER, J. J. "Rollcrete techniques unique to SA make Wriggleswade a winner", in: The Civil Engineer in South Africa, South African Institute of Civil Engineers. Johannesburg, January 1992. vol. 34, nº 1.

92.19 GIOVAGNOLI, M.; ERCOLI, F. and SCHRADER, E. "Concepcion Dam Design & Construction Problems and Their Solution", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.20 GIOVAGNOLI, M.; SCHRADER, E. and ERCOLI, F. "Concepcion Dam: a practical solution to RCC problems", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44. nº 2.

92.21 GOMEZ LAA, G. "Roller compacted concrete dams in Spain", in: International Water Power & Dam Construction. United Kingdom, September 1992. vol. 44, nº 9.

92.22 GOUBET, A. and GUÉRINET, M. "Experience with the construction of the Riou Dam", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.23 HANSEN, K. D. "RCC for Rehabilitation of Dams in the USA - An Overview", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California ASCE. New York, February 1992.

92.24 HANSEN, K. D. "Roller - Compacted Concrete for Overtopping Protection of Embankment Dams", in: Modification of Dams to Accept Major Floods, Twelfth Annual USCOLD Lecture Series. Fort Worth, Texas, April 1992.

92.25 HANSEN K. D. and MCLEAN, F. G. (eds.). "Roller Compacted Concrete III", in: Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.26 HOLLINGWORTH, F. and GERINGER, J. J. "Cracking and Leaking in RCC Dams", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.27 HOLLINGWORTH, F. and GERINGER, J. J. "Roller Compacted Concrete Arch/Gravity Dams – South African Experience", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.28 HOPMAN, R. D. "Lessons Learned from Elk Creek Dam", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference. San Diego, California. ASCE. New York, February 1992.

92.29 IFFLA, J. A.; MILLMORE, J. P. and DUNSTAN, M. R. H. "The use of RCC for small flood alleviation dams in the UK", in: International Water Power & Dam Construction United Kingdom, February 1992. vol. 44, nº 2.

92.30 JOHNSON, D. L.; SKERMER, N. A. and BERGSTROM, F. "Roller Compacted Concrete Tailing Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.31 LEMONS, R. M. "Concrete-Faced RCC Dams", in: Roller Compacted Concrete III Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.32 LONDE, P. and LINO, M. "The faced symmetrical hardfill dam: a new concept for RCC", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.33 LORENZO, A. C. and CALIVARI, S. S. "Behavior of Urugua-I Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California, ASCE. New York, February 1992.

92.34 MAROLD, W. J. "Design of the Boney Falls RCC Emergency Spillway", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE, New York, February 1992.

92.35 MARULANDA, A. et al. "Design of Miel II - A High RCC Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.36 HANG, Ma Zhong; HEMING, Cai and KOLLGAARD, E. B. "The Design and Construction of Shuikou Project RCC Diversion Wall", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.37 METCALF, M. et al. "Santa Cruz Dam Modification", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.37 "Near-Record 16 Projects Entered in Race for Outstanding CE Achievement Crown for 1992", in: ASCE News. New York,, March 1992. vol. 17, nº 3.

92.39 "News: RCC Conference Traces Decade of Progress", in: Civil Engineering ASCE. New York, April 1992. vol. 62, nº 4.

92.40 OSIPOV, A. D. et al. "Rolled Concrete Having High Strength, Frost Resistance, and Waterproofness", in: Russian Journal of Hydraulic Structures, Gidrotekhnicheskoe Stroitelstvo. Moscow, July 1992.

92.41 OURY, R., and SCHRADER, E. "Mixing and Delivery of Roller Compacted Concrete", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.42 PARKER, J. W. "Economic Factors in Roller Compacted Concrete Dam Construction", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.43 "Post-symposium tour to Fujian province", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.44 "Project Updates", in: Handbook 1992. International Water Power & Dam Construction. United Kingdom, 1992.

92.45 RAPHAEL, J. M. "The Optimum Gravity Dam and Discussion by R. E. Davis", in: Roller Compacted Concrete III, Proceedings of the RCC Specialty Conference, San Diego. California. ASCE. New York, February 1992.

92.46 RICHARDSON, A. T. "Performance of Upper Stillwater Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.47 "Roller-Compacted Concrete, Engineering and Design", in: EM 1110-2-2006, US Army Corps of Engineers. Washington D.C., February 1992.

92.48 SCHRADER, E. K. "Roller Compacted Concrete for Dams: The State-of-the-Art", in: Advances in Concrete Technology, Proceedings of the Conference in Athens, Greece. CANMET, Energy, Mines and Resources, Ottawa, May 1992.

92.49 SEXTON, D. L., et al. "Design of Pena Colorada Tailings Retention Dam", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.50 STERENBERG, J. "The RCC technique: a perfect integration in the field of gravity dams", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol. 44, nº 2.

92.51 TATRO, S., and HINDS, J. K. "Roller Compacted Concrete Mix Design", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.52 TATRO, S., and SCHRADER, E. "Thermal Analysis of RCC - A Practical Approach", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.53 WARK, R. J., and MANN, G. B. "Design and construction aspects of New Victoria dam", in: International Water Power & Dam Construction. United Kingdom, February 1992. vol.44, nº 2.

92.54 WARK, R. J., et al. "The Construction of New Victoria Dam, Australia", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.55 WONG, N. C., et al. "Final Design and Construction of Gibraltar Dam Strengthening", in: Roller Compacted Concrete III. Proceedings of the RCC Specialty Conference, San Diego, California. ASCE. New York, February 1992.

