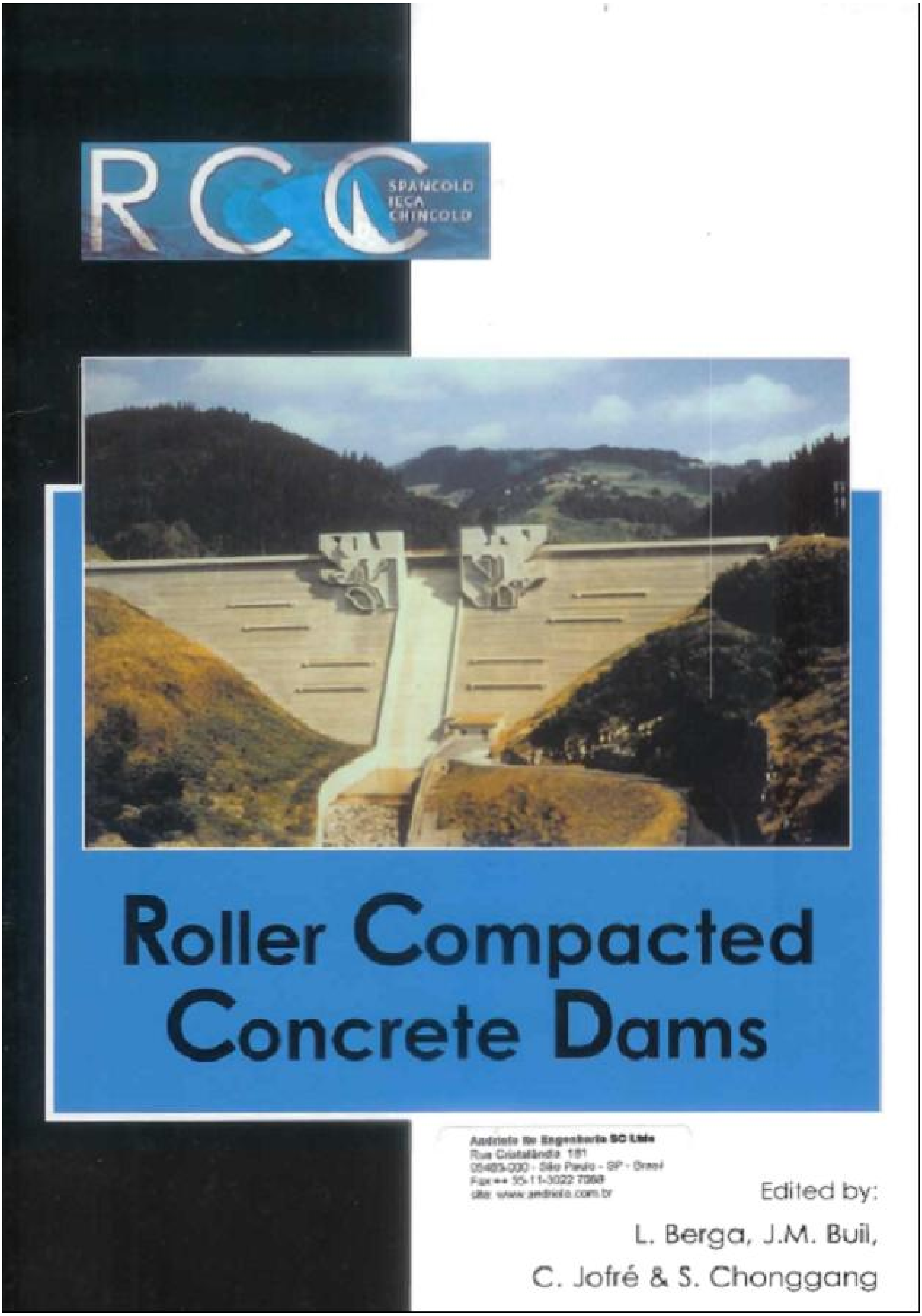

MATERIALS AND RCC QUALITY REQUIREMENTS

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Andriolo, Francisco Rodrigues

ANDRIOLO ITO ENGENHARIA SC LTDA
Rua Cristalândia 181- Alto de Pinheiros
05465-000- São Paulo- Brazil
www.andriolo.com.br; fandrio@attglobal.net

ABSTRACT: This presentation is composed of 4 Parts: Materials, RCC Mix Proportions, Tests and Properties, Inspection and Quality Control. The part referring to Materials mentions the ample scenery open by the RCC Methodology for the best use of the materials available. The Mix Proportion discuss a routine for RCC mix design.

The Tests and Properties Part exposes in a comparative way the CVC and RCC Properties. The text about Inspection and Quality Control presents information about the RCC control in several jobs. We are trying through these two topics to evidence that the RCC is a CONCRETE, leaving no doubts about its performance.

1 MATERIALS

1.1 *General*

Roller **C**ompacted **C**oncrete (RCC) is a ***CONCRETE,*** but differs from traditional concrete principally in that it has a consistency that will support a vibratory roller and an aggregate grading and proportion suitable for compaction by such a roller.

The objective of the selection of the materials for and design of the mixture proportions of an RCC is to provide a stable concrete that meets all the in-situ properties as strength, durability, and permeability requirements of the structure. When considering the materials (and mixture proportions) for an RCC dam, the Designer must always bear in mind that it is the in-situ properties, including those at the horizontal joints between the layers,
that are important and not the properties that might be achievable in the laboratory.

Materials for RCC can be from pit-run minimally processed aggregates with low cementitious (cement plus mineral admixture) contents to fully-processed concrete aggregates with different cementitious contents.

1.2 *Aggregates*

1.2.1 *General*

The selection of aggregates and control of aggregate grading are important factors influencing the in-situ quality and properties of RCC. The variability of aggregates during construction significantly affects the cementitious and water requirements, which in turn affect strength and yield. As the RCC is a concrete the Specifications should reflect an appropriate degree of control of aggregate quality and grading. The aggregates grading composition curve more often used in the RCC works has been of the cubical type as ***p= (d/Dmax)1/3 *100%*** type, with **"*p*"** being the percentage of a material finer han the mesh with a ***"d"*** opening and ***"Dmax"*** the maximum size of the aggregate with the major dimension used in the mixing.

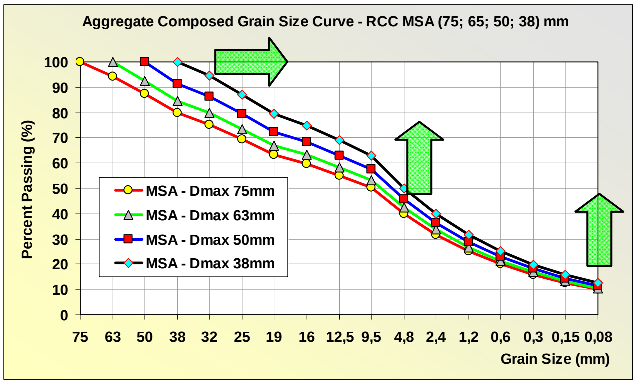
Observing the curves in Figure 01 one can see that as the aggregates Dmax in the grading composition is reduced, a greater quantity of "sand" (material inferior to 5mm) is required, as well as a greater quantity of "fines" (material inferior to 0,075mm). These conditioning items are required so that you can have closed grading concrete (RCC), with a smaller number of air voids, therefore with a maximum density and lower permeability.

The availability of natural materials with grading near optimum (curves in Figure 01) implies the need to process the aggregates, in order to attend the grading curve. In that situation, it is common the need of not only doing the sieving but also crushing the "over size" fractions so that the desired grading can be attained. Here attention is called to the content of "fines" desirable in the RCC mixes. The unavailability of "fines" will lead to the need of adopting an alternative to "close" the grading and minimize the air voids. This can be obtained by using pozzolanic material (if available at a low cost) either of Silt or of Rock Flour. The choice of the alternative must be made, prudently, on a technical and economical basis.

The majority of RCC dams have been constructed with aggregates meeting all of the traditional concrete requirements.

The presence of any significant quantity of flat and/or elongated particles is usually undesirable. However, RCC mixtures appear to be less affected by these particles than traditional concrete mixtures. This peculiarity may be because the compaction equipment provides more energy than traditional consolidation methods and because the higher mortar content tends to provide more separation of coarse aggregate particles, and the fact that the water content in RCC has not the same concept as in the CVC related to workability.

Field tests with up to 40% flat and elongated particles (with an average below about 30%) have shown to be no significant problem[1]. The US Army Corps of Engineers currently has a limit of 25% on the allowable content of flat and elongated particles [2].



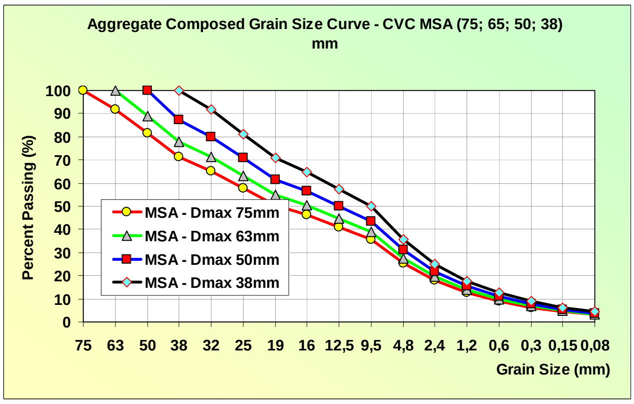


Figure 01- Usual Aggregates Grain Size Curves for RCC and CVC

Where there is a choice of source material, the material with the best combination of physical properties should be selected. Apart from the need for hard, durable aggregate, of high unit weight, characteristics that affect the thermal characteristics and cracking of the dam are important. A low elastic modulus and low coefficient of thermal expansion are desirable.

1.2.2 *Coarse Aggregate*

The most important factor to consider when selecting the source, shape and grading of a coarse aggregate is the avoidance of segregation. No matter how good the theoretical properties of an RCC are, if that concrete segregates when it is transported, spread and compacted, the in-situ performance will be less satisfactory than expected. In order to avoid segregation, it has been found that a well-graded aggregate, and with low amount of the coarsest fraction is more satisfactory. The maximum size of aggregate can have a very significant effect on segregation. Generally, the smaller the maximum size the less will be the tendency to segregate. However the additional effort required to produce aggregates with a smaller maximum size has to be balanced against the need to avoid segregation. It has been found that an increase in the proportion of the fine aggregate within the total grading can reduce the tendency for segregation.

The most popular maximum size is in the 75- to 80- mm size, although there now seems to be a trend towards smaller sizes because of the problem of segregation. The maximum size is tending towards 50 to 60 mm. The maximum size of aggregate is not related to layer thickness nor compaction machinery. Compactability is governed primarily by the workability of the concrete.

1.2.3 *Fine Aggregate*

Gradings of fine aggregate conforming to traditional concrete limits[3] have been successfully used for most RCC dams. Fine aggregates with these gradings may occasionally require more cementitious material than is needed for lean mixtures using aggregate with more fines than is generally allowed.

Unwashed aggregates with a much broader grading range than is usually specified[3] have also been used. The aggregate grading and fines content affects the relative compactability 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. Crusher fines and silty (no-plastic fines) material are usually acceptable.

