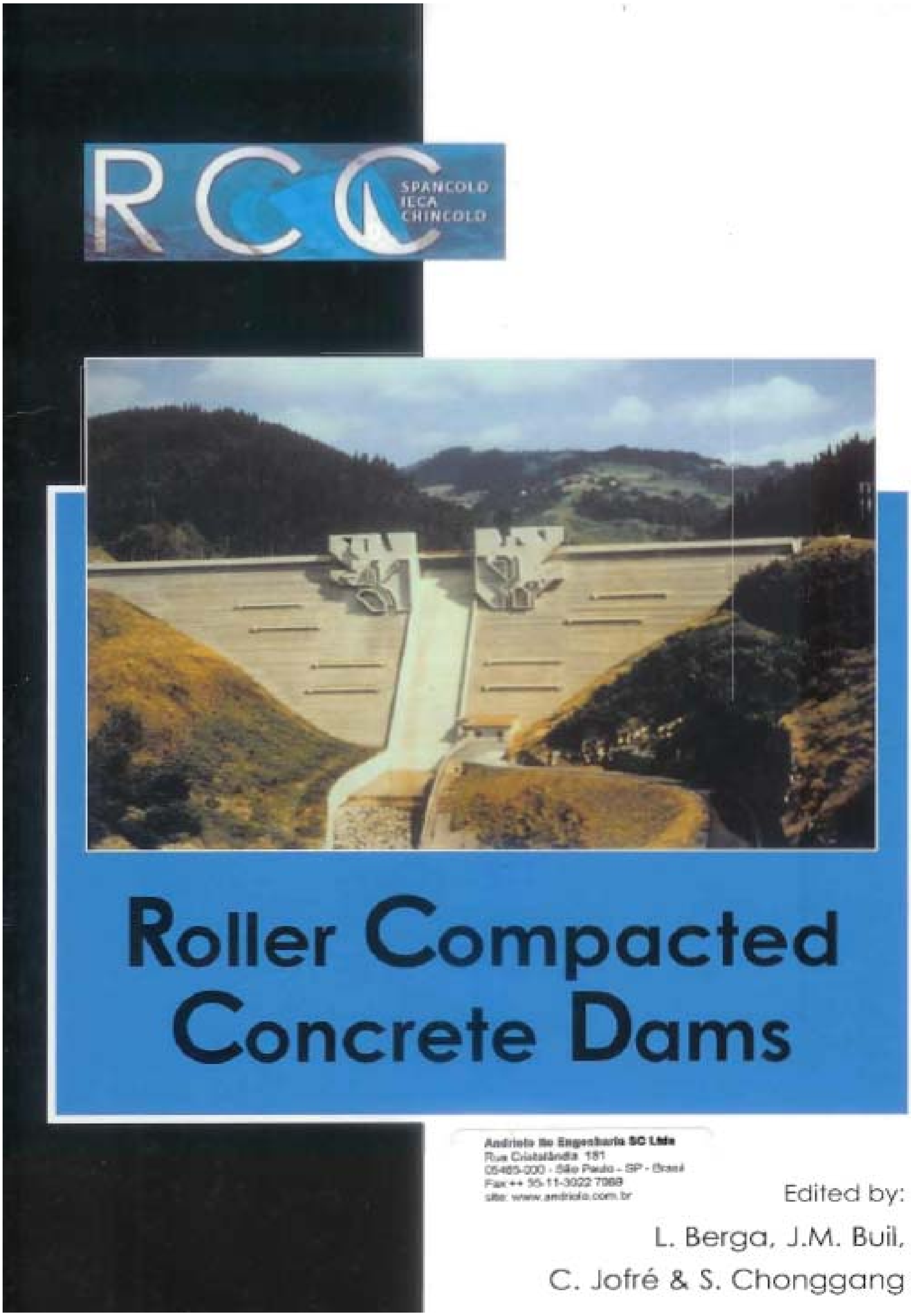

Discussions Regarding the Use of Materials and the Design of RCC Dams

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ABSTRACT: A 100-m high arch dam built in a high sismicity area usually will require a maximum compressive strength of 30 Mpa at 180 days, and a straight gravity type one may require ca. 15 Mpa, or the associated tensile strength capacity. These values will approach to 40 MPa and 20 MPa, respectively for arch dams or straight gravity dams, if the height is increased to 200m. From this perspective, why are high strengths required, and therefore high cementitious content, in straight gravity RCC dams? Is the answer in the impermeability demand? Or, is it a requirement imposed by the construction joints and construction methods? Or, is it just a heritage of the general knowledge (or lack of) in the Roller Compacted Concrete? In this paper, the Authors make a discussion on this topics mainly orientated to show evidences that the RCC is just CONCRETE, placed on site by a somehow different methodology and that there are particular tools already designed and developed that may be used during construction to guarantee the impermeability and monolithism at the construction joints. It seems like the application of so many different criteria in different site conditions and regions and by different people makes RCC something different than a concrete. However, the cares that need to be taken in the selection of materials, in the design of the site installations and in the quality control do not differ much from conventional vibrated mass concrete (CVC) practice. Those countries with a large experience in concrete dam construction that are considering the use of RCC for their future dams, should not take RCC as a new material but just as a different method of construction, that if successfully implemented, might bring a reasonable economy for the Project.

1 INTRODUCTION

Between the 50's and the 70's, a great number of dams were built in many countries around the world. These dams, for many different uses (irrigation, power generation, supply, flood control, etc.) were built with different types and materials depending on the local and climatic conditions, as well as on the availability of the materials.