92.56 GAMBALE, E. A.; FONTOURA, J. T. F.; GUEDES, Q. M.; ANDRADE, W. P. "A Resolução Numérica do Modelo Viscoelástico Linear com Envelhecimento do Concreto e sua Aplicação no Cálculo das Tensões de Origem Térmica em Barragens de CCR", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.57 HOLANDA, F. G.; BANDEIRA, O. M.; MENDONÇA, J. E. F.; SUASSUNA F. L. "Aterro Teste de Concreto Compactado a Rolo (CCR) para a UHE Xingó", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.58 HOLANDA, F. G.; CARVALHO, J. L. V.; BANDEIRA, O. M.; MENDONÇA J. E. F.; SUASSUNA F. L. "Concreto Compactado a Rolo - Aplicação sob o Salto de Esqui do Vertedouro da Obra da UHE Xingó", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.59 GOLIK, M. A. "Concreto Compactado a Rolo - Aproveitamento Hidrelétrico do rio Zamora – Equador", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.60 HOLANDA, F. G. "Concreto Compactado a Rolo - Uma Realidade Brasileira", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.61 GOLIK, M. A.; ANDRIOLO, F. R. "Desempenho da Membrana de PVC da Barragem de Urugua –i", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.62 HOLANDA, F. G.; BANDEIRA, O. M.; MENDONÇA, J. E. F.; SUASSUNA F. L. "Estudos de dosagens de concreto compactado a rolo para a UHE Xingó", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.63 SILVA, S. A.; HOLANDA, F. G.; BANDEIRA, O. M.; CAVALCANTI, A. J. C.T.; SUASSUNA F., L.; SOUZA, R. J. B. "Maciço Galgável da Barragem de Enrocamento da UHE Xingó – Proteção com CCR", in: Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazil, November 1992.

92.64 GUERRA, E. A.; CARMO, J. B. M.; NASCIMENTO, J. F. F.; FONTOURA, J. T. F.; ANDRADE, W. P. "Pesquisas de Concreto Compactado a Rolo para o Aproveitamento Hidroelétrico de São Felix – Usina Serra da Mesa e Cana-Brava" Proceedings of the XX Seminário Nacional de Grandes Barragens. Curitiba, Brazi, November 1992.

92.65 BINGHAM, William B.; HOLDERBAUM, Rodney E. "Siegrist Dam", in: RCC Newsletter, 1992.;

92.66 PRENDERGAST,John. "RCC At 10", in: Civil Engineering. October 1992.

92.67 ANDRIOLO, F. R.; SCHMIDT, M. T. "The Capanda RCC Dam in Angola", in: International Water Power & Dam Construction. February 1992.

92.68 "ACI Manual of Concrete Inspection- Publication SP 2(92)- ACI Committee 311" August 1992.

1993

93.01 "ACI Manual of Concrete Practice", in: ACI. Detroit, March 1993.

93.02 DUNSTAN, M. R. H. "RCC Dams (>25m)", in: Handbook 1993. International Water Power & Dam Construction. United Kingdom, 1993.

93.03 HILLEBRENNER, G. *Roller - Compacted Concrete Dams*. Davis' Handbook of Applied Hydraulics. New York: McGraw-Hill, Inc., 1993.

93.04 MACLEAN, F. G. and HANSEN, K. D. "Roller Compacted Concrete for Embankment Overtopping Protection", in: Geotechnical Practice in Dam Rehabilitation., Geotechnical Special Publication nº 35, Proceedings of the Geotechnical Engineering Divison of ASCE. Raleigh, North Carolina, April 1993.

93.05 SKERMER, N. A.; JOHNSON, D. L. and HANSEN, K. D. "Homer Hadley and the Conception of the RCC Dam - An Historical Note", in: Geotechnical News. Vancouver, British Columbia, June 1993. vol. 11, nº 2.

93.06 "Structural Design Using the Roller-Compacted Concrete (RCC) Construction Process", in: Engineer Technical Letter nº 1110-2-343, US Army Corps of Engineers. Washington DC, May 1993.

93.07 ZIPPARRO, V.J., and HASEN, H. (editors). *Davis' Handbook of Applied Hydraulics*. Fourth Edition, New York: McGraw-Hill, 1993.

93.08 SERT, Steve. "Construction of Marmot RCC Dam", in: Concrete International. August, 1993.

93.09 PACELLI, W. A.; ANDRIOLO, F. R.; SARKARIA, G. S. "Treatment and Performance of Construction Joints in Concrete Dams", in: Water Power & Dam Construction. November 1993.

93.10 SCHRADER, E. K. "Design and Facing Options for RCC on Various Foundations", in: Water Power & Dam Construction. February 1993.

93.11 VAZOUEZ E. "The First Application of RCC in Cuba", in: Water Power & Dam Construction. February 1993.

1994

94.01 MARCHETTI, C. G.; CAVALCANTI, A. J. C.T.; ALENCAR, G. P. R. "Utilização de CCR na UHE Xingó", in: Proceedings of the XXI Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, Dezembro 1994.

94.02 OLIVEIRA, P. J. R.; SALLES, F. M.; ANDRIOLO, F. R. "Solo - Aglomerante - Disponibilidade para Uso como Elemento Estrutural em Barramentos", in: Proceedings of the XXI Seminário Nacional de Grandes Barragens. Rio de Janeiro, Brazil, Dezembro 1994.

94.03 JAPANESE NATIONAL COMMITTEE ON LARGE DAMS. *Dams in Japan.* nº 13. 1994

94.04 FRENCH COMMITTEE ON LARGE DAMS. *Dam Professionals in FRANCE.* 1994.

94.05 SCHMIDT, M. T.; CHAGAS, L. R.; ANDRIOLO, F. R. "RCC: A Construction Technique with Economic and Planning Advantages (Staged Cosntruction)", in: Proceedings of the XVIII ICOLD Congress of large Dams. Durban, South Africa, November 1994.

94.06 YAMAZUMI, A.; HARITA, K.; TANAKA, Y.; JIKAN, S. "Long Layer Performance by the Plane Construction Method-No oint 170m Layers by the RCD Method", in: Proceedings of the XVIII ICOLD Congress of large Dams. Durban, South Africa, November 1994.