1.2.4 *Overall Grading*

As can be seen in Figure 01 there is a definite trend of a reduction in fine aggregate content with increasing maximum size of aggregate. Some cost savings might be achieved by combining two or more size ranges to reduce the number of stockpiles. The Designer and/or Contractor must balance the potential cost savings in a reduction in number of stockpiles and separate handling and weighing facilities with the potential for increased variation in aggregate grading and its impact on uniformity of the RCC. Three or four aggregates sizes are mostly used in RCC dams.

1.2.5 *Gravel or Crushed Aggregates*

Figure 02- Natural Aggregates

The RCC can be proportioned and compacted with natural aggregates (gravel) or with crushed aggregates. The most important item is that the aggregates be proportioned adequately and the admixtures comply with the properties, at a low cost.

1.3 *Cementitious Materials*

1.3.1 *General*

RCC can be made with any of the basic types of cement or, more usually, with a combination of cement and a mineral admixture. It is very well known that the great majority of RCC mixtures contain mineral admixtures (usually a ground-granulated blast-furnace slag, fly-ash, natural pozzolan, rock flour and silt). The use of mineral admixtures has the desirable effects of reducing the Portland cement content, thus usually lowering costs and reducing the heat of hydration, and giving slower strength development which can reduce thermal stresses.

1.3.2 *Cement*

RCC can be made from any of the basic types of cement. For RCC dams, cements with lower heat generation characteristics than Ordinary Portland cement (ASTM C150 [4] Type I) may be beneficial, if they are locally available. They include Type II (moderate heat), Type IP (Portland pozzolan cement), and Type IS (Portland blast-furnace slag cement). Strength development for these lower-heat cements is usually slower than for Ordinary Portland cement at early ages. At greater ages, the slower-early-strength-development cements usually ultimately produce higher strengths than Ordinary Portland cements.

1.3.3 *Mineral admixtures*

Mineral admixtures are finely divided siliceous materials that are added to cement. The use of pozzolanic materials in the massive concretes is an old and renowned practice, with the use of percentages around 15 and 25%, predominantly. The advent of RCC led to the use of higher contents of pozzolanic materials. In a special range the blast-furnace slag can be placed, which also presents pozzolanic characteristics.

Some mineral admixtures can show pozzolanic activity (fly ash, natural pozzolan and calcined clay- Figure 02), some others are cementitious (ground-granulated blast-furnace slag), whereas others are both cementitious and pozzolanic (high-lime fly ash).

Prior testing of potential sources of pozzolanic material in the RCC mixture is advisable for all structures. If no other source of mineral admixtures is available, it is possible to obtain a certain pozzolanic activity using a siliceous filler by crushing rocks with certain amount and mineralogical condition of siliceous matrix. Even if these two last materials are generally less effective than other types of materials, they have been used in RCC for dams, particularly in Brazil [5 & 6], and some other countries [7].

Use of mineral admixtures or fillers in RCC mixtures may serve one or more of the following purposes:

- as a technical purpose to minimize the Alkali-Aggregate Reaction;
- as a proportion of the cementitious content to reduce heat generation;
- as an additive to provide supplemental fines for mixture workability, and impermeability, and
- as a proportion of the cementitious content to reduce cost.

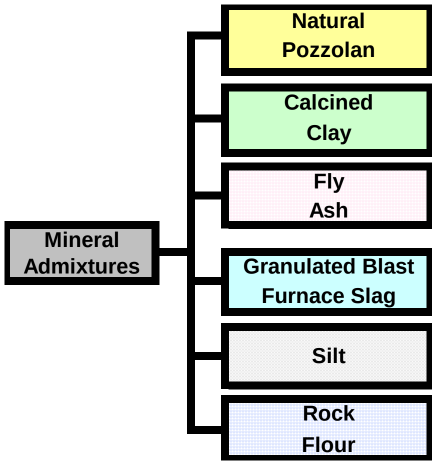


Figure 03: Forms of mineral admixtures

The convenience of adopting the cubic type of grading curve as previously mentioned, implies in having around 10 to 15% of fines (material inferior to 0.075mm), as shown in Figure 01. In order to do that it is possible to rely on the use of "Silt", obtained in natural deposits or by the production of fines using rock crushing, gravel or blast furnace slag. In these cases the rock crushing, producing the Rock Flour, may be even more beneficial, if, besides composing the desired grain curve, the rock has contents and mineralogical conditions (SiO_2; Al_2O_3 and Fe_2O_3) that have satisfactory pozzolanic activities.

The indiscriminate and irrational use of high contents of pozzolanic material is not advisable under two aspects:

- The occasional unavailability of Calcium composites, present in the Cement, to react fully with the components of the pozzolanic material.
- Costs

This is to say that the adequate content of Pozzolanic material to be used depends on the Pozzolanic Activity, to be shown together with the cement, in tests with different combination contents of **cement: pozzolanic material**.

A good example about this evaluation can be observed in Japanese [8 & 9], Chinese [10], and Brazilian [5, 6 & 11], studies, where it is evidenced:

- The Japanese studies - *"…As a result, it became clear that by mixing the filler of proper quantity, the VC value (Vibrating Compacting Value) of concrete quantity dropped, and compacting became easy, and compressive strength was increased. Moreover it is thought that the use non-washing crushed stone is possible…"*(See graphics in Figures 04 & 05);
- The Chinese studies - *"…The optimum content of Fly Ash should be determined according to the quality of Fly Ash, strength and strength design age of concrete, variety and strength grading of cement, price ratio of cement to Fly Ash and so on…"*(See graphics in Figures 06);

The Brazilian studies – *"…Improved resistance obtained with the use of Filler on the CVC, plus the improvement observed in reduction of the RCC permeability prove that the use of this material is worthwhile…"*[12]; *"…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; The set of data submitted in this report makes evident a substantial Pozzolanic characteristic of the Fillers studied which states the validity of its use in RCC and also in conventional types of concrete which corroborates the theoretical expectation mentioned in the text…"* [5]

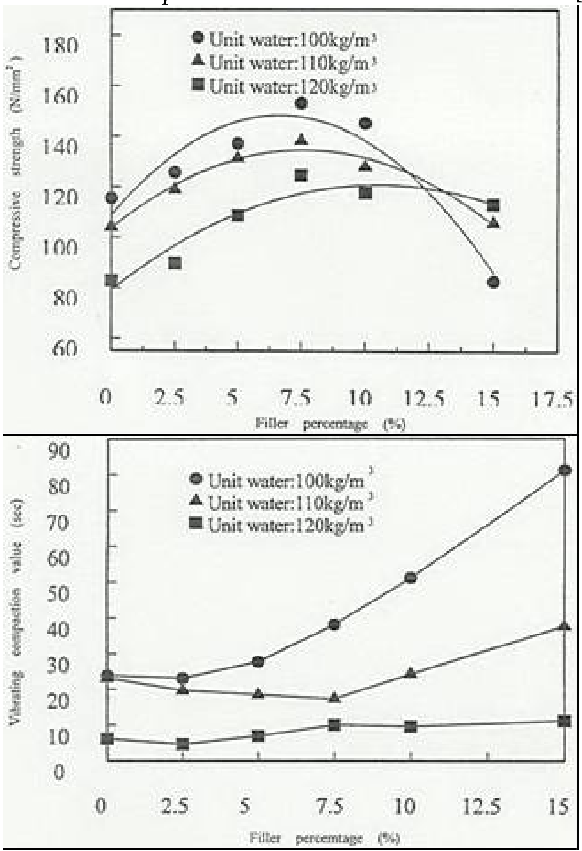


Figure 04-Compressive Strength and Vibrating Comapcting Value with different Fines Content (From [8])

The use of pozzolanic material has made the designer revise the properties control age, which around the sixties was between 28 and 90 days, with very few countries using the ages of 180 days and one year, to the present situation where the properties began to be controlled mainly with more than 90 days.

The use of high contents makes part of the pozzolanic material act as "Filler" and this must be economically evaluated (as mentioned before).

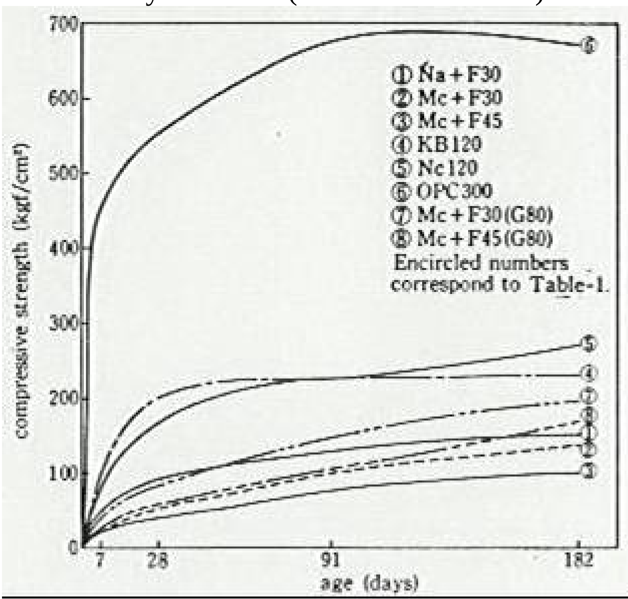


Figure 05- Compressive Strength of RCC Versus Age with Different Fly Ash Replacement Ratios; and with different cement type (From [9])

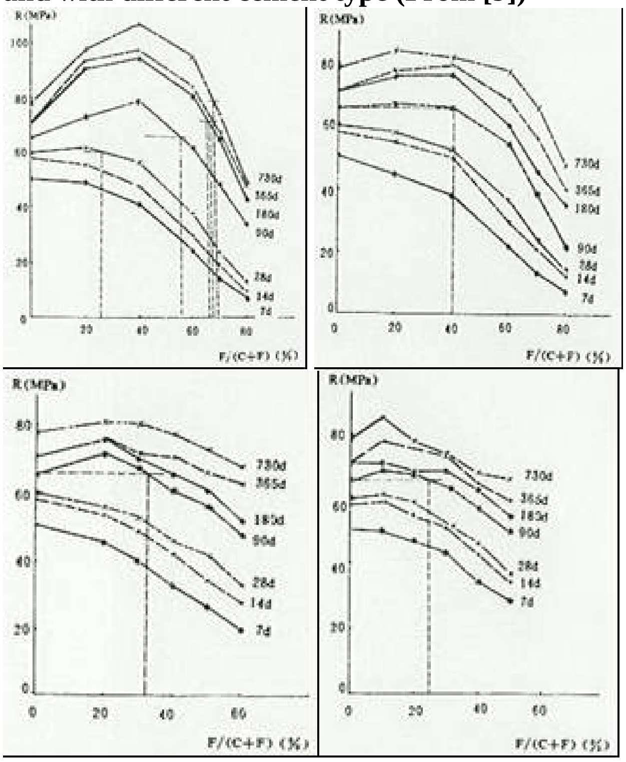


Figure 06- Compressive Strength curves for mortar with different Fly Ash contents and different types of Fly Ash (From [10])

1.4. ***Admixtures***

The use of additives in RCC is a relatively new approach. The use of chemical additives has increased since mid 90’s, aiming at controlling the “Set” and broadening the operational margin for RCC transportation and compaction [13 to 17]. Its use has propitiated, besides control of the set, gains in resistant properties and that becomes a technical parameter with economic implications that must be analyzed (see Figure 09). The choice of any admixture should be confirmed by laboratory trial mixes and ideally after full-scale trials. Particular admixtures work well with particular cementitious materials and not so well with other materials.

