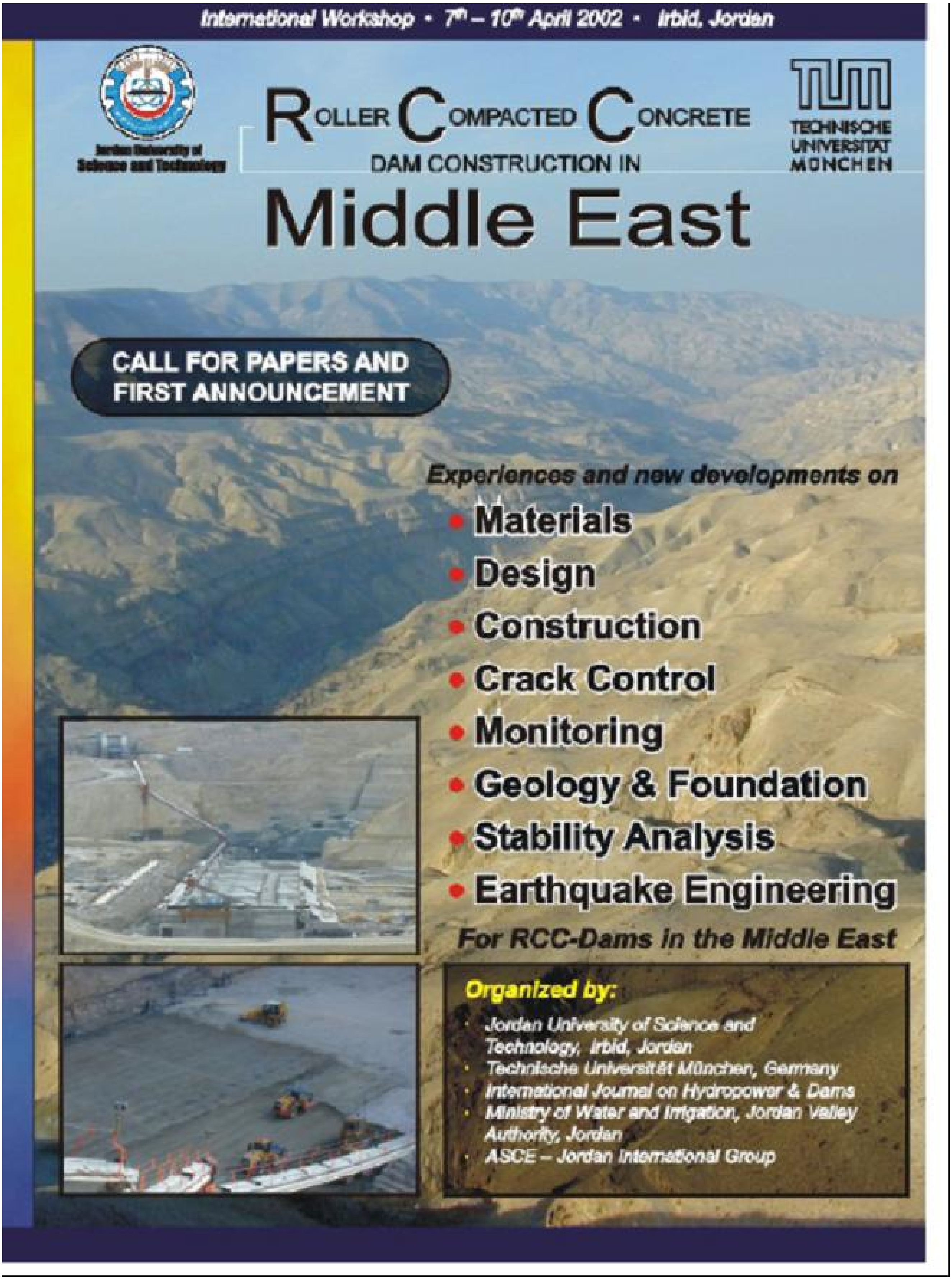

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ROLLER COMPACTED CONCRETE
DAM CONSTRUCTION IN
Middle East

RCC- MATERIALS AVAILABILITY- PROPERTIES AND PRACTICES IN DIFFERENT REGIONS

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ABSTRACT

Large and/or different countries with few resources or where materials are not readily available must have technical options available for the execution of Dam projects. The purpose of the paper is to present studies carried out in Laboratories and at job site to make data from a lengthy study of different materials available to the technicians, with the intention of using said materials as the structural element of dams. Test data of the normal properties in the Dam Projects are presented,

PRESENTATION

From 76's up to now a large research laboratory RCC test program was developed by Government Agencies, Laboratories, and Contractors in Brazil, based on each Professional idea and tendency. Symposiums and Congresses were held to discuss information, test- results and points of view.

The RCC dam-construction start-up in Brazil was at Saco de Nova Olinda Dam, following some isolated Fill Test Sections, Back- Filling and partial studies. A large data support, from laboratory tests and Fill Sections is available.

There are more than 500 major dams in Brazil, that is, dams more than 15m high. To put together this group of dams, almost 62,700,000m^3 of different types of concrete were used since the end of the XIX century.