The availability of the equipment industry (concrete plants, aggregates production systems, refrigeration systems, cranes, material handling systems, compaction equipments and form types) through continuous evolution, made possible the optimization of construction periods and the costs reduction.

A continuous evolution has been observed since that time in the concepts of risks, safety and quality, the quality system no longer being a procedure of obtaining results and figures, to become a group of actions that allow redirecting the procedures and the use of materials.

Through monitoring equipment, the design has had the possibility of improving the Project and requisites criteria of the material properties. The technical specifications, though, have had a slower improvement rhythm.

In a rock-fill or earth-fill dam, its body conception aims at using the materials in quantity and quality available in the surroundings. As to concrete constructions, though, in some cases this conditioning item is not adopted and a less flexible scheme of materials is used. Is there a need to act this way in those cases?

Some discussions are presented below.

2 DAM BODY - BARRIER

2.1 *General View*

A barrier wall must basically be inserted into one of the concepts schematically presented in Figure 01, or rather:

- A solid body built with materials in a way that attends the parameters imposed for its stability;
- A baseline with dimensions compatible with the foundation's geo-mechanical support capacity. The geometry in the plant and/or transversal section derive from the support capacity,

- Upstream face or of contact with the hydrostatic load, as to attend the desired degree of watertightness and durability,
- Downstream face, when not imposed by the desired durability, built in such a way as to create a pleasant aspect inserted in the work environment,
- A draining system in a way to control the seepage and reduce the pressure.

All these conceptual points must be arranged in such a way as to attain an economic, durable and safe project that can be built within a feasible length of time, with the required quality. Schematically we could display those requirements as shown is Figure 1. However this approach to the solution does not meet one of the most important requirements of an RCC dam, its simplicity for a rapid construction.