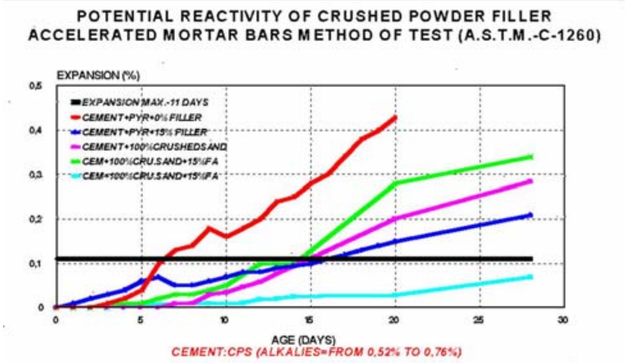


Figure 07-Reduction of the Mortar Expansion due to the Use of Rock Flour (From [5])

Mortar Test		Control	Sample as produced - Blaine 2,962 cm2/g				Sample grinded - Blaine 4,024 cm2/g			
Fly Ash Content (%)		0	10	15	20	30	10	15	20	30
Compressive Strength (kgf/cm2)	7 days	209	166	159	139	107	205	192	172	116
	28 days	331	254	243	233	169	319	318	282	199
	90 days	397	342	352	327	279	433	423	420	308
	365 days	426	435	471	472	389	548	538	537	466
Heat of Hydration	7 days	76	63	60	63	52	68	64	61	62
	28 days	80	74	72	72	68	83	73	73	73
Activity: Strength / Heat	28 days	100%	83%	82%	78%	60%	93%	105%	93%	66%
	90 days	100%	93%	99%	92%	83%	105%	117%	116%	85%
	365 days	100%	110%	123%	123%	107%	124%	138%	138%	120%

Mortar Test		Sample grinded - Blaine 5,200 cm2/g				Sample grinded - Blaine 6,056 cm2/g				Sample grinded - Blaine 7,142 cm2/g			
Fly Ash Content (%)		10	15	20	30	10	15	20	30	10	15	20	30
Compressive Strength (kgf/cm2)	7 days	237	211	188	155	238	198	163	152	226	205	214	169
	28 days	351	325	296	253	365	339	303	298	391	372	377	345
	90 days	436	421	428	413	479	452	455	477	450	481	500	502
	365 days	559	563	548	579	557	553	566	583	551	569	569	605
Heat of Hydration	7 days	68	65	61	57	64	62	59	60	68	66	63	56
	28 days	76	74	70	71	73	74	75	71	78	78	70	70
Activity: Strength / Heat	28 days	112%	106%	102%	86%	121%	111%	98%	101%	121%	115%	130%	119%
	90 days	116%	115%	123%	117%	132%	123%	122%	135%	116%	124%	144%	145%
	365 days	138%	143%	147%	153%	143%	140%	142%	154%	133%	137%	153%	162%

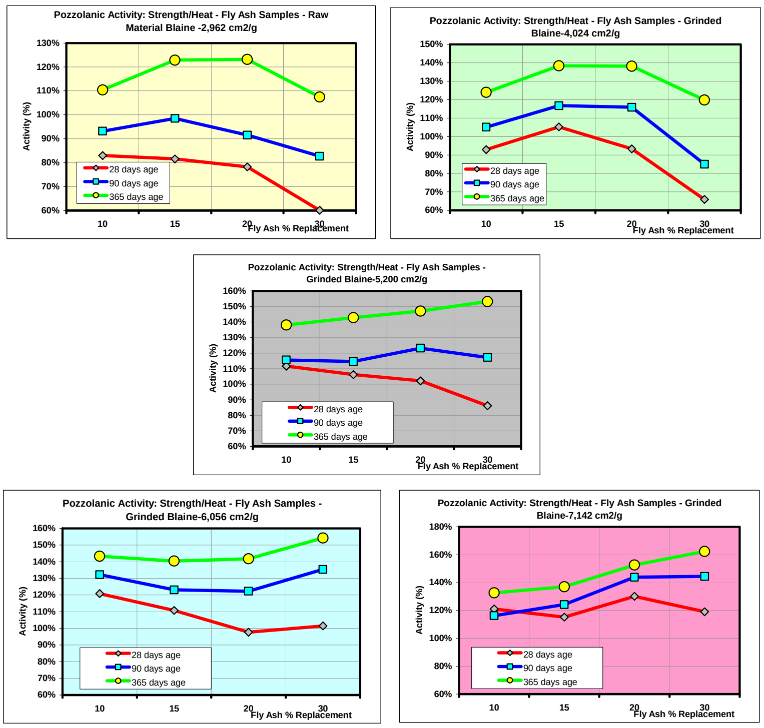


Figure 08- Compressive Strength of Mortar with different contents of Fly Ash at different Fineness (from [11])

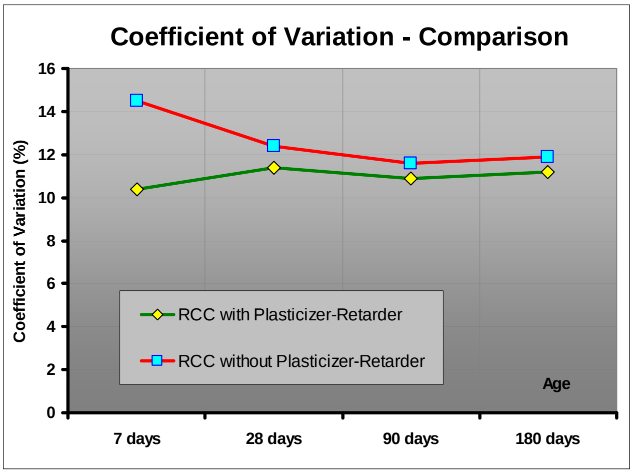


Figure 09- dvantages in using Water reducer/Set Retarder admixtures, concerning the Mix Efficiency and Uniformity (coefficient of Variation) (From [14])

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 [13; 15 & 16] and Spain [17].

1.5. *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 alkalis, acids, or organic matter that might inhibit proper strength gain.

2 RCC MIX DESIGN

2.1 *General*

Roller Compacted Concrete (RCC) is a relative easy and simple construction technique, but unfortunately up to now, has not yet a consolidated methodology for design, mixes proportioning and laboratory tests. Some authors or technical groups have shown tendencies or advantages in adopting a procedure for mix design. In a general point of view this could be summarized in specific tendency or experience that could not be accepted as a general rule. There are a number of methods that have been used for the design of the mixture proportions of an 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 saturatedsurface- dry (SSD) aggregate condition***.

A practical reason for using this standard convention is that most RCC mixing plants require that mixture constituents be thus identified for input for the plant-control system.

A number of mixture 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.

Emphasis is placed on determining optimum water content for compactability at fixed cementitious materials content. Selection of cementitious materials content and water content is determined from design requirements, (Compressive, Tensile, Shear Strengths; Permeability, etc…), with consideration of minimizing the cementitious materials content to avoid thermal cracking. It could be said that the mix design of a concrete is a process by which can be obtained an adequate and economic combination of binder, aggregate, water and admixtures producing a concrete which performs to the required specifications throughout its service life.

It is the authors' opinion that design features should take advantage of the economies of RCC construction, looking for simplicity, quality, and being economical. A mix design process must assure the required property values; no segregation occurs by handling operations and performance requirements are met using the proper materials. The diversity of the structural designs, the environmental, geographical and other conditions reflected, justifies why several types of concrete exist which differ in their composition and characteristics.

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.

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. RCC presents two fundamental differences in composition with respect to their CVC counterparts:

- Firstly, RCC generally use an aggregate combination that reduces the coarse fraction and increases the use of fine material, as previously mentioned, and;
- Secondly, 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.

2.2 *Routine*

As described, there are several methods that use the **'concrete'** approach for the design of the mixture proportions of an RCC including that used for the design of RCD mixtures. All the methods have similarities and follow similar procedures although there are minor differences. The routine [6] below show the main conceptual points of the mentioned approaches. The suggested procedure is as follows:

a) Optimize the gradation of the fine and coarse aggregates to produce minimum voids in each using additional mineral fines in the fine aggregate or available pozzolanic material if necessary. The mixes were proportioned in attempting the main objective to reach the maximum specific gravity. So the aggregates can be combined to adjust as near as possible from a curve type ***p= (d/Dmax)1/3 *100%;***

b) Proportion the Portland cement, pozzolanic material (if any), water and admixture (if any) to obtain the required property to obtain the proportions of the paste. This can be modified to choose the minimum cost mixture. For example if the pozzolanic material is cheap relatively to the cement and/or the available fine material (silt, crushed powder filler or other equivalent), a higher proportion of the cementitious content would be pozzolanic, while if it is near the cost of the Portland cement, a lower proportion would be used;

c) Check that there is sufficient cementitious material (and a proportion of mineral fines, if used) to provide the design permeability and durability;

d) Check that the fine aggregate/coarse aggregate ratio is close to the optimum;

e) Check that the heat of hydration is within the expected limits;

f) Make any adjustments that are necessary (laboratory and field) and re-check the design.

3 TESTS AND PROPERTIES

3.1 *General*

RCC is a concrete, and so, the significant material characteristics and properties of RCC include:

- Fresh RCC: consistency, unity weight, setting time and uniformity;
- Hardened RCC: specific gravity, absorption, compressive strength, tensile strength, biaxial and triaxial shear strength, modulus of elasticity, Poisson's ratio, tensile strain capacity, volume change (thermal, drying, and autogenous), thermal coefficient of expansion, specific heat, creep, thermal conductivity, thermal stress coefficient, diffusivity, permeability, and durability.

On a general point of view some doubts and questions remain that 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 paper intends to discuss the RCC properties and quality in comparison with CVC properties, considering the large data obtained at job construction.

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 to that which occurs in CVC concretes.

3.2 *Fresh RCC Properties*

3.2.1 *Consistency Tests - Workability*

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 he desired strength properties. Workability of RCC mixtures is normally measured using a modified VeBe apparatus[18] or the VC test in Japan[19]. 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 that one which produces a maximum dry density. 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 compactable mix as determined by construction of a test section. RCC mixtures with the degree of workability necessary for ease of compaction and production of uniform density from top to bottom of the lifts and for support of compaction equipment generally have a VeBe time of 20 to 30 seconds.

3.2.2 *Water Content- DMA- Brazilian Method*

Pacelli and al [20] 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 production.

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 situ. 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/m^3) will be correlated. An example of the calibration curves is shown in the Figure 10.

Theoretical Unit Water (Kg/m3)	Measured Water Content (Kg/m3) WMD-"DMA"	Measured Specific Weight (Kg/m3) WMD-"DMA"	Measured Specific Weight (Kg/m3) 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

Figure 10- Measured Volume (WMD) * Unit Water [6 & 20]

The apparatus used for these tests for measuring the liquid displaced by the RCC is the same as the one used before, at concrete batchers, for determination of sand content. The time spent in carrying out each test is around 8±2 minutes. The device is shown in Figure (11) below.