Up to December/2001, there were 38 RCC Dams completed, or under construction, and 5 planned for the next year. The RCC total volume is about 7,700,000m3. The cementitious content averaged is less than 80 (79) kg/m3.

INTRODUCTION

In Brazil, the adoption of RCC technique was not only based on cementitious consumption reduction. Since the 60s, concrete class zoning has become very popular (CVC-conventional concrete mass), as well as required strength control at one year age or at least 180 days. These concepts were intended as a way of emphasizing the material's potential. In fact, Brazil's vast territorial extent, without remarkable seismic action, obliged optimization of materials found near the job site and reduction of the chances of materials being rejected on arrival. On account of this, a series of control procedures evolved and were adopted on the largest concrete dams in the country like Ilha Solteira, Itaipu, Tucurui and others.

Brazilian Dams where have being used Conventional Mass Concrete with cementitious content less than 100kg/m3.

Another consequence of the country's vastness is the installation of laboratories in certain strategic locations with the purpose of understanding and pre-qualifying materials, techniques and technologies, as well as labor training and quality control support. The following important events exemplify these actions:

Hydroelectric- CVC Concrete Volume	**Period**	**Event**
Ilha Solteira- 3,680,000m3	1970-1972	Use of CVC Mass with an 84kg/m3 of cementitious consumption (61 cement + 23 Pozzolan). Concretes controlled at 180 days age.
Itumbiara- 2,080,000m3	1975-1980	Concrete class zoning, with age control from 90 to 180 days.
Itaipu- 13,000,000m3	1977-1982	Concrete class zoning, with age control from 180 and 360 days. 90 kg/m3 of cementitious content. Production rate above 750m3/h
Tucurui- 6,000,000m3	1978-1984	Concrete class zoning, with age control at 180 days. Up to 95 kg/m3 of cementitious content. Production rate above 500m3/h

The construction of Ilha Solteira and Itaipu Projects can be considered milestones in the embracing of a quality control system for CVC concretes. The concrete placing speed possible in Itaipu, at times more than 750m3/h, was possible because of an adequate control plan.

This way, when observing bibliographic references that attribute to RCC the advantage of reducing cement content, changing control ages to older dates like 180 or 360 days, or still, greater construction speed, consider the job's dimension rather than a determined methodology or control routine.

Brazil is now among the five major RCC dam builders, and among the sixth major civil construction in the world, having established particularities based on difficulties, characteristics and the potential of its territorial vastness, as well as economical adversities, technical development rate and professional capacity of labor workmen. It is clear then, ***there is no need to set records***.

On the other hand, RCC construction is based on *simplicity*, and not on the chance of not having to perform certain procedures.

It is a construction technique based on making it simple not making it poorly!

CONCEPT

Roller ***C***ompacted ***C***oncrete - **RCC** - is a technique characterized mainly by its use of rollers for compaction. Roller compacted concrete (RCC) is a construction methodology, not a Design Criteria or technology, that uses a concrete (and is "a concrete as material") of no-slump consistency in its unhardened state that 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 which require that measures be taken to cope with the generation of heat from hydration of the cementitious materials and attendant volume change to minimize cracking. 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 vibrating 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. It has some interface with granular soil cement, which may use similar placement methods, but contains a larger amount of coarse aggregate and develops properties similar to conventionally placed concrete. RCC encompasses a broad range of mixtures with *properties that are primarily dependent on the quality of* *materials used, the cementitious materials content*, the degree of compaction, and the degree of control exercised.

The resulting material is denser with lower amount of water than usual **C**onventional **V**ibrated **C**oncrete (**“CVC” will be used in this text to identify Conventional Concretes**)

This methodology has been used successfully in a number of major dams in the world. The use of RCC for gravity, and arch dams construction 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 concrete mix designs are traditional, and can reach high strengths and densities it becomes useful for pavements, rehabilitation, replacements and protections.

The lower cost as compared with CVC derives chiefly from the opportunity for continuous mixing, hauling, as well from the feasible simplifications on planning, saving in financial points of interest charges during the shorter construction time.

MATERIALS

GENERAL

RCC is a concrete that differs from conventional concrete principally in that it has a consistency that will support a vibratory roller and 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 and fine and coarse aggregates, should be similar in quality to those considered suitable for 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 materials (cement plus pozzolanic material) contents to fully processed concrete aggregates with moderate to high cementitious materials content. The mixture design for Saco de Nova Olinda Dam in Brazil used a combination of crushed quarry rock and natural silty graded in a curve with 76mm maximum size aggregate (MSA) with 75Kg/m^3 cementitious materials (Portland Pozzolanic Cement). Urugua-i (Argentine), Capanda (Angola), Jordão Dam and Salto Caxias Dams (in 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-Jordão and Salto Caxias) Portland Cement content. In these dams a graded continuous curve with MSA between 76mm and 50mm was used. Cindere Dam in Turkey will use 63 to 76mm MSA rounded gravel with around 60Kg/m^3 cementitious materials.