94.07 HANSEN, Kenneth D. "Built in the USA-RCC Dams of the 1990's", in: International Water Power & Dam Construction. April 1994.

94.08 AMERICAN CONCRETE INSTITUTE *Quality Assurance in Concrete Construction.* Compilation 16.

1995

95.01 ANDRIOLO, F. R. "RCC Propenties", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.02 KREMPEL, A. F; ANDRIOLO, F. R. "High paste content and low cement mixes, finely crushed rock, specific gravity, compacting ratio, low cost... Discussions and values obtained", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.03 KREMPEL, A.; CREVILARA, C.; HOLANDA F. G. "Jordão River derivation dam. Study of RCC mixes design with low cement content", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.04 KREMPEL, A. F.; ANDRIOLO, F. R. "The use of basaltic crushed powder filler in the RCC", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.05 OLIVEIRA, P. J.; SALLES, F. M.; ANDRIOLO, F. R. "Crushed powder filler. The use on RCC and the reduction of expansion due to the alkali-aggregate reaction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.06 OLIVEIRA, P. J.; SALLES, F. M.; ANDRIOLO, F. R. "Soils & cementitious materials. A technical option for use as a structural element for dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.07 OLIVEIRA, P. J.; SALLES, F. M.; ANDRIOLO, F. R. "Studies of various types of RCC mix designs. Laboratory test results", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.08 ROBITAILLE, F.; BEAULIEU, J. " Lake Robertson dam: construction techniques and RCC properties", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.09 LI, Zeng; KUNHE, Fang "The setting state of RCC and the control of binding quality between the layers", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.10 SHOUXIAN, Zhou; HUAQUAN, Yang ; YALI, Kuang. "Properties of low portland cement clinker content RCC", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.11 TEJADA, L. C. "Roller compacted concrete mix design for Porce II dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.12 GUIRAUD, P. "Barlac: a hydraulic binder adapted to roller compacted concrete", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.13 KHANH, M. Ho Ta; DELORME, F.; VALON, R. "RCC laboratory tests: experience acquired in the past ten years and new developments", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.14 OMRAN, M. E.; NAYAK, G. C.; JAIN, S. C. "Experimental studies on roller compacted concrete for dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.15 NAGAYAMA, I.; WATANABE, K.; NIITAKA Y. "A study on the compactation mechanism of RCD using large-sized specimens and standard specimens", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.16 KOGAN, E. A.; FEDOSSOV, V. E. "Roller compacted concrete and horizontal construction joints strength", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.17 PAK, A. P.; YUDELEVICH, A. M. "Tensile strength of roller compacted concrete", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.18 DÍEZ-CASCÓN, J.; POLANCO, J. A.; ARRIBA, R. García de. "University of Cantabria methods for measuring the consistences and mix design of roller compacted concretes", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.19 ARRIBA, H. García de; DÍEZ-CASCÓN, J.; POLANCO, J. A. "Determination of the porosity and permeability of hardened concrete", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.20 POLANCO, J. A.; DÍEZ-CASCÓN, J.; SANTAELLA, L. H.; ARRIBA, R. García de. "Characterization of blended portland conglomerates", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.21 HESS, J. "Design and materials for Auburn dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.22 TOLEDO Y EUGUI, J. M. Octavio de; ECHEVERRIA, G. Huarte; GALARZA, S. Lizarraga; JANÍN, T. Vera "Design of type V cement to be applied in the dam of Urdalur", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.23 GIOVAMBATTISTA, A. "Urugua-í dam. Thermal analysis design criteria and performance", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.24 GOLIK, M. A.; JULIANI, M. A. C.; ANDRIOLO, F. R. "Inspection gallery and drainage in small dams: problem or solution?", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.25 BLINDER, S.; TONIATTI, N. B.; KREMPEL, A. F. "RCC and CFR Dams - Costs Comparison", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.26 KAMEL, K. S. F.; BABÁ, L. J. N.; BLINDER, S.; RAUEN, J. "Selection Studies for Salto Caxias RCC dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.27 FILHO, J. M.; MARINO, M. A., LEVIS, P.; KRUGER, D. A. V. "Jordan River diversion design", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.28 NOLLET, M. J.; ROBITAILLE, F. "General aspect of design and thermal analysis of RCC Lac Robertson dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.29 CHUSHENG, Cao. "A new concept on the design of RCC dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.30 GUANGTONG, He; XIANKANG, Zeng. "The integral RCC dam design characteristics and optimization design of its energy dissipater in Shuidong hydropower station", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.31 LIU, G. T.; MAI, J. X.; ZHANG, G. X. "Research and practice on Xi Bin roller-compacted concrete thin arch dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.32 SANYI, Wang; JIANPING, Zhou. "Special considerations in design of RCC gravity dam of Longtan hydroelectric project", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.33 ANGULO, C.; SCHRADER, E. K.; SANTANA, H.; CASTRO, G.; SALAZAR, H.; LÓPEZ, J. "Miel-I dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.34 DELORME, F.; BOURDAROT, E.; LALLEMENT, M. "Petit Saut RCC Dam: First example of a reinforced concrete face built before RCC. Lessons learnt during construction and after first impounding", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.35 HINKS, J. L.; COPLEY, A. F. "Thermal analysis for RCC dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.36 VISENTINI, G. "Italian experience in RCC dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.37 YAMAZUMI; HARITA; JIKAN; KIDO. "A study of thermal control on RCD dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.38 MURILLO-FERNÁNDEZ, H. "RCC Mexican dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.39 ROUGUI, H.; MAHFOUD, J. "RCC dams. Moroccan experience", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.40 FEDOSSOV, V. E.; KOGAN, E. A. "RCC dam with the zone placement of different concrete mixes", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.41 FRADKINA, N. I. "Computer aided research of RCC dam thermal stress state (Formulation of the problem. Mathematical model. Results of analysis)", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.42 GERINGER, J. J; OFFICER, A. K. "Stepped spillway hydraulic research for RCC dams. Quo vadis?", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.43 BAYÁN-JARDÍN, B. J. "Compacted concrete stepped spillway of the Puebla de Cazalla dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.44 BLAS, J. de; SÁNCHEZ-SUDÓN, J. F.; MAÑUECO, M. G. "Thermal analysis of RCC dams. Methodology. Application to Cenza dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.45 CIFRES, E.; LANCHA, J. C. "Prediction of the thermal state of dams using mathematical models application to the Algar dam (Valencia-Spain)", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.46 SALETE, E.; LANCHA, J. C.; MARCO, C. "Sensibility of thermal transient analysis of dams on the convection coefficient", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.47 SANCHEZ-SUDÓN, J. F.; MAÑUECO, M. G. "The Cenza dam. Project of a roller compacted concrete dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.48 