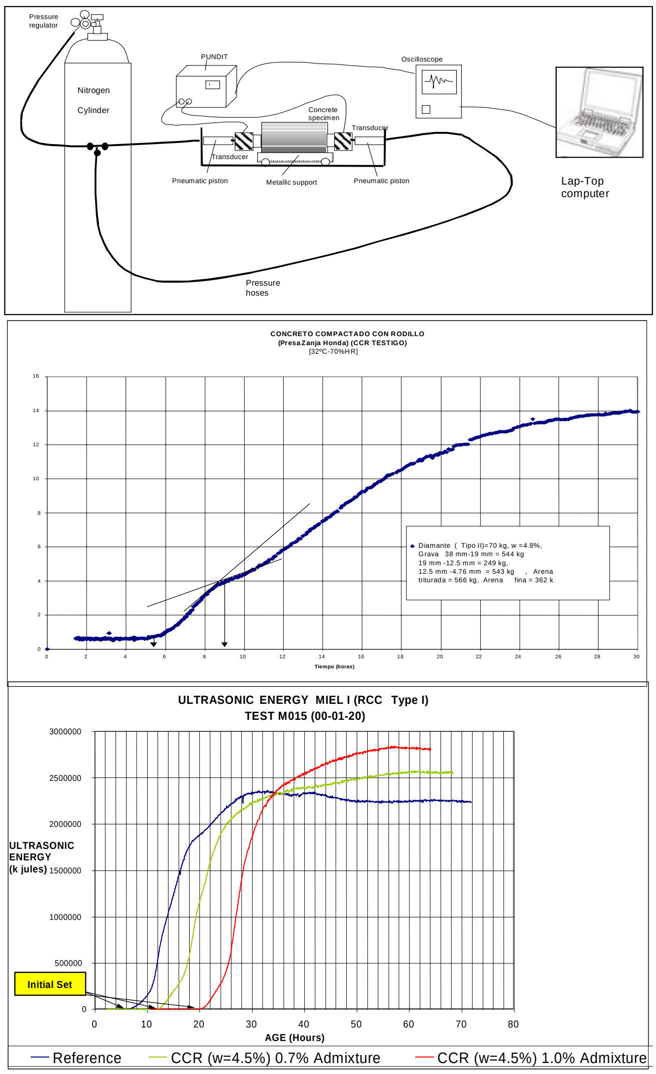
Figure 11- Device for determination of unit weight and unit water of RCC

3.2.3 *Unit Weight- Specific Weight-Specific Gravity-Density*

Although the density is mainly dependent upon the Relative Density of the aggregates to be used in the concrete, any entrapped air will lead to a loss of properties and also, if the air content is significant, to a greater volume of concrete having to be placed. 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.

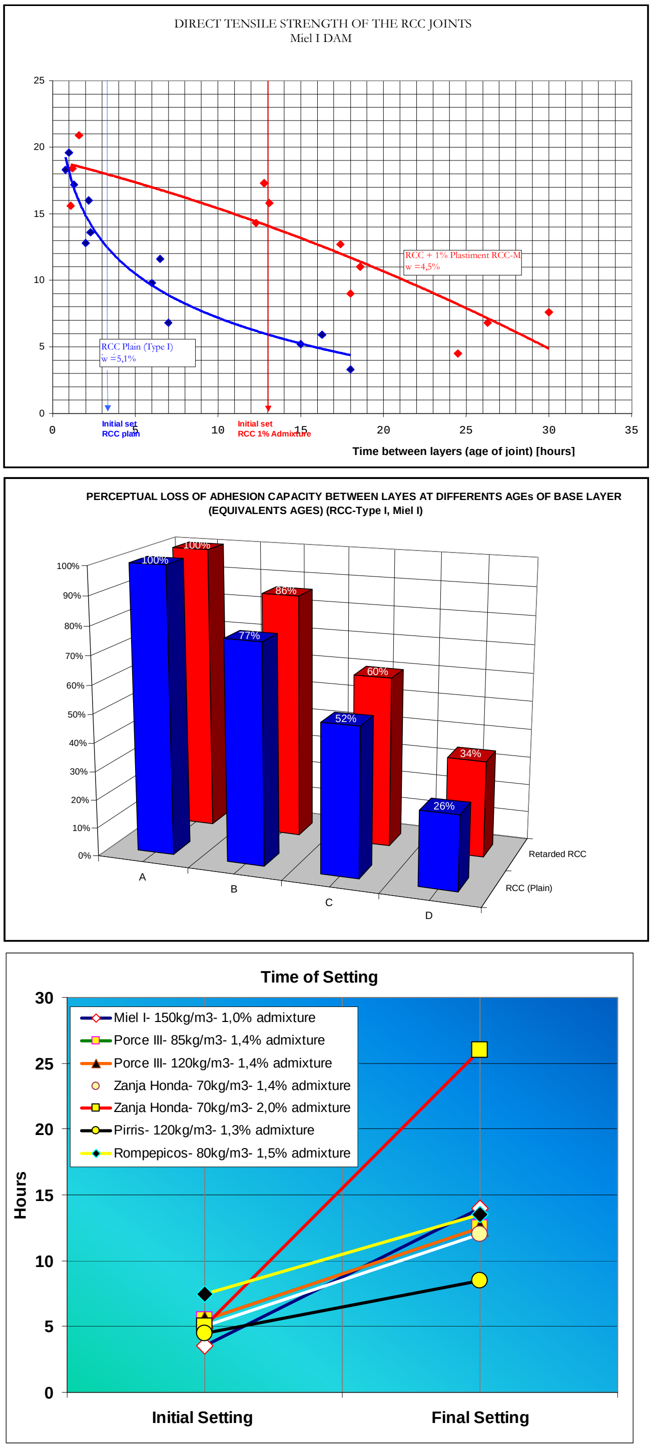
3.2.4 *Setting Times*

The importance of identifying the setting times on the RCC which has just been compacted and, is still fresh, is based on assuring an adequate adherence between layers. The horizontal joints between layers, where the bond is required, becomes from the impermeability and shear point of view, one of the most vulnerable parts of the dam. The correct identification of the setting times, for different atmospheric conditions, allows establishing the limits in time, for which a superficial treatment on the joint should or should not be done, or the use of mortars of bond, in order to guarantee the level of adherence of design between layers. A recent methodology to identify the setting times on RCC based on the analysis of an ultrasound wave was introduced [21]. The new methodology permits to identify the moment when the initial setting begins on RCC, using the ultrasonic energy parameter. The direct tension and/or shear strength between layers and the time of setting can be correlated.



Figures 12a- Ultrasonic energy values evolution and initial times of setting for different admixture doses under controlled temperature and relative humidity [21 & 22]

The ultrasonic energy concept becomes one of these new advantages and permits to detect the progressive growth of the solid phase (crystals) in a composite material. The energy parameter takes into account the amplitude, frequency and intensity variations of the wave that goes through the material. The material on its fresh stage, composed by a set of initial phase proportions, gaseous, liquid and solid, changes these proportions when becomes rigid and sets.



Figures 12b- Direct Tensile Strength at Construction Joints and Time of Setting with and without Set Control Admixtures [21 & 22]

3.2.5 *Uniformity*

A major objective in the proportioning of RCC mixtures is to produce a cohesive mixture with the least possible tendency to segregate. Limiting the maximum size of aggregate also helps reduce the potential for segregation.

3.3 *Hardened RCC Properties*

3.3.1 *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 main reason for higher RCC specific gravity is its lower water content and the compaction ratio. Figure (13) shows some typical RCC and CVC test-values, used at some projects [6].

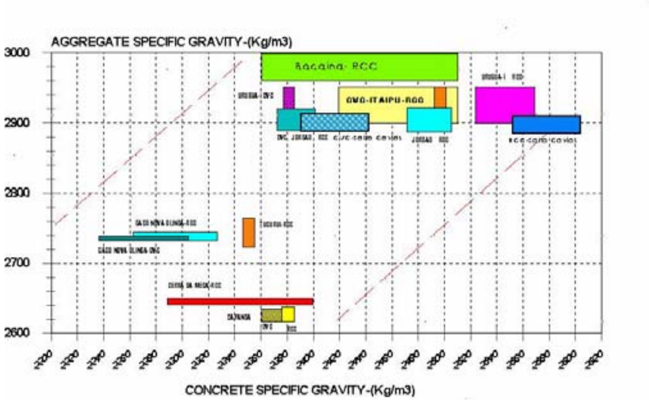


Figure 13- Specific gravity of concretes related with aggregate specific gravity [6]

3.3.2 *Strengths 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 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. 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.

To discuss the compressive strength in a general way is very difficult because it depends of the cementitious content (cement+pozzolanic material). A normal way that can be used to correlate this parameter is based on "**mix efficiency** = η " that is a factor [6]: η = **[Compressive Strength (Kgf/cm^2)] / [Cementitious materials (cement + pozzolanic materials in Kg/m^3)].**

"Mix Efficiency" at various ages for 60 RCC and 18 CVC dams or studies is plotted in Figure (14) where data for these 18 CVC concretes could compare RCC and CVC using the same constituents.

Generally, “mix efficiency” at lager 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 pozzolanic material content. These types of mixes can develop more strength due to the best combination of cement and pozzolanic material.

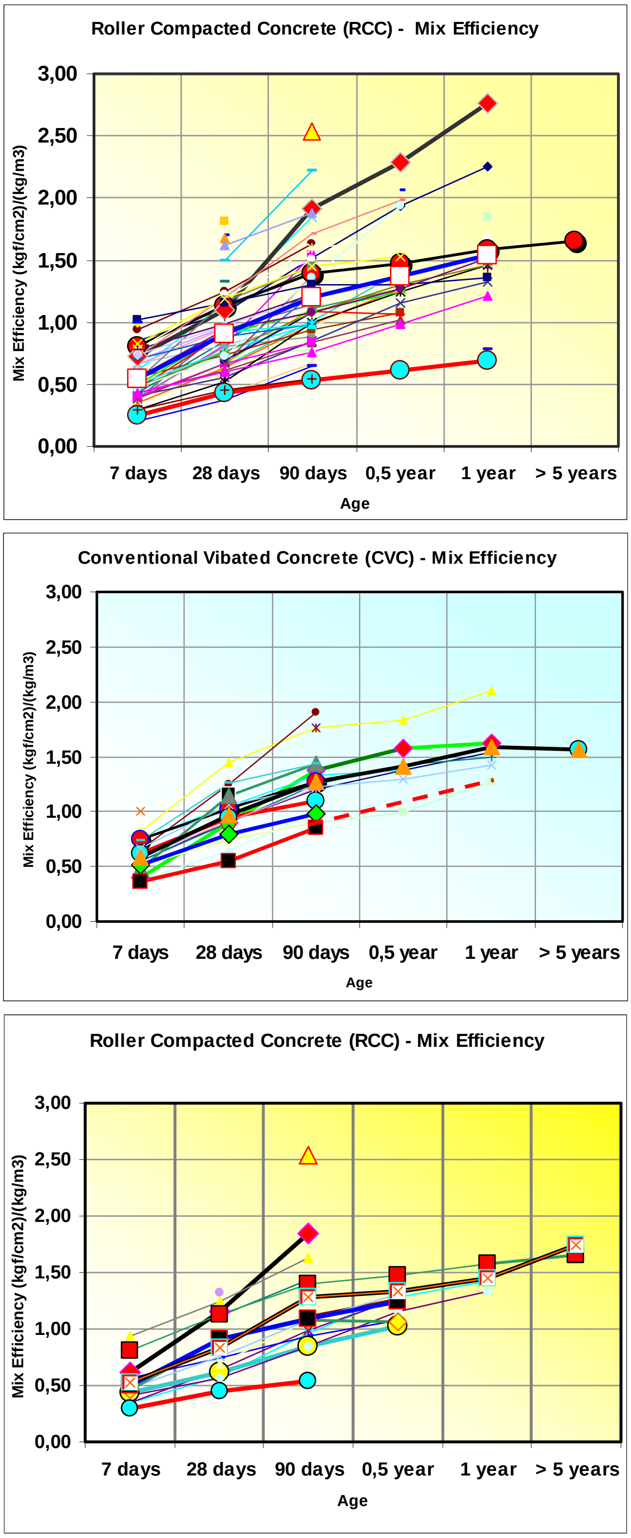


Figure 14- Mix Efficiency- RCC and CVC concretes

3.3.2.2- 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 28 dams or testing programs indicate that the average tensile strength of RCC is also 10% to 15% of its compressive strength, also.