The larger the RCC dam the more sensitive will be the unit cost based on the source and quality of aggregate and cementitious materials. A few key factors related to production of RCC and consequently cost are:

CEMENTITIOUS MATERIALS

General

RCC can be made with any of the basic types of cement or a combination of cement and pozzolanic materials. Selection of cementitious materials for chemical resistance to sulfate attack and potential alkali reactivity with certain aggregates should follow the same procedures of the adopted standard for CVC. The strength of RCC is primarily dependent upon the:

- 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 require consideration of 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 l20 kg/m^3 and pozzolanic material (Fly Ash) in amounts from 20% to 30% by 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 the RCC is used in a massive structure consideration must be given to the generation of heat by the cementitious materials of the RCC mass. 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 is dependent on strength requirements and the pozzolanic activity to reduce water requirements as well as cement contents. The economic benefit of heat reduction through the use of pozzolanic materials is dependent on the relative cost of materials, including handling.

Large quantities of cementitious materials required for very high RCC dams may exceed the supplier's delivery capacity, for that market. Non availability of cementitious materials to meet production needs might force a reduction in rate of placement and/or higher prices if transport of materials from a longer distance is necessary. Likewise very high RCC dam with large volumes will require a great number of bulk transport vehicles travelling on public roads which in addition to environmental impacts might disrupt local traffic and increase road maintenance.

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 on Figure (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:

"...from the first stage of construction of 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 on similar future construction might be expected to substantially reduce the tendency toward cracking ....."

and:

"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 ***Safety and Impermeable Structure*** is one built with a "rich" (or unnecessarily high cement content) concrete. But, normally, this rich concrete will increase the crack potentiality and becomes permeable (through the cracks). The optimum cement or cementitious content for CVC and RCC needs to be based on laboratory proportioning mixes tests carefully carried on.

Pozzolanic Materials

The selection of a pozzolanic suitable for RCC should be based on its conformance with adopted standard (ASTM C- 618 or other applicable standard), its cost and availability.

ASTM C-6l8 defines a 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 pozzolanic material type can include the 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:
a) as a partial replacement for cement to reduce heat generation;
b) to increase the compressive strength at large ages, if the material has large Pozzolanic Activity with cement;
c) to increase the durability;
d) to reduce cost, and;
e) as a mineral addition to the mixture to provide fines to improve workability.

The partial replacement for cement (to a same strength level) and the cost benefit depends on the Pozzolanic Activity from the material with the cement that is related with Hydroxides released during the hydration, for the reaction with main elements (Silica; Aluminum; Iron Oxides) from the pozzolanic material. The use of high content of pozzolanic material replacing the cement can "overdose" the available hydroxides and part of the pozzolan acts only as a filler (the 5th 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 occupied by cement or water. To occupy 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.

Fillers

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 mixing.

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 Pozzolans, Diatomaceous earth, Silt and also the "Crushed Powder" (called "***Pó de Pedra***" in Brazil), 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 mixing while fresh, but also reducing the expansions resulting from the reactions with the cement alkali, as function of the Silica mineralogical form and its content.

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 washing (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 harmful 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 material.

This situation gave rise to the evaluation of that reject with views of incorporating it to the CVC and RCC conventional types of concrete. Contemporaneously, during the construction of the Urugua-i Dam (Argentine), in RCC, the use of a cubic grading curve type for the aggregates' (from Basaltic rock) composition, required to incorporate a certain amount of fines. As a part of the mixing studies for the Urugua-i Dam, was carried out at the Itaipu Laboratory, it was suggested the incorporation of the basalt "Stone Crushed Powder" to the mixing, and this was adopted.

At that opportunity, the physical improvement of the properties was noticed but the physical-chemical action of the "Stone Crushed Powder" fines were 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 large studies 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 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, was already mentioned and it has been recommended, e.g.:

..."The fine material in a 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"...

The compressive strength and the watertightness of the RCC and CVC concretes are improved with the inclusion of the “Stone Powder”. 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 cited that:

“... The reaction of active forms of silica with lime improves strength...”

It is known that:

“... Diffusion of ions or molecules through a gel containing a 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...”

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. It is recommended to have a $Ca(OH)_2$ minimum fixation of 30mg per 100g of fine material.

It is very important to 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... ”

“... When the reactive mineral is powdered, it can be used in a wide range of proportions without causing expansion. This was demonstrated by Vivian when opal was ground to pass N° 300 sieve and used in several proportions, expansion was practically zero for all proportions, the particle size of the reactive mineral is clearly an important factor...”
“...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, Stanton and others... “

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. Filler used in Jordão and Salto Caxias RCC dams which were originally obtained by mean 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;
- Grading curves obtained with the Filler produced by distinct machines has 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;
- Averaged 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 Ossipov method) as it 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.

AGGREGATES

The selection of aggregates and control of aggregate grading 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 a 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 concrete 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 concrete mixes. This is particularly so if the fines are non-plastic, fill voids in the aggregate, and lead to decreased water demand and improved compactibility.