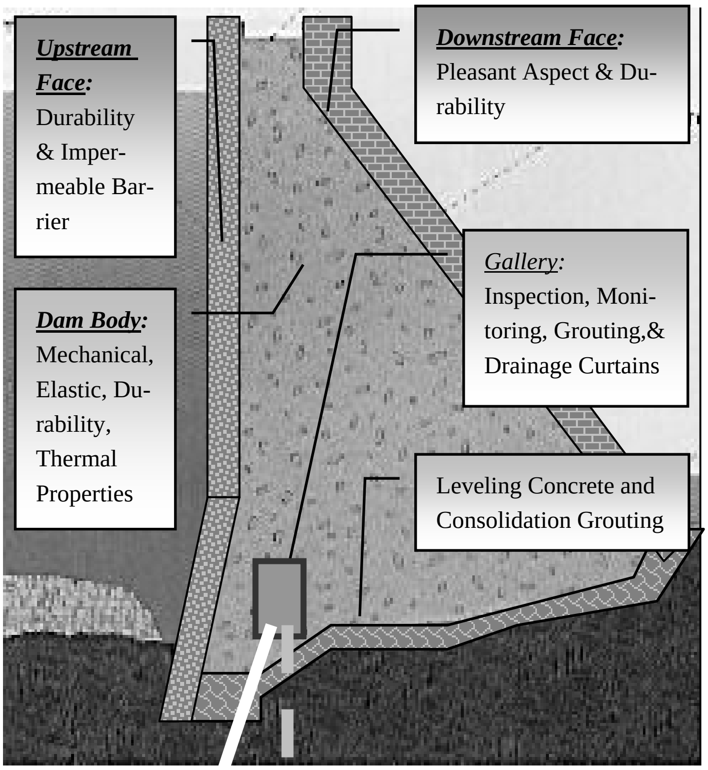

Figure 1. Conceptual aspects for a not-optimized Concrete Dam cross-section

As is the case in concrete dams constructed in the traditional way (CVC dams), the most effective way to tackle the design of an RCC dam is to work out a mix with properties that could satisfy all requirements of the structure at the same time. In this way, it would be much more easy to reach the essentials of the RCC construction concept, i.e. the speed of construction. This appears as the number one and main difference from CVC dams.

All efforts during not just the design of the dam itself, but also the design of the construction plants and installations of an RCC dam should lead to reduce to a minimum the number of different elements involved. Therefore the RCC has to be viewed as a concrete, its performance in hardened status as those of CVC, and in particular, the strength and impermeability.

The background and experience in conventional mass concrete dam construction are extremely helpful. The good practice in the selection and quality control of the materials should not be put aside at all, as it will be a very useful knowledge when designing an RCC dam.

As a result of what has been discussed above, a much more efficient approach of the design of an RCC dam would be the one shown in Figure 2.

There are no doubts that the other structures (for the river diversion, inserts, surface spillway etc.) may be relevant when choosing the “lay out” and therefore affect the costs, but this is not pertinent to the present discussion.