The Direct Tensile Strength shows values from 55% to 98% when related to Indirect Splitting Tensile tests.

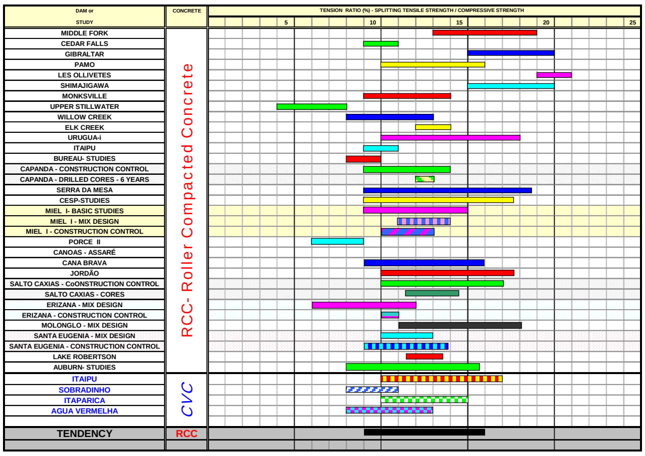


Figure 15- Ratio Indirect Tensile and Compressive Strength

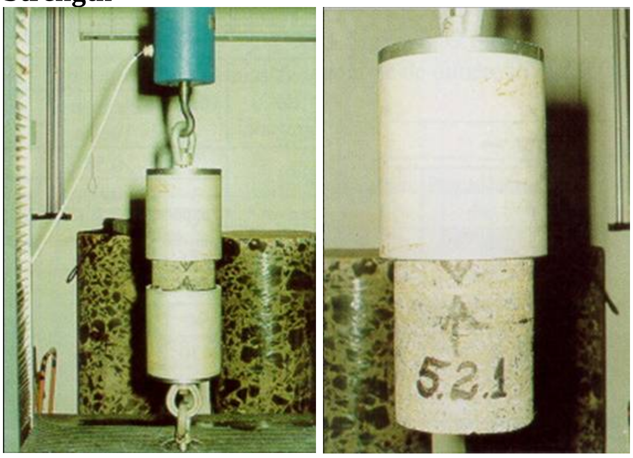


Figure 16- Direct Tensile Test

3.3.2.3- Shear

The shear strength of RCC is dependent upon 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 structure with lift lines every 0.3m to 1.0 m vertically. The shear strength at the compacted lift lines is more important to the designer than the shear strength of the parent material. 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. Horizontal joints are inevitable in

CVC and RCC dams because of the layered method of construction.

The performance of an RCC dam will almost entirely be dictated by the performance of the horizontal joints between the layers. In addition the joint surfaces must be scrupulously clean. However, if any of these factors are not present, the performance of the joint may be less satisfactory. 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. Bedding mixes used on the surface of the layer will improve the shear and tensile strength of the joint for a given set of conditions.

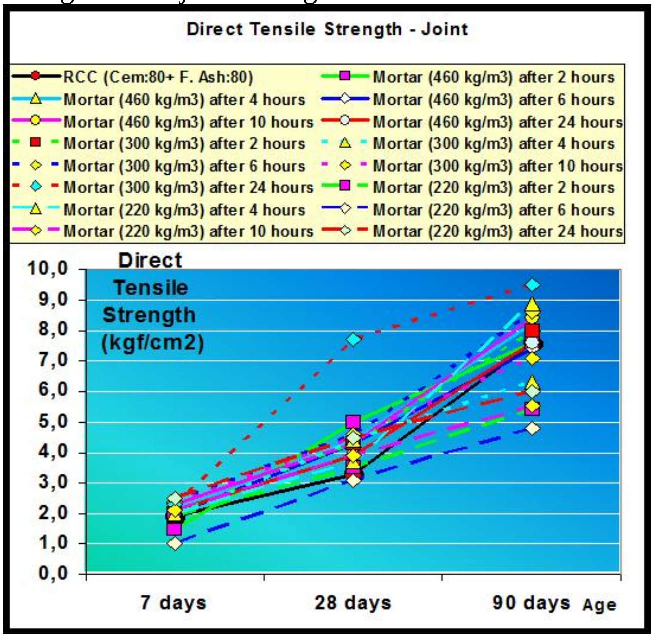


Figure 17a- Direct tensile strength on the RCC joints with mortar compared with parent RCC

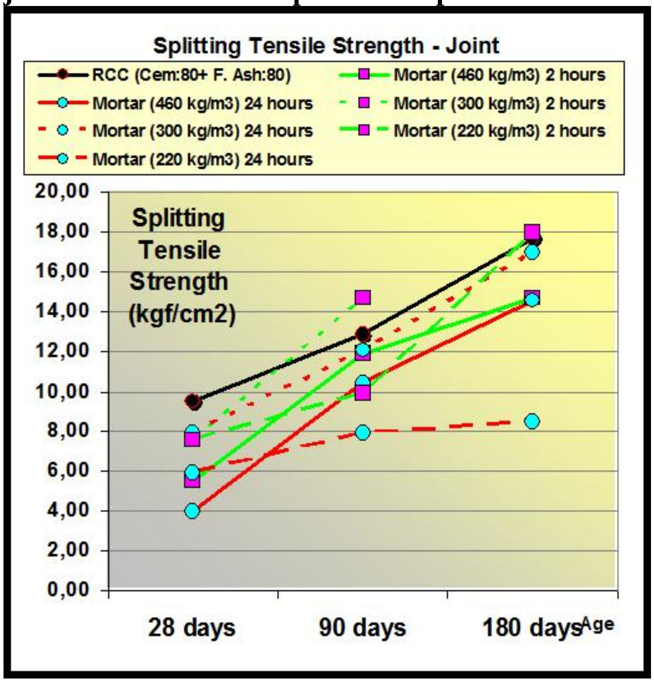


Figure 17b- Splitting tensile strength on the RCC joints with mortar compared with parent RCC

From references [21 & 22] can be seen (Figure 17) that the direct tensile strength on the horizontal joints decreases after the initial setting of the base layer, between 50 to 60% of the initial value obtained when the joint is fabricated just after the base layer was compacted. The direct tensile strength on the horizontal joint decreases progressively with the time of exposure of the base layer, even before the initial setting takes place. The definition of the limit of hot joint as the instant of initial setting, takes into account a drop in the capacity of bond to 77% - 86% to the direct tensile strength, obtained in joints fabricated immediately after base layer was compacted. An investigation[23] 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 interval time between lifts.

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 (18). The total shear strength can be determined using Coulomb's equation:

$$\tau = C + \sigma * \tan(\Phi)$$

where

τ = unit shear stress;

C = unit cohesion;

σ = unit normal stress, and;

Φ = the angle of internal friction

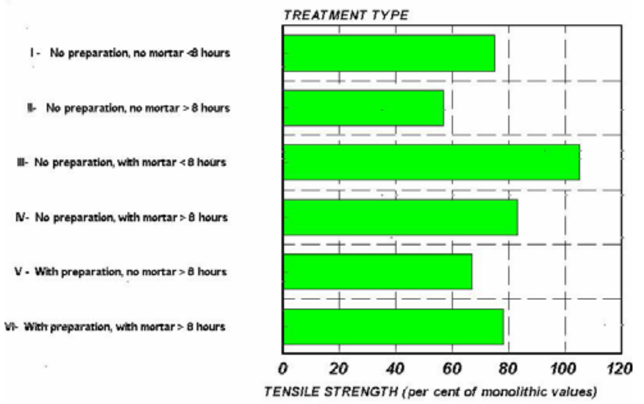


Figure 18- Serra da Mesa Cofferdam Tensile Stength [6 &23]

The cohesion **C** is also called the bond stress, while σ*tang(Φ) 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) a friction angle Φ . The laboratory tests on monolithic- RCCspecimens could be done in:

- Triaxial Chamber similar in aspect, but greater in dimensions than that used for soil-mechanics, or rockmechanics. In this way it is possible to change the confining pressure and determine the axial compressive value, as shown in Figure 19; or

- Direct Biaxial Shear test, is normally used in rock-mechanics, when a normal load is applied and the shear (with a little angle of the plane due the methodology) load measured (see Figures (20); or
- Direct Unconfined Shear test, based on the CRDC- 90, Corps of Engineers Method of Test, where the shear load is applied in a single and non-confined plane.

Figure 19- Triaxial chamber used for concrete tests

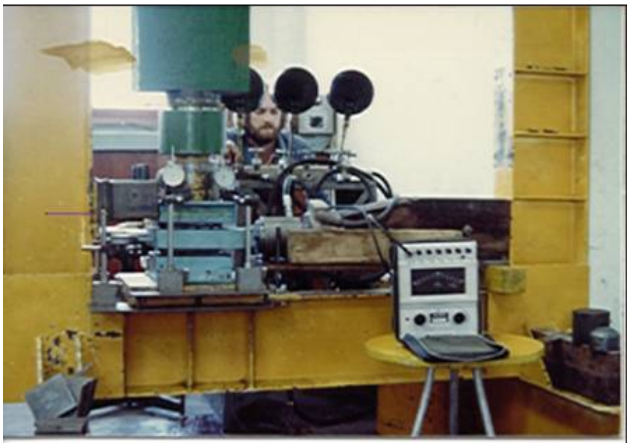


Figure 20- Biaxial shear test apparatus

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

- **Direct Biaxial Shear test - "in laboratory"-** as shown in Figures 20 and 21, 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 drilling a core throughout the construction-joint); or
- **Direct Biaxial Shear test - "in situ"-** in a large scale test-fill, as done at Urugua-I, Capanda and Salto Caxias Dam dams and as shown in Figures 22.

Typical values of shear strength parameters for some RCC and CVC dams and studies are shown in Figures 23. Figures 24 show values from Figure 23, and Figure 25 compares values from shear tests from the rock (meta-sandstone) foundation contact at Capanda dam[6].

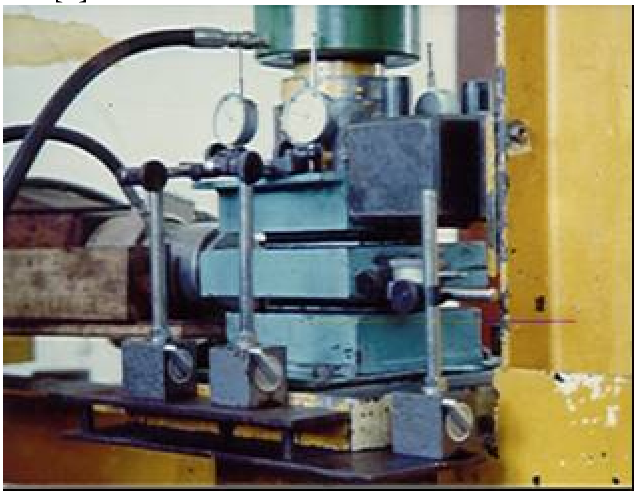


Figure 22- Biaxial shear test for concrete cores

Figure 23- Biaxial shear test in situ at Salto Caxias Dam- Brazil

It is very important to show this, because it is possible to see 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.