For RCC there is normally not enough material-cost savings from using aggregate sizes larger than 76mm to offset the added batching cost and 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.

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 deposited. 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.

In massive concrete placements, control of the temperature rise should have a greater significance than material 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 concrete. Where pozzolanic material is used, the generation of heat may be reduced substantially. The use of aggregate 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. 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.

The grading of fine aggregate strongly influences paste requirements and compactibility of RCC. Grading of sand within the limits shown in ASTM C 33 has been used. This sand may require more cementitious material than is needed for lean mixtures using aggregate 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. The aggregate grading and the type and quality of fines content affects the relative compactibility of the RCC and may influence the minimum number of vibrating passes required for full consolidation of a given layer thickness. It also affects the water and cementitious material requirements needed to fill the voids in the aggregate and coat the aggregate particles.

The quality of the aggregate required for the RCC need be checked by standard tests. 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 aggregate for RCC can come from a variety of sources, but the material closest to the dam site should be investigated first.

Since higher strength concrete will be required for very high RCC dams the quality of aggregate will have a greater effect on the cementitious content of the RCC mix and consequently the in-place cost. Likewise, thermal characteristics of the aggregate will take on greater importance because of their impact on the cracking potential.

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.

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 effects 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 labor costs required to control segregation.

Sand percentages have generally been between 30% to 50% of total aggregate. The percentage of fines passing the Nº 200 (0.075mm) sieve was initially limited to 3 percent of the total weight of aggregate, but this had a new approach. The amount and type of minus 200 fines allowed have varied considerably. It has ranged from 0 to15 percent of total aggregate. In many cases, unwashed aggregate can be appropriate for RCC.

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 to reduce water requirements and improve RCC cohesiveness and compactibility.

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 2.700.000m3 mix of RCC used at Tarbela Dam 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.

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 aggregate 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. Another characteristic approached by the cubic type curve is the reduction of the coarsest part of the aggregates, which usually causes segregation.

WATER

As RCC is a concrete, the usual requirement for water in CVC is adopted for RCC mixes. The requirement is that it be free from excessive amounts of alkalies, acids, or organic matter that might inhibit proper strength gain. Most RCC mixes require 90 to 160 kg/m3 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.

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 and Spain. 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.

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 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 soils 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.

PROPERTIES

GENERAL

RCC is a concrete, and so, the 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), thermal coefficient of expansion, specific heat, creep, thermal conductivity, thermal stress coefficient, diffusivity, permeability, and, durability.

Beside this some doubts and questions remain. Questions like :

- Are there RCC Dams higher than 100m ?
- Which is the maximum high that could be reached by a RCC Dam?
- How does RCC compare with CVC as a material suitable for building high and large gravity or arch-gravity dams with same durability and quality as existing dams which have performed well for several decades?
- How need the construction joint treatment be?
- And so on! In a general point of view it comes from the inexperience of some technicians in the correlation and comparison of the RCC data with those of CVC concrete, or in terms of dams, with the CVC mass concrete.

It means that, besides the available data, there is no familiarity with the RCC Properties. Based on those doubts, this chapter intends to discuss the RCC properties and quality in comparison with CVC properties , considering the large data obtained at job construction and same kind of materials used for proportioning-mix studies.

The in situ properties of RCC depend on the quality of the materials used, or the proportions of the mixture, and on the grade of compaction that is achieved. Given that very diverse mixtures have been employed, going from lean mixes to mixes with a high-cementitious content, the values obtained in a series of properties have also varied very extensively. The properties which depend on the nature of aggregates, such as their elastic or thermal characteristics, are seen to be influenced by these latter in a similar manner as that which occurs in CVC concretes.

FRESH RCC PROPERTIES

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.

The same specimen compacted and used for consistency can be useful for moisture-density tests. After the consistency test the container is weighed and the optimum water content (moisture) can be determined as the one which produces a maximum dry density. A five-point curve is general practice.

Optimum water content (moisture) content is thus determined for construction and should be in the mix at the time of compaction, not at the time of mixing. It therefore may be necessary to introduce more water than optimum during mixing to account for moisture loss due to handling, evaporation, and early hydration of cement. Also, field adjustments may have to be made to produce a more compactible mix as determined by construction of a test section.

Water Content- DMA- Brazilian Method

Pacelli and all, 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 having as physical principle the density of materials compounding concrete. That is, as water is a material with lower density, the more water in a RCC mix, the lower the 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 an also known water volume. The higher the water content in a RCC sample, the higher the water volume displaced by the sample. For each RCC mix, the specific calibration curve must be made. This curve is achieved in laboratory by simulating the conditions of water variation of the RCC mix established to be used in site.

Such simulation is carried out by batching at least five RCC mixes with the same cement consumption 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/m3) x unit weight (kg/m3) will be correlated. Laboratory tests showed to meet the needs, as well as the use of this device at COPEL's Salto Caxias Dam, in Brazil.

The apparatus used for these tests for measuring the liquid displaced by the RCC is the same one used before, at concrete batchers, for determination of sand content. The time spent in carrying out each test is around 8±2 minutes.