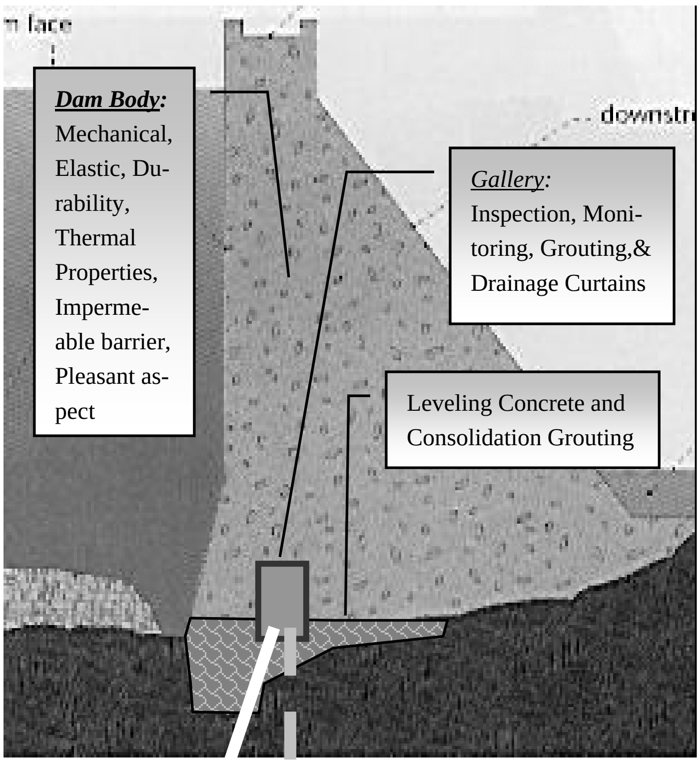

Figure 2. Conceptual aspects for an optimized Concrete Dam cross-section

2.2 *Stability analysis*

It is evident that the stability analysis will not be changed for the change of the characteristics of the concrete or of the type of concrete (CVC or RCC), but it is this material itself that may be “dosed” differently to attend the properties resulting from the analysis made.

In face of that, the parameters required for CVC or RCC dams are the same.

In RCC dams, the increased number of horizontal joints between the layers that is created due to the construction process requires more attention in the design and specification of their particular treatments.

The way of solving this ‘weakness’ of the RCC dams may highly determine both the technical and economical success of the Project. Horizontal joints treatments of the blocks in CVC dams do not represent such a big issue as in RCC dams relatively to the rest of the structure.

For example an RCC design that specifies bedding mixes in every single joint, or for time between layers as low as a couple of hours, will be less easy to construct than those specifying no treatment of the horizontal joints apart from curing. In the second case the RCC mix might need probably be more expensive than in the first one, but the overall picture will show a much more simple construction that will directly lead to economy. Both concepts should be balanced very carefully during the design stage.

2.3 *Geo-mechanical conditioning items*

This results from nature at the site where the dam is to be built. The stability analysis and the geo-mechanical characteristics interact in a way as to establish the requisites for the body of the dam, be it CVC or RCC.

2.4 *Watertightness system*

The watertightness system has rarely been imagined differently in CVC dams. However, the RCC methodology has arisen the curiosity for application of different systems to guarantee watertightness. This has come up into discussion due to failures observed in the construction of the first generation of RCC dams that were designed following more a concept of RCC as a ‘soil’ rather than a ‘concrete’.

The experience of RCC dam construction during the last 25 years has shown that it is possible to design and construct an RCC dam achieving the same objectives in watertightness that had been obtained in the past in CVC dams. This has been possible also without using additional impermeable barriers at the upstream face as that shown in Figure 1. The RCC itself (Figure 2) and the horizontal joints can be designed to be watertight to the desired levels, which in fact are not the same in every Project. To that end, the adequate materials and construction techniques have to be selected. Therefore we must refer here again to the importance of the adequate design of the RCC mix and the treatment of the horizontal joints between the layers.

In any case, the solutions finally adopted for the watertightness of the dam should find a technical-economical equilibrium that would depend upon the desired levels of impermeability, materials available, the objectives of the time schedule and rest of local conditions.

2.5 *Draining system*

The draining system is usually imposed by the stability conditions and by the foundations characteristics. Additionally, the conception of the “head drains” is adopted at the dam upstream zone concrete.

3 MATERIALS AVAILABILITY

Engineering good practices compel to do it well, at low costs with the available materials!

The availability of natural aggregates, of pozzolanic materials, near the surroundings of the future dam enables adjusting technically and economically the solutions to match and attend the requisites of stability and watertightness.

3.1 *Aggregates*

The aggregates grading composition curve more often used in the RCC works has been of the $p = (d/D_{max})^n * 100\%$ type, with ‘p’ being the percentage of a material finer than the mesh with a ‘d’ opening and ‘D_{max}’ the maximum size of the aggregate with the major dimension used in the mixing, and ‘n’ variable between 0.33 and 0.50.