3.3.3 *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:

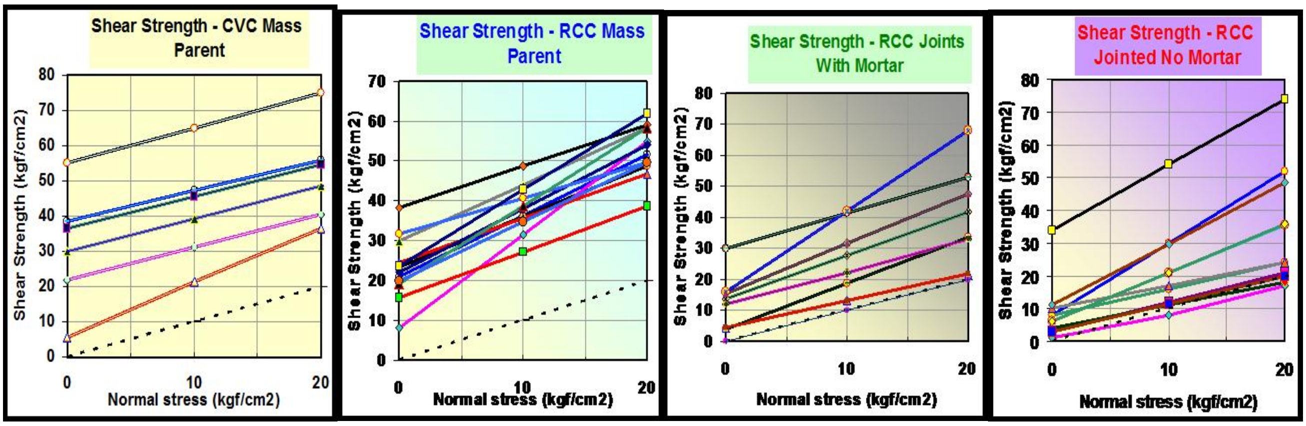
- Age of tests- The modulus increase with age up to maximum value that correspond to the maximum that could be reached by the mortar or the aggregate (which is lesser);

- Aggregate type (and its modulus)- At large ages the concrete modulus could be similar to the one of the aggregate if a rich mortar was used;
- Water cement ratio (or the "paste" proportioning)- As concluded from the above mentioned, rich mix: high values, and poor mix: low values.

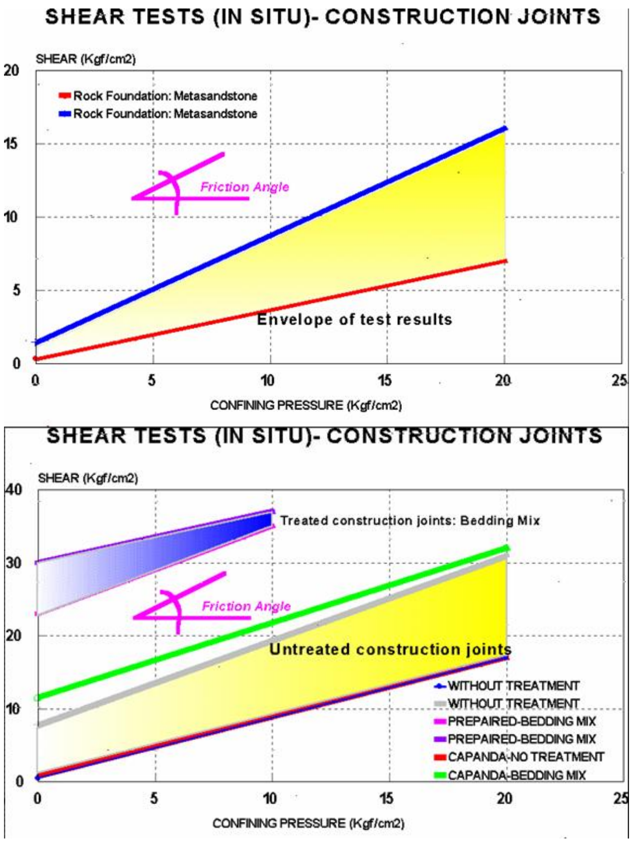
Aggregate such as quartzite and argillite can generally produce higher than average elastic modulus values for a given strength concrete. Similarly, a lower elastic modulus results from the use of a sandstone or similar aggregate. RCC mixtures made with conventional concrete aggregate and a relatively 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.

Dam	Concrete		Cementitious			Condition or Joint Treatment	0	10	20
Capanda	A-(1)	CVC			140	Monolithic	36,5	45,5	54,5
Capanda	A-(2)	CVC			140	Monolithic	29,9	39,2	48,5
Capanda	A-(3)	CVC			180	Monolithic	38,5	47,2	55,9
Ilha Solteira	B-(1)	CVC			200	Monolithic	55	65	75
Itaipu	C-(1)	CVC			100	Monolithic	22	31,3	40,6
Ilha Solteira	B-(2)	CVC	109		109	No treated	5,5	21,3	36,6
Tamagawa	2	RCC	91	39	130	Monolithic	30	44	58,4
Upper Stillwater	4	RCC	80	173	253	Monolithic	21	36,3	51,6
Galesville	7	RCC	54	52	106	Monolithic	23,3	36	48,7
Elk Creek	12	RCC	70	36	106	Monolithic	8	31,5	55
Urugua - i	17	RCC	60		60	Monolithic	24,6	35,7	46,8
Serra da Mesa	18	RCC	60	140	200	Monolithic	22	38	54
Capanda	19-(1)	RCC	100		100	Monolithic	31,7	40,7	49,7
Capanda	19-(2)	RCC	60		60	Monolithic	15,7	27,2	38,7
Capanda	19-(3)	RCC	100		100	Monolithic	38,3	48,7	59,1
Cuchillo Negro		RCC			136	Monolithic	23,7	42,8	61,9
Victoria Replacement		RCC			134	Monolithic	19,3	38,8	58,3
Zintel Canyon		RCC			74	Monolithic	20	34,8	49,6
Tamagawa		RCD	91	39	130	Mortar	30	41,5	53
Elk Creek		RCC	70	36	106	Water jet + Mortar	4	18,8	33,6
Capanda		RCC			80	Water jet + Mortar	12	22	33
Salto Caxias		RCC			100	Mortar	4,5	13,2	21,9
Cuchillo Negro		RCC			136	Mortar	15,5	31,5	47,5
Victoria Replacement		RCC			134	Mortar	15,9	41,9	67,9
Zintel Canyon		RCC			74	Mortar	13,8	27,7	41,6
Upper Stillwater		RCC			253	No treated	34	54	74
Galesville		RCC			106	No treated	8	30	52
Elk Creek		RCC			106	No treated	8	16	24
Capanda		RCC			80	No treated	1	8	17
Salto Caxias		RCC			100	No treated	10	17	24
Cuchillo Negro		RCC			136	No treated	11	29,8	48,6
Victoria Replacement		RCC			134	No treated	6	20,8	35,6
Zintel Canyon		RCC			74	No treated	6	20,9	35,8
Urugua - i		RCC			60	200°C*H+ No bedding mortar	3	12	21
Urugua - i		RCC			60	500°C*H+ No bedding mortar	4	11	18
Urugua - i		RCC			60	780°C*H+ No bedding mortar	3	11,4	19,8

Figures 24a. .- Typical shear values (Coehesion and Friction) from tests and conditions on RCC and CVC



Figures 24a. .- Typical shear values (Coehesion and Friction) from tests at RCC Construction Joints



Figures 25- Shear test results (Cohesion Friction)- Rock Foundation Contact- Metasandstone and RCC

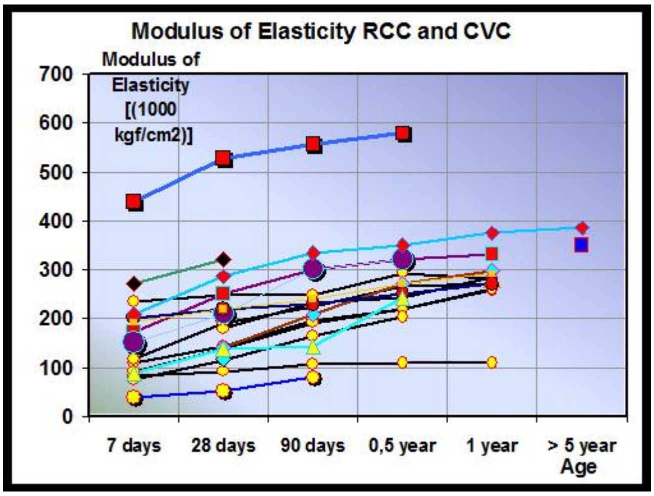


Figure 26- Modulus of Elasticity – CVC and RCC Results

3.3.4 *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 as shown in Figure 27.

3.3.5 *Creep*

It can be noted that from the creep equation **ε={[1/E] +[$f_{(k)}$]*[log (t +1)]},** normally used, the ratio **1/E** of RCC mixes - at early ages- is grater 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 "**$f_{(k)}$**" of RCC is larger than that obtained for CVC made of similar aggregates.

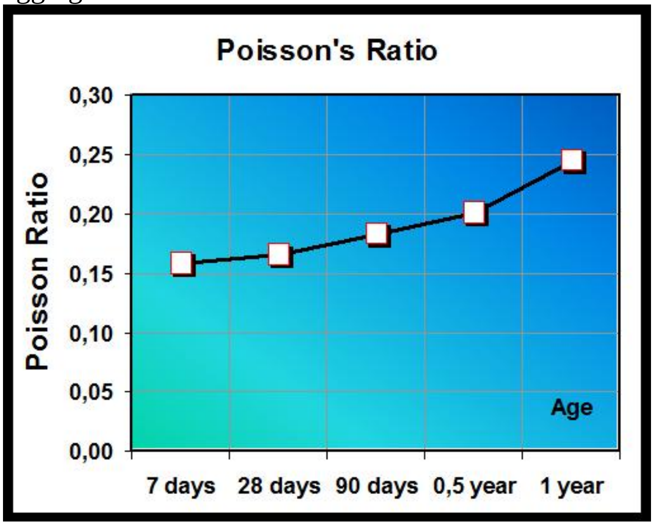


Figure 27- Poisson's Ratio

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. Figure (28) show some values[6] in comparison with creep values of CVC

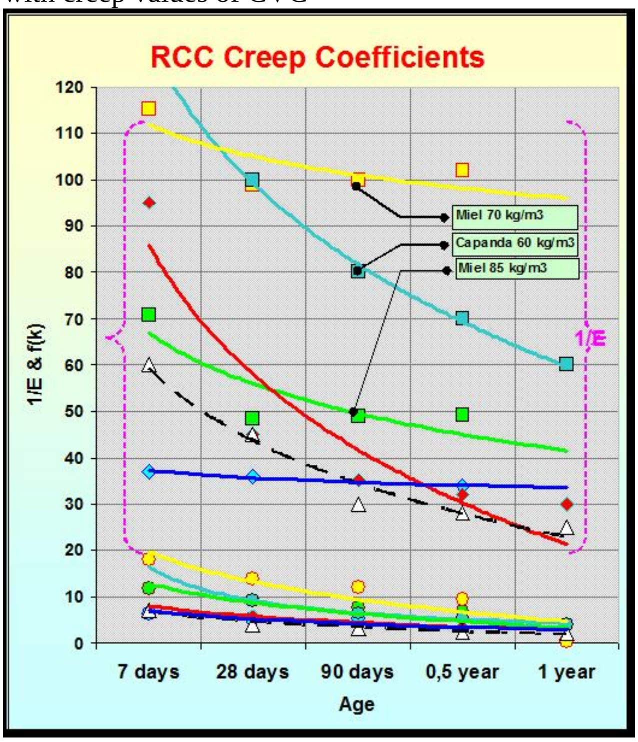


Figure 28 - Creep values from RCC and CVC concretes

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.