HARDENED RCC PROPERTIES

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 higher RCC specific gravity is its lower water content and the compaction ratio.

Strength

Compressive Strength

Compressive strength is normally required because it is relatively very easy to determine. Many other properties are directly related to the concrete's 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 some of the long-term strength development of concretes containing pozzolanic material. The choice of design age will site specific depending upon the time of loading of the structure, the mixture proportions used, etc.

RCC strength is dependent upon the quality and grading of the aggregates, the proportions of cement, pozzolanic material, and water, and the degree of compaction. For most mixtures, the compressive strength of RCC is a function of the water/cementitious ratio (w/(c+p)), similar to traditional concrete.

The compressive strength increases with a reduction in water content as long as the 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 for the material. Water contents less than optimum produce lower compressive strength. This indicates that the presence of voids in the mix has greater negative effect on strength than the positive effect of water reduction. For most RCC dams, the consistency tests establishes a relatively fixed water content which is 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. Compressive strength increases with time and the amount of cementitious materials in the mix.

To discuss the compressive strength in a general way is very difficult because it depends on the cementitious content (cement+pozzolanic material). A normal way that can be used to correlate these parameter is based on "**mix efficiency = η**" that is a factor:

η = [Compressive Strength (Kgf/cm2)] / [Cementitious materials (cement + pozzolanic materials in Kg/m3)].

Generally, "mix efficiency" at larger ages is higher for RCC than comparable CVC, meaning that desired compressive strength of RCC can be obtained using lower cementitious content, particularly Portland Cement, and higher pozolanic material content. These types of mixes can develop more strength due to the best combination of cement and pozzolanic material.

Tensile Strength

The ratio of tensile strength to compressive strength for RCC mixtures have typically varied depending on aggregate quality, age, cement content, and strength. Tensile strength of RCC can either be determined by tests to measure direct tension or splitting (indirect) tension. The splitting tension test is also known as the Brazilian test.

Like compressive strength, tensile strength of RCC and CVC also depends on the cementitious content and age. For CVC tensile strength is considered to be 10% to 15% of compressive strength. Data from 22 dams or testing programs, indicates that the average tensile strength of RCC is also 10% to 15% of its compressive strength.

Shear

The shear strength of RCC is dependent on its tensile bond properties (cohesion) and angle of internal friction. Minimum strength occurs at construction joints and along the interface between lifts of RCC. Construction of a concrete dam using RCC methods produces a structure with lift lines every 0.3m to 1.0m vertically. The shear strength at the compacted lift lines is more important to the designer than the shear strength of the parent material.

✓ 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 plane of weakness in the concrete mass.

External and internal loads, including those due to temperature changes, imposed against 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. Near the upstream face the joint will also be subjected to internal hydraulic pore pressures, possibly of greater magnitude and over a larger area than in the adjoining concrete.

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 further increase 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 behavior of the entire concrete structure.

✓ Construction Joints in RCC dams

⇒ Serra da Mesa Cofferdam Investigations

Under ideal conditions, in a RCC dam, zero-slump concrete is placed in thin layers and compacted by vibratory rollers, in a continuous operation with successive layers being placed without significant interruption. However, for large RCC placements, continuous operation may not be feasible and some cold or construction joints are likely to occur. How should these joints be treated?

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.
- Clean-up of the RCC joints with low-pressure air-water jets showed only a small improvement in joint strength (16%).

The total shear strength can be determined using Coulomb's equation:

$\boldsymbol{\tau = C + \sigma * \tan(\Phi)}$ where

τ = unit shear stress;
C = unit cohesion;
σ = unit normal stress, and;
Φ = the angle of internal friction

The cohesion **C** is also called the bond stress, while $\boldsymbol{\sigma * \tan(\Phi)}$ defines the sliding friction resistance. A direct shear test is the usual method for obtaining cohesion and angle of friction data using various normal loads. The break bond shear strength may also be called the peak strength, and the “sliding friction” values denote the residual shear strengths.

These tests are done to get the Mohr-Coulomb Envelope, and so the cohesion **C** (shear strength) an friction angle **Φ**. The laboratory tests on monolithic- RCC- specimens could be done in:

- ➢ Triaxial Chamber similar in aspect, but greater in dimensions than that used for soil-mechanics, or rock-mechanics. In this way it is possible to change the confining pressure and determine the axial compressive value; or

- Direct Biaxial Shear test, is normally used in rock-mechanics, when it a normal load is applied and measure the shear (with a little angle of the plane due to the methodology) load; or
- Direct Unconfined Shear test, based in the CRD-C-90, Corps of Engineers Method of Test, where the shear load is applied in a single and non-confined plane.

The specimens from the RCC-Construction Joints, could be tested in:

- **Direct Biaxial Shear test - "in laboratory"**- on specimens drilled core from a trench, or from a large scale test-fill, or from a large specimen (for instance cast a 45x90cm specimen with a construction-joint in the central part, and after drilled a core throughout the construction-joint); or
- **Direct Biaxial Shear test - "in situ"**- in a large scale test-fill, as done at Urugua-i and Capanda dams.