BERGA, L. "Hydrologic safety of existing embankment dams and RCC for Overtopping protection", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.49 VARATORN, Obe-Ua; STERENBERG, J. "The roller compacted concrete alternative at Mae Suai dam, Thailand", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.50 BURNS, J. F.; DIEWAID, G. "Design changes during construction of Cuchillo Negro dam, New Mexico", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.51 CALVINO, M. G.; ROGERS, M. F. "Roller compacted concrete spillways for three embankment dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.52 MOLER, W. A.; JACKSON, H. E. "How high RCC?", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.53 TABATABAEI, J.; SMITH, M. "Design and construction of Lower Molongo Bypass storage dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.54 KREMPEL, A. F.; HOLANDA F. G.; ANDRIOLO, F. R. "Jordan River derivation dam. Data obtained from the test fill", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.55 KREMPEL, A. F.; LEVIS, P.; ANDRIOLO, F. R. "Jordan River derivation dam. Foundation conditions for placing the RCC", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.56 KREMPEL, A. F.; CREVILARA, C.; HOLANDA F. G. "Jordan river derivation dam. Quality control plan for materials and concrete (RCC and conventional)", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.57 NETTO, F. F.; BETIOLI, I.; CARRERA, J. D. D.; ROSARIO, L. C.; BRAGA, J. A.; SÁ, S. N. de; MISAEL, S. Abu-Jamra. "A contribution to the development of RCC in Brazil", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.58 TAVARES, M.; SCHMIDT, M. T.; RESENDE, F. D.; FONTOURA, P. A. F.; ANDRIOLO, F. R. "Capanda -Angola- hydroelectric development. Quality control of materials and conventional and roller compacted concretes", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.59 PINILLA, L. "Pangue dam construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.60 CHENGQIAN, Li; CHUSHENG, Cao. "New development on application and study of RCC on Panjiakou water control project", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.61 BAILE, Wang; DONGGENG, Wang "Continuous placement technique without partition for Puding RCC arch dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.62 BRINK, J. H. "Small roller compacted concrete dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.63 NISSEN, L. C. E.; MERWE, C. J. van der. "Owner-built, small RCC dam construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.64 SOUTHWOOD, S. R. "Taung roller compacted concrete dam. A case history", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.65 ALCAZAR, J.; LACASTA, F. "Aspects of the construction of the Rialb dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.66 ALCAZAR, J.; MONTAÑEZ, E. "Rialb dam's facilities", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.67 ALZU, S.; ALBÁÑEZ, R.; PALACIOS, P. "Roller compacted concrete used for construction of the Maroño dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.68 BARRAU, J. "Sierra Brava dam. Results obtained in the construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.69 HIJÓS, F.; MORENO, F. "A study of roller compacted concrete for the Rialb dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.70 MARTÍN-BARÓN, J.; MARSELLÁ, J. A.; ORTEGA-SANTOS, F. "Use of RCC for Cenza dam construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.71 RODRÍGUEZ-CABELIOS, J. A. "The Guadalemar dam project, construction and quality control", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.72 TATAY, A.; RIO, J. A. del. "Placement of compacted concrete in the intermediate outlets of the new Tous dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.73 EDWARDS, R. G.; PETERSON, J. C. "Cooling of RCC concrete", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.74 XIANKANG, Zeng; GUANGTONG, He. "Dinamic temperature control of roller compacted concrete dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.75 GERINGER, J. J. "The design and construction of the groutable crack joints of Wolwedans dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.76 HATTINGH, L. C.; HEINZ, W. F.; OOSTHUIZEN, C. "Joint grouting of a RCC arch/gravity dam: practical aspects", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.77 OOSTHUIZEN, C. "Performance of RCC arch/gravity dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.78 AGUIRRE, E.; VILLARROEL, J. M. "Thermal analysis and behavior of the Arriaran dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.79 DIEZ-CASCÓN, J.; ARRIBA, R. Garcia de; POLANCO, J. A. "Characterization of roller compacted concrete", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.80 GUERREIRO, M. Q.; FERNANDEZ-CUEVAS, R. "Behavior of compacted concrete used in dams construction. Two fundamental aspects", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.81 GONZÁLEZ-SERENO, M.; BARRAU-PELOCHE, J. M. "A thermal study of the Sierra Brava dam. A comparison of a mathematical model with real temperatures recordings", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.82 LAMA, J. L.; RIO-IGLESIAS, F. "Santa Eugenia dam: an impermeable compacted concrete dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.83 PÉREZ-SAIZ, A.; GÓMEZ-ARRUCHE, J. "Auscultation of roller compacted concrete dams. The Sierra Brava dam", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.84 JOHNSON, D. L.; WONG, N. C. "Rehabilitation of existing dams with RCC. Seismic upgrade experience on two U.S. dams", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.86 SCHRADER, E.; STEFANAKOS, J. "RCC cavitation and erosion resistance", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.87 LIU, T. C.; TATRO, S. B. "Performance of roller-compacted concrete dams: Corps of Engineer's experience", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.88 UJIIE, K. "Efficient construction of Myagase dam and the RCD method", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.89 DÍEZ-CASCÓN, J. "General Reporter - Materials", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.90 DUNSTAN, M. "General Reporter- Planning And Design", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.91 SCHRADER, E. K. "General Reporter - Construction", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.92 GÓMEZ-LÁA, G. "General Reporter - Behavior And Rehabilitation", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.93 HANSEN, K. D. "Special Conference - Roller compacted concrete dams in the USA: 1995", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.94 KUPERMAN, S. C. "Special Conference - Brazilian roller compacted concrete dams. Past, present and future", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.95 YAMAZUMI, A. "Special Conference - An Overview of the Japanese RCD construction method, from the viewpoint of the plane construction method", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.96 ALONSO-FRANCO, M. "Special Conference - Compacted concrete dams in Spain. Evolution and constructive details", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.97 FORBES, B. A. "Special Conference - Australian RCC practice: nine dams all different", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.98 CHONGGANG, Shen "Special Conference - New technical progress of RCC dam construction in China", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.99 GERINGER, J. "Special Conference -The design and construction of RCC dams in Southern Africa", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.100 ZABALETA, H. "Special Conference - General concepts for a systematization of the study of RCC", in: Proceedings of the International Symposium on Roller Compacted Concrete Dams. Santander, Spain, October 1995.