3.3.6 *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 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.

3.3.7 *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.

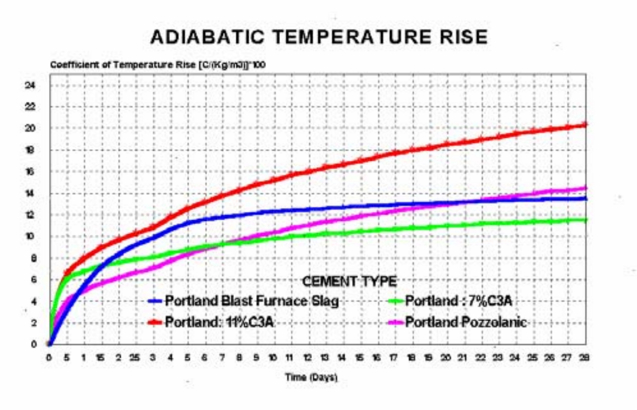


Figure 29- Adiabatic temperature rise in terms of “coefficient of temperature rise values” from RCC and CVC concretes

The values can be shown in two different manners. One in terms of temperature degrees, in an absolute value range; Other manner that gives a simples 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**” and is shown in Figure (29) [6]. The most important item is to get the maximum “**mix efficiency**” (as described previously), and the minimum “**coefficient of temperature rise**”. RCC produces an adiabatic temperature rise in a manner similar to CVC concrete.

3.3.8 *Thermal Properties*

The thermal properties- Diffusivity, Specific Heat, Conductivity and Coefficient of Thermal Expansion [6] (see Figure 30) - 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.

3.3.9 *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.

3.3.9.1- 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.

3.3.9.2- 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 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.

3.3.10 *Permeability*

The coefficient of permeability is obtained by tests using an apparatus like the one shown in Figure (31). The coefficient of permeability values from RCC and CVC mixes are shown in Figure (32) [6].

COEFFICIENT OF THERMAL EXPANSION					
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	COEFFICIENT OF THERMAL EXPANSION $10^{-6}/^{o}C$
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
MIEL I	TEST	RCC	QUARTZITE- GNEISS	75	7,5

SPECIFIC HEAT					
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	SPECIFIC HEAT cal / g.^{o}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
MIEL I		RCC	QUARTZITE- GNEISS	70	0,225
				85	0,235
				130	0,245
CANOAS		RCC	QUARTZITE	80	0,25

THERMAL DIFFUSIVITY AND THERMAL CONDUCTIVITY						
DAM	MIX	CONCRETE	AGGREGATE	CEMENTITIOUS CONTENT Kg/m3	THERMAL CONDUCTIVITY 10^{-3}(cal /cm.s.^{o}C)	THERMAL DIFFUSIVITY 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
Miel		RCC	QUARTZITE - GNEISS	85	6,8	0,110
Canoas		RCC	QUARTZITE	80	8,9	0,110

Figure 30- Thermal properties values from RCC and CVC concretes

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 through any cracks or joints in the structure.

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, contributes to its low permeability, without increasing the potential for thermal cracking.

Figure- 31 -Permeability apparatus test, at FURNAS laboratory- Brazil

The coefficient of permeability of the tested construction joints ranged from $1*10^{-9}$ to $1*10^{-11}$m/s, which is comparable to that of the concrete. As shown in Figure 32 the Coefficient of Permeabilty of RCC 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.

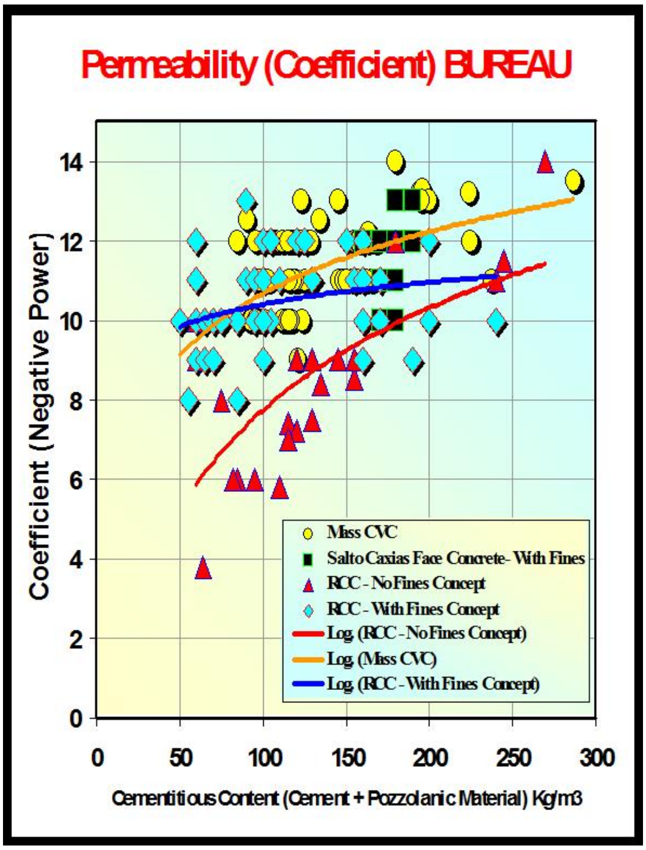


Figure 32- Coefficient of Permeability values from RCC and CVC concrete mixes, with and without fines and pozolanic materials [6]

3.3.11 *Durability*

The RCC mixture should provide the required degree of durability based on the exposure conditions, the materials used and the expected level of performance. RCC should be free of damaging effects of alkali-aggregate reactivity by proper evaluation and selection of materials. 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.

3.3.11.1- 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.

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 ponding dam. Salto Caxias RCC Dam, during the period from August/1997 to November/1997, was overtopped five times with a flow of 5,500m^3/s (13,100m^3/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.

3.3.11.2- 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 freezethaw weight loss tests and criteria as developed for soilcement, 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.

4 INSPECTION AND QUALITY CONTROL REQUIREMENTS AND PRACTICES

4.1 *General Aspects*

Who is it that 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?
- Why is it necessary to consider what it takes to get and assure quality?
- Perhaps the answer lies on 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.

Quality control 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 slumps (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.

4.2 *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.

4.3 *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. 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. 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 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.

Inspection is not an end in itself. 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 must also be recognized that quality is achieved only by implementation of an adequate quality 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.

4.4 *Statistical Concepts in Quality Control*

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.

4.5 *Records*

Quality control 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.

4.6 *Quality Plan*

An overall (Total?) 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 under way, the more traditional concepts of quality control become evident, but advance planning and preparation continue to be important.

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 Control 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 has been achieved on some large projects. 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:

a) Insufficient materials
b) Foundation preparation and cleanup
c) Joint cleanup
d) Equipment breakdown
e) 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 suggeste 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 33 shows a flow chart of actions with the following points:

Action 1 - Pre-qualification and knowledge – This corresponds to the stage of initial studies, knowledge and selection of materials and suppliers;
Action 2 – Information on handling;
Action 3 - 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 can be performed by each supplier;
Action 4 - Control during production - This action is to evaluate the points or procedures that could be vulnerable during production;
Action 5 - Control of application - This point consists of disciplinary actions during production.
Action 6 - Inspection during execution - This action will have the function of evaluating the best procedures for executing the works;
Action 7 - Structure commissioning – This item will have the function of formal commissioning of each stage of structures or services.

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 inplace compaction. An example of possible tests and test frequencies are given in Figure 34, which was successfully adopted during Capanda RCC Dam construction in Angola and others RCC jobs where the author have cooperated [6]. 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 Contractor'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 34 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 in 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 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.