Typical values of shear strength parameters for some RCC and CVC dams and studies shows that:

- The shear (cohesion and friction) values at construction-joint, (normally well treated and with "Bedding-mix"), are greater than the one 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.
- Results of direct, biaxial and triaxial tests performed on cores obtained from test fills and completed dams, and "in situ" tests, indicate that the shear strength components **C** and **Φ** are comparable to that of CVC made from similar aggregates. While cohesion is dependent on the cementitious content, the angle of friction is affected by the quality and gradation of the aggregates.

Modulus of Elasticity

The modulus of elasticity "E", also known as Young's modulus, is the ratio of the normal stress to its corresponding strain for compressive or tensile stresses below the proportional elastic limit of the material. Principal factors that can affect the modulus of elasticity of RCC and CVC values are:

- Age of tests- The modulus increase with age up to maximum value that corresponds 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 that of the aggregate if a rich mortar was used;
- Water cement ratio (or the "paste" proportioning)- As concluded from the above mentioned, rich mix : high values, and poor mix : low values.

Aggregate 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.

Poisson's Ratio

Poisson's ratio value is the ratio of transverse (lateral) strain to the corresponding axial (longitudinal) strain resulting from uniformly distributed axial stress below the proportional limit of the material. It appears that values for RCC are similar to values reported for CVC mixtures. A range from about 0.17 to 0.22 has occurred.

Creep

When 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.

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.

In comparison with creep values of CVC it can be noted that from the creep equation $\varepsilon = \{[1/E] + [f_{(k)}] x [\log (t + 1)]\}$, 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 as compared to that in CVC mixes, the coefficient of creep “$f_{(k)}$“ of RCC is larger than that obtained for CVC made of similar aggregates.

Generally, aggregates with a low modulus of elasticity will produce concrete with high creep. For most mass concrete applications, the ability to relieve sustained stress is desirable to relieve thermal stress. Higher strength mixtures generally have a more rigid cementing matrix and lower creep, which results in increased thermal stress. Lean mixtures and those made with inert fillers of natural or manufactured fines have higher than normal creep.

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 thresh-hold 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.

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 rate of loading, type of aggregate, shape characteristics (angular as produced by crushing versus natural round), and the cement content. Generally, the hard brittle aggregates such as argillite and quartzite produce lower strain capacity. Crushing or addition of crushed material usually improves strain capacity by increasing tensile strength.

Adiabatic Temperature Rise

The adiabatic temperature rise due to the heat of hydration, for both types of concretes is obtained by the same way, 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 manners. One, in terms of temperature degrees, in an absolute value range. Another manner that gives a simple way to general comparisons is a ratio between temperature degrees of adiabatic rise, per cementitious (cement plus pozzolanic material) content that is called “**coefficient of temperature rise**”. The most important is to get the maximum "**mix efficiency**", and the minimum "**coefficient of temperature rise**". RCC produces an adiabatic temperature rise in a manner similar to CVC concrete.

Thermal Properties

The thermal properties- Difusivity; Specific Heat; Conductivity; and Coefficient of Thermal Expansion- depend mostly on the aggregates thermal properties and the degree of saturation 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 tensile-strain capacity.

Volume change

In any massive concrete structure, the understanding of and the design for volume changes is necessary to minimize uncontrolled cracking. The reduction of volume due to thermal, or drying shrinkage, or autogenous volume is of concern in the design of RCC dams.

Drying shrinkage

Volume change from drying shrinkage in RCC is minimized by virtue of the reduced water content. Increases in moisture cause concrete to expand and decreases in moisture cause it to shrink. In the cement hydration process, water combines with the cement so the basic process is one of 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. Because RCC requires less water on the other hand, if marginal aggregates that have a high water demand and resulting drying shrinkage are used to produce RCC, it will have a corresponding volume reduction with moisture loss.

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 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.

Permeability

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 is sufficient fines, controlled fine-particle distribution to minimize the air void system, and full compaction, RCC will be relatively impervious. In general, an un-jointed 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 CVC concrete.

The property that has caused greatest concern to designers of RCC dam is the in-situ permeability of RCC. Although the permeability of the parent (un-jointed) material may be low, it is the joints between the layers that are 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 that passing through any cracks or joints in the structure.

Some authors propose that impermeability of RCC can be directly related to its cementitious content. This fact is especially applicable to RCC mixtures that conform to the concrete approach where the paste exceeds the voids in the aggregate. Therefore, greater cementitious content produce a more watertight paste, which controls the permeability of the RCC material. For soils approach mixes, greater impermeability can be achieved by a combination of increased cementitious content, greater compaction, and sufficient fines and well-graded aggregate, all of which reduce voids in the material.

The improved RCC mixes which have about the same coefficient of permeability as CVC, are more suited for construction of high gravity or arch/gravity dams. The use of higher percentage of non-cement fines, or filler, or pozzolanic material, in a RCC mix, contribute to its low permeability, without increasing the potential for thermal cracking.