95.101 CAVALCANTI, Alberto Jorge C. T.; VASCONCELOS, Aurélio Alves de. "Anteprojeto da Barragem de Itapebi", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.102 VIVÁN, Milton Emilio; TERADA, Masato. "Aspectos Determinantes na Utilização de Concreto Compactado a Rolo no Projeto Executivo da Barragem de Franca-Sabesp", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.103 KREMPEL, Antonio Fernando; BLINDER, Simão. "Controle Tecnológico de CCR - Exemplo de Especificações", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.104 RENÊ, Antonio; LEITE, C. A. Paula; ASTOLPHI, Julio Cesar; GONTIJO, Marcelo Cardoso; KUPERMAN, Selmo C.; ONUMA, Nelson Takashi; VIEIRA, Luiz Prado Junior. "Proteção do Espigão de Jusante da Uhe Porto Primavera-Projeto e Comportamento do CCR", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.105 MACHADO, Rafael; REZENDE, Paulo F. V. S.; AMARO, Paulo Roberto; KUPERMAN, Selmo C. "Relação de Projetos de Barragens Brasileiras de Concreto Compactado Com Rolo", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.106 SCHRADER, Enest. "Roller Contacted Concrete for Dams Current Practice and the New ACI Report", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.107 HOLANDA, Francisco Gladston; SILVA, Ricardo Fernandes da; MARQUES, Afonso C. Moruzzi; ROCHA, Cristiano C. A. "Utilização de Quartzito Britado como Agregado de CCR nos Aproveitamentos Multiplos Jequitai I e II", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.108 KREMPEL, Antonio Femando; CREVILARO, Celso Chincli; ANDRIOLO, Francisco Rodrigues; HOLANDA, Francisco Gladston. "Derivaçao do Rio Jordão-Programa de Caracterização de Materiais e Concretos", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.109 HOLANDA, Francisco Gladston; KREMPEL, Antonio Fernando; CREVILARO, Celso Chinelli. "Dosagem de Misturas de CCR para a Construçao da Barragem de Derivaçao do Rio Jordão - Utilização de 100% de Areia Artificial", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.110 CARMO, João Bosco Moreira do; FONTOURA, José Tomaz França; ANDRADE, Moacir A. Souza de; ANDRADE, Walton Pacelli de. "Estudo de Dosagens de Concreto Compactado a Rolo, Combinando Cimento e Agregado Pulverizado com Escória de Alto-Forno e Fly-Ash", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.111 HOLANDA, Francisco Gladston; FILHO, Mauro G. S.; ROCHA, Cristiano. "Estudos de Dosagens de Concreto Contactado a Rolo (CCR) nos Aproveitamentos Multiplos Jequitai I E II", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.112 NETTO, Francilino Fernandes; BETIOLI, Ideval; DUARTE, José Domingo Carrera; ROSÁRIO, Luiz César; BRAGA, José Augusto; SA, Sérgio Nogueira de; MISAEL, Sérgio Abu-Jamra; ANDRIOLO, Francisco Rodrigues. "Aplicação, Ensaios e Pesquisas do Concreto Compactado a Rolo na Itaipu Binacional", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.113 GAMBALE, Eduardo Aquino; FONTOURA, José Tomaz França; GUEDES, Quintiliano M. "Estudo da Fluência no Concreto Compactado a Rolo em Idade Jovem", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.114 DOLEN, T. P.; FAY, Kurt F. Von. "The Development of Roller Compacted Concrete Mixtures for Bureau of Reclamation Mass Concrete Construction", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.115 OLIVEIRA, Paulo José R.; SALLES, Flavio Moreira. "Concreto Compactado a Rolo - Caracteristicas e Propriedades", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.116 DOELHER, Flávio Dutra; OLIVEIRA, Gilceu de; FERREIRA, Maria Cecilia N. F. "Barragem de Caraíbas – CEMIG - Companhia Energética de Minas Gerais", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.117 ONUMA, Nelson Takashi; GONTIJO, Marcelo Cardoso; KUPERMAN, Selmo Chapira; VIEIRA, Luiz Prado Junior. "O Emprego de Concreto Compactado Com Rolo para Reabilitação de Obras Hidráulicas", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.118 EDSON, José; MENDONÇA, F. de; HOLANDA, Francisco Gladston. "Consolidação da Experiência com uso de CCR na UHE Xingó", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.119 HOLANDA, Francisco