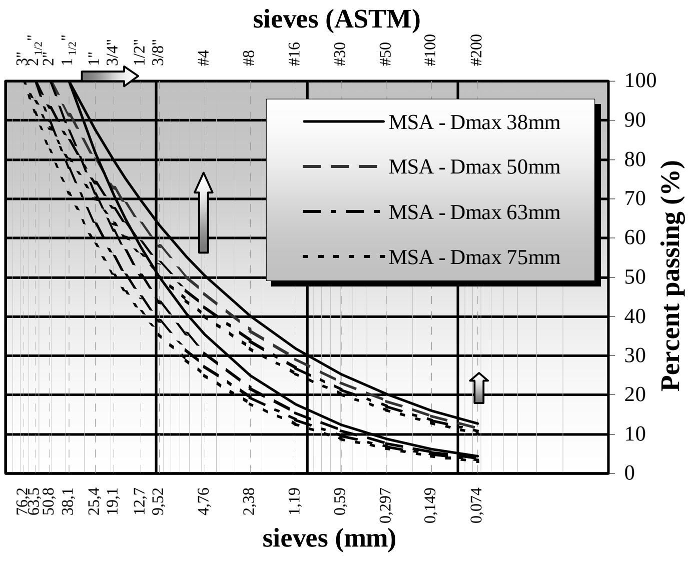

Figure 3. Aggregates Grain Size Curves for RCC

Observing the curves in Figure 3 one can see that as the aggregates D_{max} 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. In each particular Project the curves for minimum voids are confirmed by testing with the materials available, and a certain grading range for the RCC is established.

The availability of natural materials with grading near optimum (curves in Figure 3) 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 attended. 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.

3.2 *Pozzolanic Materials*

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.

However in some circumstances, the use of high contents of pozzolanic material might not be advisable under two aspects:

- The occasional unavailability of calcium composites, present in the cement, to react fully with the components of the pozzolanic material. The use of high contents makes part of the pozzolanic material act as a 'filler' and this must be economically evaluated against the other additional advantages,
- 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.

The use of pozzolanic material has made the designers 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, and frequently at 180 and 365 days.

On the other hand it has been confirmed that beyond the additional gain in long-term strength, the extensive use of some pozzolanic materials (mainly fly ash) have a positive effect in opposition of the extensive use of some kinds of filler (rock flour). This positive effect is related with the higher workability of the RCC mixes including fly-ash (or as an extension, any kind of pozzolan) and the lower water demand for a given consistency that affects directly to the strengths.

3.3 *Fillers*

The convenience of adopting the cubic type of grading curve as previously mentioned, implies in having around 5 to 10% and in some cases up to 12% of fines (material inferior to 0.075mm), as shown in Figure 3.

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.

As mentioned before, there are two aspects that need to be checked before an extensive use of the 'filler':

- minimum voids content need separate checking within the overall gradation of the 'sand' (below 5mm), and
- potential undesirable increase of water demand.

3.4 *Cement*

The Ordinary Portland Cements (OPC), Pozzolanic Cement and High Blast Furnace Slag Cement have been more frequently used. The options have been made on economic bases and on the availability of aggregating pozzolanic materials.

3.5 *Admixtures*

The use of chemical additives has increased since mid 90's, aiming at controlling the setting time and broadening the operational margin for RCC transportation and compaction.

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. The use of chemical admixtures acting at the same time as retarders and as water reducing agents have become most popular in RCC mix design, mainly in sites located in hot climates.

3.6 *Optimizing the use of the materials*

Considering the wide range of possibilities in the use of materials for RCC dams, the RCC mix design should be as global as possible, guided by technical and economical principles, and avoiding rigid criteria that are fixed beforehand.

Analysis of the materials available, looking through the different approaches and test results of permeability and strength (of the material itself but mainly at joints between layers) should be, together with the costing of the solutions, the main outlines of the RCC mix design process.

4 CONSTRUCTION PERIOD

The construction period of a work is usually imposed by the urgency of having the Project completed, by the financial availability and also if the two preceding are attended, by the constructor's interest in reducing the indirect costs. Generally, the construction period or the construction speed of an RCC dam may lead to the following conditions:

Table 1. Discussion of some of the parameters interrelated with the construction period of an RCC dam.