The Coefficient of Permeability of RCC ranges from 10^{-6} m/s to 10^{-12} m/s with cementitious content from 60Kg/m3-250kg/m^3, as compared to 10^{-9} to 10^{-12}m/s for CVC with similar cementitious content.

Durability

- How does RCC compare with CVC as a material suitable for building high and large gravity dams of the same durability and quality as existing dams which have performed well for several decades?
- How does RCC compare with CVC as a material suitable for building pavements of the same durability and quality as existing pavements which have performed well for several decades?

Comparison of certain pertinent properties of RCC and CVC can be made to answer this question. Durability of RCC is especially important if the material is exposed to weather or severe hydraulic forces. Its durability has been documented by both laboratory tests and case studies in the field.

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. 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 on many projects. The most notable are the Salto Caxias dam, the spillway rehabilitation at Tarbela Dam, the spillway for the North Fork of the Toutle River debris retention dam, and the Kerrville pounding dam.

Salto Caxias dam, during the period from August/1997 to November/1997, was overtopped five times with a flow of 5500m3/s (13,100m3/s in total with 7,600m3/s throughout the sluiceways)

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.

Freeze-thaw resistance

Experience has shown that RCC made with a substantial amount of clayey fines will check and crack when subjected to alternating wet-dry cycles. RCC made with non-plastic fines or with no fines has shown no deterioration from wetting and drying.

Because proper air entrainment 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 to achieve other properties such as compressive strength. Little or no pozzolan replacement for cement is advised where horizontal RCC surfaces will be exposed to early freeze-thaw cycles while wet because high early strength is required under these conditions.

RCC DESIGN AND CONSTRUCTION- BRAZILIAN PRACTICES

Design

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

The use of drainage galleries and the shape of uplift diagrams have been a matter of discussion mainly when the RCC dam height is lower that 40m. Several Brazilian RCC dams constructed, under construction or still being designed have one line of internal drains as a supplementary guarantee against eventual seepage. Several Brazilian RCC dams either built, under construction or being designed were previously embankment dams. The change in the type of dam 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 constructive phases;
- taking advantage of the concrete characteristics.

Joint Treatment and Upstream Face

It is common knowledge that RCC is a construction technique and not a design concept. However, when discussing projects that may use the RCC technique, two basic points are usually considered:

- Treatment and characteristics of construction joints between lifts; and
- Watertightness and durability, upstream face type, seepage and drainage factors and control.

The treatment of construction joints between lifts has been much debated in numerous occasions and papers. These discussions and data from Test Fill Sections lead to the conclusion that tests should be done for each design requirement in order to determine surface treatment.

So, for dams in non-seismic areas, like Brazil, a friction corresponding to 45° stabilizes acting tensile forces. For arch-gravity dams, very high dams (more than 100m high), or projects in seismic areas, there may be a need to increase friction above 45°, and cohesion above 5 Kgflcm2. Cohesion and friction parameters for specific projects must be given considering materials and mixes at the job. In general way in the design for the Brazilian RCC dams it is common to specify bedding mix for using in partial or total construction joint surface area.

The second point usually debated regards watertightness and durability, upstream face type, seepage and drainage control. CVC (conventional mass concrete) Gravity Dam construction in Brazil, one of the largest practices in the world, demonstrates that Brazilian dams use concrete that complies with different durability and impermeability standards for the water-contact area. (*Examples of this are: Ilha Solteira; Água Vermelha; Porto Primavera; Tres Irmãos; Nova Avanhandava; ltumbiara; Marimbondo; São Simão; Tucurui, among others*)

In the case of Ilha Solteira Dam, concrete zoning, besides complying to resistance criterion, used an additional permeability requirement **"α"** with **$K < 10^{-9}$** cm/sec, for the face concrete. Many RCC jobs in Brazil (Jordão; Saco Nova Olinda; Caraíbas) have used this concept.

Generally speaking, when considering the design of a dam, resistance parameters are not so important as durability. This condition has led most concrete dams, specialy mass concrete, to use concrete zoning.

A conventional CVC mass concrete impermeable membrane, considering its watertightness measured by its permeability and deformation capacity (thermal tensile strength), evaluated by testing, has revealed itself the most attractive and adequate alternative for RCC dams.

When proportioning concrete mixes with volumetric stability, low permeability, and maximum density (lower void ratio) a concrete with greater "Durability" is characterized by the ability to bear the many agents that may act on it, not only the mechanic. However these concretes must have a minimum cracking potential (maximum strain capacity), reducing possible loss of impermeability through cracks.

Based on permeability tests, the thickness of a dam's impervious membrane, for both CVC mass concrete and RCC dams, can be dimensioned bearing in mind:

- minimizing cementitious content in order to keep concrete volume stable;
- compatibility of structures with thermal aspects through studies that regard control of face concrete temperature;
- optimization of non-cohesive fines content (pozzolanic or not, but preferably pozzolanic) in the mix;
- search for construction simplicity with less mistakes and/or failures;
- search for a low-cost, technically safe, alternative.