Gladston; ANDRIOLO, Francisco Rodrigues; KREMPEL, Antonio Femando; CREVILARO, Celso Chinelli; PEREIRA, Marcos Aurélio C. "Procedimento para Execução de Aterro Experimental de Concreto Compactado a Rolo para a Barragem da Derivação do Rio Jordão", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.120 TARALLO, João Júnior; CARNEIRO, Edvaldo Fábio. "Utilização de Densímetro Nuclear no Controle de Qualidade do Concreto Compactado a Rolo", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.121 LUCENA, Antonio M. de; CARMO, João Bosco M. do; FREIRE, José Antonio Jr; FONTOURA, José Tomaz F.; ANDRADE, Walton P. de. "Concreto Compactado com Rolo Aplicado na Barragem Canoas – Ceará", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.122 GUERRA, Elcio Antonio; OLIVEIRA, João Carlos F. de; GRAÇA, Newton Goulart; ANDRADE, Walton P. de. "Análise do Desempenho das Ensecadeiras Galgáveis em CCR de Serra da Mesa Após Cinco Períodos de Galgamento", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.123 NASCIMENTO, José Francisco F. do; FONTOURA, José Tomaz França; ALMEIDA, Manuel Tavares de; ANDRADE, Walton Pacelli de. "Concreto Compactado a Rolo Aplicado no Aproveitamento Hidroelétrico do Médio Kwanza - Barragem de Capanda", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.124 BLINDER, Simão; TONIATTI, Nelson Buhr; KREMPEL, Antonio Fernando. "CCR X EFC Comparativo de Custos", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.125 TRICHÊS, Glicério; CARDOSO, Samuel H. "Misturas Granulares Cimentadas para Serem Empregadas na Pavimentação como Concreto Compactado a Rolo: Estudo do Contortamento da Fadiga", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.126 TRICHÊS, Glicério; CARDOSO, Samuel H. "Misturas Granulares Cimentadas para Serem Empregadas como Concreto Compactado a Rolo na Pavimentação: Estudo das Propriedades Mecânicas", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.127 HOLANDA, Francisco G. "Pavimentação em Concreto Compactado a Rolo -Relato de uma Pista Experimental", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.128 TRICHÊS, Glicério. "Pavimentação do Trecho Experimental de Itajai, com Concreto Contactado a Rolo: Aspectos do Processo Construtivo, Qualidade do Pavimento Acabado e Recomendações para Construções Futuras", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.129 TRICHÊS, Glicério; CARDOSO, Samuel H. "Dimensionamento de Camadas de Concreto Compactado a Rolo para Fins de Pavimentação Rodoviária", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.130 GROSSI, Luiz Carlos; BALTHAZAR, Marcelo Antônio Barbosa; REGO, Jalves José Verçosa. "Çoncepção, Objetivos e Programação da Utilização da Pista Experimental Circular do IPR/DNER no Estudo dos Pavimentos de Concreto Rolado", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.131 GODINHO, Dalter Pacheco; GROSSÍ, Luiz Carlos. "Construção de Pavimentos de Concreto Rolado", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.132 GODINHO, Dalter Pacheco; GROSSI, Luiz Carlos. "Controle Estatistico de Qualidade de Pavimentos de Concreto Rolado", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.133 CARVALHO, Marcos Dutra de. "O Estado da Arte do Dimensionamento de Pavimentos com Concreto Rolado", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.134 CARVALHO, Marcos Dutra de. "Dimensionamento de Pavimentos de Concreto Rolado para Veículos Especiais", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.135 PITTA, Marcio Rocha; DÍAZ, Patricio Hurtado. "Estado-Del-Arte de Los Pavimentos de Concreto Compactado con Rodillo", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.136 CARVALHO, Marcos Dutra de. "O Concreto Rolado como Camada Final de Base e Revestimento de Pavimentos Urbanos", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.137 SUZUKI, Carlos Yukio; DÍAZ, Patricio Hurtido; MOTOMATSU, Ricardo Kenzo. "Solução por Microcomputador para Dimensionamento de Pavimentos de Concreto Rolado para Pisos Industriais", in: Proceedings of The I Simpósio de Obras em Concreto Compactado Com Rolo. São Paulo, Brazil, April 1995.