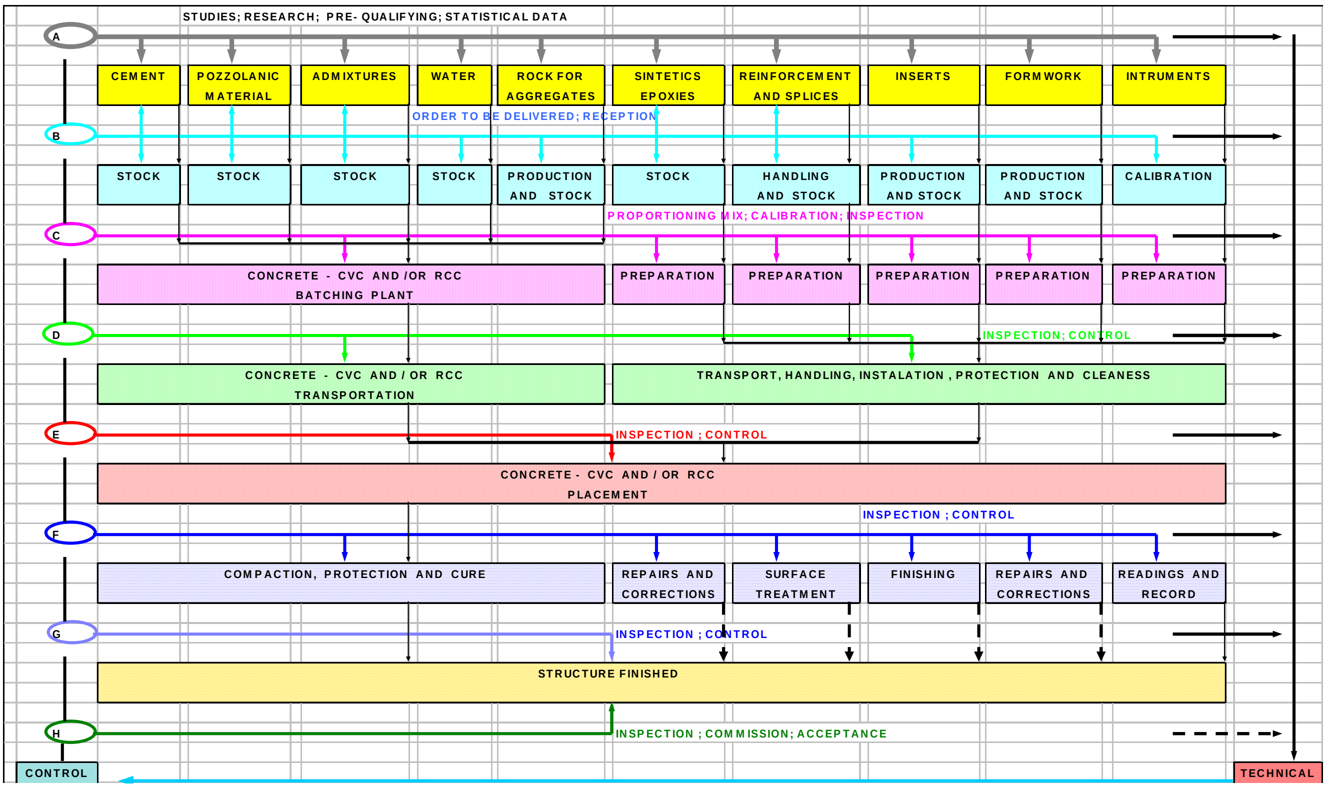


Figure 33- Quality Control Actions

MATERIAL OR SYSTEM	SAMPLE POINT	STANDARD REFFERED	TYPE OR INTENTION	FREQUENCY	LABORATORY	TESTS OR EVALUATION
REINFORCING STEEL	STOCKS	ADOPTED STANDARD IN THE COUNTRY	RECEPTION	EACH TRUCK (30t)	JOB SITE	WEIGHTLINEAR, YELD STRENGTH, RUPTURE STRENGTH, ELONGATION, BENDING
REINFORCING SPLICES	STRUCTURES		CONTROL	2 % OF TOTAL SPLICES	JOB SITE	RUPTURE STRENGTH
WATER	BATCH PLANT		CONTROL	WEAKLY	JOB SITE	SOLIDS, pH, O2, SO4, Cl
ADMIXTURES	BATCH PLANT		CONTROL	ONE / 1000Kg	JOB SITE	SOLIDS, pH, SPECIFIC GRAVITY
WATER STOP	SUPLIER		DELIVERY	ONE / 200m	OFFICIAL LAB.	ALKALIES, HARDNESS, TENSILE STRENGTH ELONGATION AT RUPTURE
CEMENT	SUPLIER		DELIVERY	ONE / 2HOURS OR ONE / 100t	CEMENT FACTORY	FREE LIME, FINENESS BLAINE TIME OF SET, LOSS ON IGNITION
			CONTROL	ONE / DAILY ONE / 500t	CEMENT FACTORY	SiO2; Fe2O3; Al2O3; SO3; CaO;MgO; FREE LIME; LOSS ON IGNITION; INSOLUBLE RESIDUE; TIME OF SET,RESIDUE ON # 200; # 325 SPECIFIC GRAVITY; AUTOCLAVE EXPANSION EXPANSION "LE CHATELIER" COMPRESSIVE STRENGTH
	CONTAINERS		RECEPTION	ONE / 100t	JOB SITE	
	BATCH PLANT		CONTROL	ONE / WEAKLY	JOB SITE	
			INTER-LABORATORY	ONE / 5000t	OFFICIAL LAB.	
AGGREGATES	CRUSHER SYSTEM		PRODUCTION	ONE / WEAKLY	JOB SITE	GRAIN SIZE; APPARENT AND ABSOLUTE DENSITIES ABSORTION; FLATNESS
	BATCH PLANT		CONTROL	ONE / SHIFT	BATCH PLANT	UMIDITY; ADJUSTMENT MIXES
				ONE / WEAKLY	JOB SITE	GRAIN SIZE; APPARENT AND ABSOLUTE DENSITIES ABSORTION; FLATNESS
CONCRETES CVC	BATCH PLANTS		CONTROL	ONE / 200m3	JOB SITE	SLUMP; AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH
				ONE / 2000m3	JOB SITE	SLUMP; AIR; TEMPERATURE; SPECIFIC GRAVITY COMPRESSIVE STRENGTH, MODULUS, TENSILE SPLITTING
CONCRETE RCC	BATCH PLANTS		CONTROL	ONE / SHIFT	BATCH PLANT	GRAIN SIZE; CEMENT CONTENT; CONSISTENCY (VeBe) COMPRESSIVE STRENGTH; SPECIFIC GRAVITY
	DAM BODY		CONTROL	ONE / 100m3	DAM SITE	SPECIFIC GRAVITY, COMPACTION RATIO, UMIDITY
DRLLED CORES	DAM BODY		CONTROL	ONE / 10000m3	JOB SITE	SPECIFIC GRAVITY; MODULUS; PERMEABILITY COMPRESSIVE STRENGTH
CRUSHER PLANT			INSPECTION	DAILY	SYSTEM	CHECK LIST
BATCH PLANT			INSPECTION	DAILY	SYSTEM	CHECK LIST

Figure 34- Test plan and frequency adopted for the Capanda Dam- Angola [6]

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 gage 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.

4.7 *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 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. 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 well adjusted.

While Quality Control (QC) is customarily considered to be an activity performed during RCC placement, it is also important that the degree of control be considered during design, specification, planning and the initial phases of construction of an RCC dam.

Rapid construction, which is one of the keys to the economics of RCC dams, causes quality control of the concrete constituents and the production facilities to be a most important factor in ensuring concrete quality. Once the RCC has been produced and compacted in the dam, it is expensive and unrealistic to remove the deficient material. Quality control after production should provide final verification of the concrete properties. At the dam, quality control of the fresh concrete must thus emphasize test methods that can give a quick indication of concrete quality and an indication of any minor adjustments required to maintain the concrete within the Specification. Further testing will of course be required for documentation of concrete properties, as for any other concrete construction.

4.8 *Full-Scale Trial*

The full-scale trial is an essential part of the QC program. In addition to the testing of the production and placing equipment, the testing done at this stage can form the database required to judge the RCC quality from preliminary test data. For all but the smallest dams, it is strongly recommended that a full-scale trial be constructed prior to the start of placement in the dam.

The first RCC that will be placed in the dam will be typically at the lowest point and thus amongst the most critical concrete in the dam. Consequently the trial should be outside the dam body or in a less-critical section of the work such as high on one abutment or as part of a stilling basin. The objectives of the trial are typically:

I- To train the personnel who will work on the dam; only those that have worked on the full-scale trial should be allowed to work on the initial stages of the RCC placement;

II- To demonstrate and confirm the suitability of the equipment and procedures the Contractor intends to use for mixing, handling and placing the RCC (and any traditional concrete to be placed in conjunction with it). However, the trial should not be at the time that the Contractor commissions his plant; all the plant should be fully operational before the trial commences;

III- To evaluate the RCC mix performance, i.e. segregation, proportions and compactability, including under unusual conditions, such as heavy rain;

IV- To establish correlations between tests done at the
time of concrete placement and the properties of the hardened concrete.

Experience shows that it is often advantageous to evaluate the mixture performance including the consistency separately from, and in advance of, the full-scale trial.

4.9 *Inspection and Testing During Placement*

Quality control during RCC placement involves two operations, inspection and testing. Inspection is the first opportunity to observe an RCC problem and institute measures to correct it. The RCC testing program should monitor the aggregate properties, RCC mixture proportions, fresh-concrete properties, hardened-concrete properties and in-situ compaction.

4.10. Control of Fresh Concrete

Quality control of the fresh concrete at the dam involves careful judgment and quality consideration of the following components and works:

- spreading and compaction
- density and moisture content
- lift joint bonding
- curing
- temperature control

Density control is more important for RCC as compared to traditional concrete. Insufficient density can be the consequence of too high or too low moisture, poor grading or segregation, incorrect spreading, inadequate vibratory amplitude or frequency and vibration energy, delays to compaction, inaccurate layer thickness or too low a number of roller passes.

Density control is typically done by nuclear densimeters that measure density at different depths in the layer. Normal frequency of measurements ranges between one test per 200 to 500 m^3 of RCC placed depending upon the size of the project.

Quality control of intended lift joint bonding comprises the detection of possible contamination at the surface and the identification of cold joints. The first will be accomplished by specifying cleanliness of equipment at the RCC surface, method and equipment to be used on lift surface cleanup and preparation and by its visual inspection prior to placing the next layer. It is common practice for large RCC projects to limit all traffic to vehicles staying on the dam or to clean the tires of vehicles entering the concrete surface. Records should be kept that identify cold joints and that distinguish between joints which may or may not require special treatment.

4.11 *Control of Hardened Concrete*

The methods of quality control of hardened RCC in the dam are the same as those employed in the full-scale trial. Concrete cylinders are made at the time of placement, cured and then tested for strength and modulus. Further specimens are typically obtained by coring and are subject to the same tests. Core samples contain the joints between lifts that can be subjected to detailed inspection and strength testing.

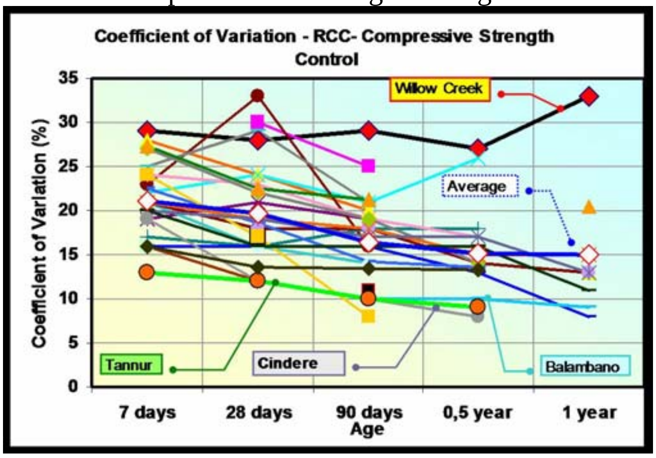


Figure 35: Coefficients of Variation obtained during control of RCC Dams

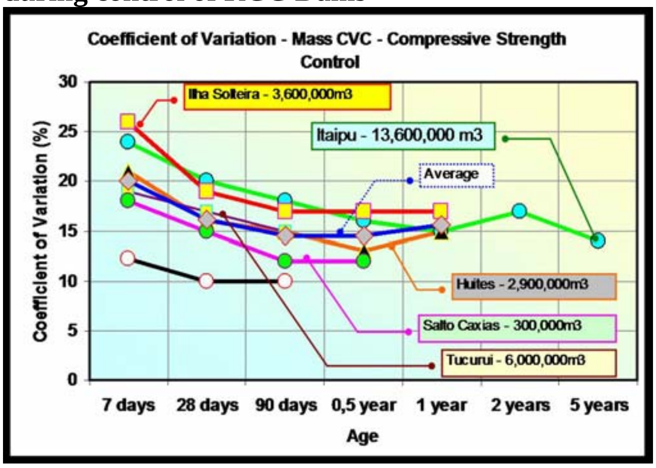


Figure 36: Comparison of Coefficients of Variation obtained during control of CVC Dams

As with traditional concrete, the test results from the RCC are typically evaluated statistically and compared with the design requirements. One method of assessing strength control of RCC is to review the Coefficients of Variation (CV).

Careful curing and handling of the test specimens can reduce the coefficient of variations of strength. Detailed investigations on such individual influences on the CV of the compressive in-situ strength should be evaluated.

5 THE AUTHOR'S COMMENTS ON RCC AS A CONSTRUCTION MATERIAL

5.1 *General*

Regarding the structural behavior of RCC, the main conclusions drove from the use and observations carried out for years, are as follows:

a) It is possible to construct dams of RCC with the same watertightness as that of concrete dams built with traditional methods;

b) 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;

c) The impermeability of RCC can be improved by increasing its fines content;

d) 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;

e) The majority of the cracks in RCC dams can be attributed to stresses of thermal origin in most of the richer mixes;

f) The transverse construction joints, having waterstops 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;

g) Cracks are always produced in transverse joints where transverse sections have 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;

h) Cracks of RCC dams are in general vertical, perpendicular to the axis of the dam, and do not affect its structural stability;

i) 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.

5.2 *Structural and Materials Properties*

The comparison of important physical properties of RCC and CVC 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 properties 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, cracking 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, analyzing 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 construction 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.

5.3 *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 choose one or other type of dam need to be reviewed considering all factors, conditions, time scheduled, and costs.

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