Materials

The installed capacity for power generation in Brazil (up to 2001) is $70x10^3$ MW. About 8% come from thermoelectric powerplants moved by diesel, coal and nuclear. Coal is responsible for only 2% of the total and is used in powerplants that are located in the south of the Country.

Hence it is almost impossible the use of fly-ash in the North and Northeastern parts of the country due to the high cost of transportation that may sometimes increase the cost of the material to a level higher than 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 or thermal cracking,
- reduced material for alkali-aggregate reactions;
- lower cost of the mix,

Silt was used in Brazil for some RCC mixes however one of the most important development in the concrete mix design refers to the use of stone dust or crushed powder as a filler. First experiments began at Itaipu laboratories 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 that the cost-benefit will be low. The use of silica-fume has not proved yet to be economical for the RCC mixes used in the country [87.07; 89.12; 89.21; 96.01; 96.27].

Proportioning RCC Mixes

The basic goal of a study on mixture proportioning is to establish a relation between **“available**” materials, so as to achieve concrete that:

- **While still fresh-**
    - Does not segregate, maintaining its uniformity;
    - Is reasonably stable under normal climatic conditions;
    - Can be manipulated for some time, without significant changes to its workability;
- **After hardening -**
    - Has the required properties;
    - Be volumetrically stable (regarding thermal and autogenous volume changes);
    - Be durable;
    - Satisfies established density requirements; and
- **Be low-cost**.

The proportioning study must aim at achieving quality and assurance at a low cost, concentrating therefore on materials **“available”** near the job site. When RCC is established as mass concrete, the need for achieving maximum density is relatively important and must be taken into account. **Economy**, though, must always be considered. Achieving maximum density may originate some discussion.

In countries like Brazil, with long distances and sometimes poor transportation condition, it is almost impossible to assume only one category of the above. Resources of certain basic materials may, or may not, be available near the job site.

It is well known that the transportation of materials is one of the most important items in the cost composition. Based on this, the use of more expensive materials should always be optimized. This way, it is very important to understand the concepts involved in RCC mixtures proportioning and professionals should look for low-cost complying alternatives.

Mixture proportioning should aim at achieving the highest specific gravity, or the lowest void ratio. Aggregates (according to the grain sizes in which they were produced) should then be combined so as to form a Grain Size curve (combining the individual sizes) closest to the following:

$\mathbf{P = (d/MSA)^{n} \times 100\%}$, where:

P = % passing through sieve “d”;
d = size of the sieve (mm);
MSA = Maximum size of coarse aggregate (mm); and
n= exponent , usually adopted ½ to ¼.

The cubic-type curve is characterized by requiring a certain amount of material smaller than 0.075mm (sieve No. 200). This amount is approximately 8% to 12% of the total amount of aggregates in the mixture. Another characteristic revealed in the cubic-type curve is the reduction of coarse aggregates that usually cause segregation.

At this point, the fine fraction of the cubic-type curve becomes important because the fines (smaller than 0.075mm), at an 8% to 12% recommended ratio, are helpful in filling the voids and allowing for adequate consistency, mixture cohesiveness and compaction. The use of fines in the RCC mix, based on the cubic-type curve, has shown innumerous advantages not only increasing the mixture's cohesiveness in its fresh state, but also accounting for benefits in the RCC in its hardened state.

It is possible to fill these voids with fly ash or milled slag, or by using a "filler" produced by the crushing of aggregates, or silt. Brazilian practice, with an high fines content, is more capable of reducing costs with comparable resistance and durability. Mixes with high fines content are those that use less external materials (in weight) (in this case, cementitious materials) so the potential for reducing costs is great. The kind of fines adopted will depend on the convenience at each job but it is wise to remember that the choice should be made on technical and economic basis.

Construction

Up to now the small projects in Brazil have used unsophisticated equipments for RCC production and placement. 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 with 0,25m in the first trials have increased to 0,40m in some projects, but in average it is around 0,30m.

Galleries construction embedded in the RCC have varied widely according to the requirements of each design. Several methods have been used such as:

- placing coarse or fine aggregate in that 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 and,
- 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 the removal was easy. The use of wood separators or of small precast elements has shown to be a good solution and improves the aesthetics. The use of coarse aggregate after compaction becomes a problem to be removed, being dificult and time consuming.

Procedures to built 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 the tendency that is being done in other projects in the world.

Quality Control

An overall Quality Plan or System for a construction is normally used 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.

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. The Overall Quality Plan is, normaly adjusted to local conditions taking into account the workman labor performance, equipment and technical knowledge. RCC placing rates can be extremely high when compared to conventional concrete. With such rapid placement rates or short term construction periods, problems must be evaluated and solutions implemented in a short period of time.

In addition to inspection activities, a comprehensive RCC quality control program can monitor the aggregate properties, RCC mixture proportions, fresh concrete properties, hardened concrete properties, and in-place compaction.

Logistic conditions for construction of the development were also considered such as, procurement 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.

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.

Emphasis on thorough control of materials (gradation, cementitious content, and moisture content) and conditions during placement is essential to proper RCC. An advantage of RCC and the above approach is that unacceptable material is identified early and can be removed at relatively low cost

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.