95.138 ACI COMMITTEE 207-2R/95. *Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete.*

95.139 JAPAN DAM ENGINEERING CENTER. *Japanese RCD Technology Showcase.* September 1995.

95.140 SARKARIA, G. S.; ANDRIOLO, F. R. "Special Factors in Design of High RCC Gravity Dams", in: Internnational Water Power & Dam Construction. April/August 1995.

1996

96.01 ALVES, Eduardo Ferreira da Rocha; CARMO, João Bosco Moreira do; NASCIMENTO, José Francisco Farage do; FONTOURA, José Tomaz França. "Utilização de Sílica Ativa no Concreto Compactado Com Rolo", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.02 KREMPEL, Antônio Fernando; ANDRIOLO, Francisco Rodrigues. "Barragens em Ccr - Especificações Técnicas: Pontos de Interesse, Conflito e Discussões", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.03 LUNA, Sérgio; FRANCO, Hélio; KATORI, Leonardo; KUPERMAN, Selmo Chapira. "Utilização de Concreto Compactado com Rolo na 2ª Etapa da UHE Tucuruí", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.04 AVILA, Clovis Melo. "Derivação do Rio Jordão - A Opção por Concreto Rolado", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.05 GOLIK, Miguel Alfredo; STOCK, Rubens Filho; GONTIJO, Marcelo Cardoso; ONUMA, Nelson. "Emprego do CCR na Ampliação da UHE Rio do Peixe", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.06 KAMEL, Kamal F. S.; BABA, Lourengo J. N.; XAVIER, Lailton V.; AVILA, Clóvis M. "Estudos de Seleção da Barragem de CCR para Salto Caxias", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.07 TOZZI, Marcos; TANIGUCHI, Edie; OTA, José. "Concentração de Ar em Escoamentos sobre Vertedouros com Degraus", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.08 KAMEL, Kamel F. S.; BABA, Lourenço J. N.; XAVIER, Lailton V.; KREMPEL, Antônio F. "Pista Experimental de CCR de Salto Caxias - Características e Procedimentos de Construção", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.09 MARQUES, José Filho; MARINO, Marcos Antônio; GARBINIO, Antônio Sérgio Guerra; KIDO, Arnaldo Tomok. "Parâmetros Necessários ao Projeto de Barragens de CCC – Barragem de Derivação do Jordão como Exemplo", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.10 PIMENTA, Gilson Viviani ; ANDRIOLO, Francisco Rodrigues. "Importância do Planejamento nas Obras em CCR", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.11 PEREIRA, Marcos Aurélio Cassias. "Derivação do Rio Jordão - Aspectos Construtivos da Barragem do Jordão", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.12 VILAR, Crivalda Padilha; MOTA, Anisio Coelho; JUSTINO, José Maria; ACCIOLY, José Claudio; OLIVEIRA, Sebastião 0. M. de; HOLANDA, Francisco Gladston. "Barragem Mocotó - Emater /Pe", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.13 ANDRIOLO, Francisco Rodrigues. "Barragens em CCR - Controle de Qualidade", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.14 GAMBALE, Eduardo de Aquino; CARMO, João Bosco Moreira do; GUEDES, QUINtiliano Mascarenhas; BITTENCOURT, Rubens Machado; ANDRADE, Walton Pacelli de. "Análise Térmica do Concreto da Barragem Canoas – Ce", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.15 DONADON, José Marcos. "A Copel e o CCR", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.16 RAUEN, Joel; BLINDER, Simão; SILVA, Ademar Cury de; STEFFEN, Ruy Dikram. "O Simpósio Internacional da Espanha sobre Barragens de Concreto Compactado com Rolo", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.17 SCUERO, Alberto M.; VASCHETTI, Gabriela L. "Synthetic Geocomposites as Impermeable Barriers on RCC Dams: Two Different Systems at Stake", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.18 TRICHÊS, Glicério. "Importância do Controle da Densificação das Camadas de Pavimentos Rodoviários de Concreto Compactado a Rolo", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.19 CALMON, J. L.; MIRAMBELL, E. E. "Determinación del Campo de Temperaturas en Bloques de Presa de Hormigón Construidos Evolutivamente por Tongadas", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.20 CARMO, João Bosco Moreira do; SANTOS, Marcia Campos dos Maurice Antoine Traboulsi; ANDRADE, Moacir Alexandre Souza. "Influência do Envelhecimento do Agregado Pulverizado na Resistência do Concreto Compactado Com Rolo e da Argamassa", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.21 ANDRADE, Walton Pacelli de; ANDRIOLO, Francisco Rodrigues. "Barragens em CCR - Sistemas de Impermeabilização: Discussões, Sugestões e Uso", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.22 SAGRADO, Joaquin Diez-Cascón; MADRAZO, Juan Antonio Polanco. "Concepto y Dosificación de Hormigones RCC", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.23 GUERRA, Elcio Antonio; VEIGA, Fernando Nogueira; SANTOS, Marcia Campos dos; ANDRADE, Walton Pacelli de. "Análise da Água Percolada no CCR Contendo Adição de Calcário Moído", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.24 JÚNIOR, Fernando Augusto; DANTAS, A. Francisco de Assis Souza. "Aplicação de Concreto Compactado com Rolo Servindo de Base na Reconstrução de Pavimento de Pátio de Estacionamento de Veículos e Movimentação de Cargas", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.25 ZABALETA, Hernán G. "Proposición para una Sistematización del Estudio del HCR", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.26 KUPERMAN, Selmo Chapira. "Barragens Brasileiras de Concreto Compactado com Rolo: Passado, Presente e Futuro", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.27 CERON, Clair; DONIAK, Íria Licia Oliva; HOLANDA, Francisco Gladston. "Barragem de Derivação do Rio Jordão - Definição do Material Aglomerante para uso nos Concretos da Obra", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.28 TARALLO, João Júnior. "Critérios para o Controle Tecnológico do CCR", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.29 ANDRIOLO, F. R. "El Uso de Materiales se Rejecto en el Hormigón", in: Proceedings of the II Simpósio Nacional de Concreto Compactado a Rolo. Curitiba, Brazil, March 1996.

96.30 ALMEIDA, J. Matos; CRUZ, A. Souza. "Abordagem do INAG na Problemática das Barragens em BCC", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC), Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.31 MIRANDA, M. Pinho de. "As Perspectivas de utilização do BCC em Barragens do Grupo EDP. O Caso do Aproveitamento Hidroelétrico do Baixo Sabor", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC), Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.32 JOFRÉ, Carlos. "Aplicaciones del Hormigón Compactado en la Construcción de Pavimentos", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.33 FERNANDES, J. Salvador; MOLICO, A. "O Projeto da Barragem de Veiguinhas em BCC", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.34 VAZQUEZ, Jorge; SANTO, Acácio. "Experiência da COBA no Estudo de Barragens de BCC", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.35 ALCAZAR, Jesús. "Instalaciones y Métodos Constructivos en las Presas de Hormigón Compactado con Rodillo", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.36 QUARESMA, Luis. "Utilização de Betão Pobre Compactado com Cilindros em Pavimentos Semi-Rígidos", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.37 BARRAU, José. "Presas Pequeñas em HCR", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.38 DUSTAN, Malcolm. "The State of the art of RCC Dams", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.39 FRANCO, Alonso. "Las Presas Pequeñas de Hormigón Compactado", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.40 RIBEIRO, A. Bettencourt. "Permeabilidad do BCC. Ensaios Laboratoriais", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.41 HINDS, James. "Roller Compacted Concrete Mixture Design for Mass and Structural Applications", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.42 ZUECO, Miguel. "Elección de la Técnica del HCR", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.43 CASCÓN, Diéz. "Concepto y Dosificación de Hormigones RCC", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.44 ANDRIOLO, Francisco Rodrigues. "Barragens de Betão Compactado com Cilindro (BCC). Controlo de Qualidade", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.45 SANTANA, Teresa. "Uma Análise Térmica de Barragens de BCC", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.46 SCHRADER, Ernest. "RCC - Construction", in: Proceedings of the I Conferências Portuguesas sobre Barragens de Betão Compactado com Cilindros (BCC) - Laboratório Nacional de Engenharia Civil. Lisboa, November 1996.

96.47 HANSEN, Kenneth D. "Diverging Views on RCC", in: International Water Power & Dam onstruction. August 1996.

96.48 NISHIBAYASHI, S.; KURODA, T.; TIECHENG, W.; QINGHAN, B.; XUEQUAN, W.; MINGSHU, T. "Effect of Reactive Aggregate Powder on Suppressing Expansion due to Alkali-Silica Reaction", in: Proccedings of the 10th International Conference on Alkali-Aggregate Reaction in Concrete- Melbourne. Australia, August 1996.

1997

97.01 KREMPEL, Antonio Fernando; OLIVEIRA, Luiz Fernando Prates; PEREIRA, Marcos Aurélio Cassias. "Controle de Qualidade da Compactação do CCR na Barragem da Usina Hidrelétrica de Salto Caxias", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.02 SCUERO, Alberto M.; GONTIJO, Marcelo C. "Utilização de Geomembrana de PVC como Elemento de Vedação em Barragens de CCR", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.03 KREMPEL, Antonio Fernando; PEREIRA, Marcos Aurélio Cassias. "Barragem de CCR - Usina Hidrelétrica de Salto Caxias", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.04 "Roller Compacted Concrete-RCC Dams", in: Projet National BaCaRa - 1988/1996 - Presses de L'Ecole Nationale des Ponts et Chaussées, Paris, 1997.

97.05 "Current Activities on Large Dams in Japan", in: Japanese National Committee on Large Dams, 1997.

97.06 HARDING, M. A. "RCC: An Rx for Rehabilitatings Embankments Dams", in: Concrete Construction. January 1997.

97.07 VAL, Luis Cavero; CLAVER, Fernando Lacasta. "Aditivos Polifuncionales en las Grandes Obras Hidráulicas (Presa de Rilab)", in: Cemento-Hormigón, Instituto Español del Cemento Y Sus Aplicaciones. August 1997.

97.08 ANDRADE, Walton Pacelli de (editor). *Concretos - Massa, Estrutural, Projetado e Compactado com Rolo - Ensaios e Propriedades*. Equipe de FURNAS -Laboratório de Concreto, 1997.

97.09 "RCC Dam (>15m) 1997 Yearbook", in: International Water Power & Dam Construction, 1997-UK.

1997

97.01 KREMPEL, Antonio Fernando; OLIVEIRA, Luiz Fernando Prates; PEREIRA, Marcos Aurélio Cassias. "Controle de Qualidade da Compactação do CCR na Barragem da Usina Hidrelétrica de Salto Caxias", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.02 SCUERO, Alberto M.; GONTIJO, Marcelo C. "Utilização de Geomembrana de PVC como Elemento de Vedação em Barragens de CCR", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.03 KREMPEL, Antonio Fernando; PEREIRA, Marcos Aurélio Cassias. "Barragem de CCR - Usina Hidrelétrica de Salto Caxias", in: Proceedings of the XXII Seminário Nacional de Grandes Barragens. São Paulo, Brazil, April 1997.

97.04 "Roller Compacted Concrete-RCC Dams", in: Projet National BaCaRa - 1988/1996 - Presses de L'Ecole Nationale des Ponts et Chaussées, Paris, 1997.

97.05 "Current Activities on Large Dams in Japan", in: Japanese National Committee on Large Dams, 1997.

97.06 HARDING, M. A. "RCC: An Rx for Rehabilitatings Embankments Dams", in: Concrete Construction. January 1997.

97.07 VAL, Luis Cavero; CLAVER, Fernando Lacasta. "Aditivos Polifuncionales en las Grandes Obras Hidráulicas (Presa de Rilab)", in: Cemento-Hormigón, Instituto Español del Cemento Y Sus Aplicaciones. August 1997.

97.08 ANDRADE, Walton Pacelli de (editor). *Concretos - Massa, Estrutural, Projetado e Compactado com Rolo - Ensaios e Propriedades*. Equipe de FURNAS -Laboratório de Concreto, 1997.

97.09 "RCC Dam (>15m) 1997 Yearbook", in: International Water Power & Dam Construction, 1997-UK.

can be conjured, with even greater freedom than has been used.

RCC embodies an exemplary reminder that engineering is a challenge of creativity: and this book renders it fruitful. A notorious example is given, regarding the innovative use of rock flour fines, a very important regional solution for Brazil's geology and finding the best mixture from using local materials

THE AUTHOR

Francisco Rodrigues Andriolo is a widely experienced engineer deeply rooted in dam design and construction world, both on conventional concrete technology as on RCC, of which he is a distinguished researcher and an earnest enthusiastic.

He graduated in 1969 at the University of São Paulo, Escola de Engenharia de São Carlos. He is a consulting engineer in São Paulo, Brazil, and has engaged in RCC technology for many years. He started in 1976, in the laboratory of the Itaipu project, experiments on the dam site for the first block of RCC in Brazil.

During these nearly 30 years he has been involved in testing, researching, quality control, instrumentation, design, planning and construction of all kinds of concrete dams in Brazil and abroad, both on conventional and RCC. His large experience is documented in 5 books published in Portuguese, and in over 80 national and international papers. This sixth book in English enables him to share his experience with the worldwide technical community.

ROLLER COMPACTED CONCRETE - RCC

A comprehensive handbook on design and construction of RCC works.

- history of RCC
- selection of construction materials
- concrete mixture and proportioning
- principles of the RCC design
- economic analysis
- technology of construction and quality control
- performance of completed RCC dams.

ISBN 85-86238-10-4