RCC cementitious materials content	Construction period	Speed of construction	Requirements in temperature control*	Requirements in horizontal joints treatments**
Low [125 kg/m^3	Long	Low	Practically not required	Very high
	Short	High	Might be required during hottest months	High
High >125 kg/m^3	Long	Low	Might not be required during coldest months	Medium
	Short	High	Almost certainly required	Low

* pre-cooling of concrete
** bedding mixes, 'cold' joint treatment, etc.

The need of having or not a system for RCC temperature control has implications on costs, as it does the eventual need of an extensive treatment of the horizontal joints between the layers.

Table 2. Comparison of construction periods of RCC and CVC dams of similar size and local conditions

	RCC dams		CVC dams	
Name Country Height (m)	Olivenhain USA 97	Rialb Spain 99	Alqueva Portugal 96	? Brasil?
Volume (m^3)	1,070,000 (RCC)	1,050,000 (RCC)	1,050,000 (CVC)	? (CVC)
Concrete placement in the dam	*Start:* Feb'2002 *Finish:* Oct'2002 *Duration:* 9 months	*Start:* Sep'1995 *Finish:* Sep'1999 *Duration:* 49 months	*Start:* May'1998 *Finish:* Jun'2002 *Duration:* 51 months	*Start:* ? *Finish:* ? *Duration:* ? months
Concrete transportation systems	High-speed conveyor 36in. wide + trucks	Integral high-speed conveyor 36in. wide	2 x 27 ton cable cranes + tower cranes and pumps	?
Concrete production plants	650 m^3/h batch type	330 m^3/h continuous type	330 m^3/h batch type	? m^3/h ? type

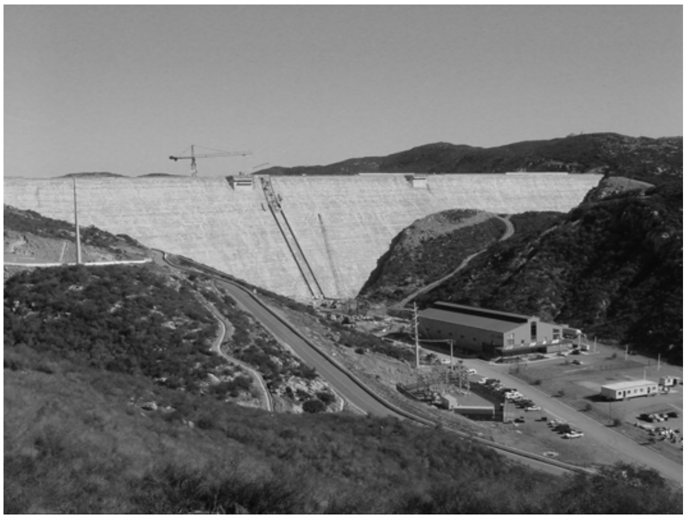

Figure 4. Olivenhain RCC dam (USA)

Figure 5. Rialb RCC dam (Spain)

Figure 6. Alqueva CVC arch dam (Portugal)

In Table 2 data from two RCC dams and two CVC dams, all built within the last ten years, are compared. They have been selected to have similar sizes, built in countries with similar working conditions, designed by renowned engineering companies and constructed by highly experienced contractors.

The comparison between the two RCC dams is showing a wide range of the speed of construction.

The construction of Olivenhain dam in USA is at the top in the list of speed in RCC dam construction, and Rialb is probably at the bottom. This is because the design of the first one was extremely simple and the RCC had no interferences at all, whilst the design of the second one was less adequate for an RCC dam.

Looking through the comparison between RCC and CVC it can be seeing that with RCC it is possible to reduce the construction period of this particular size of concrete dams and conditions in more than 5 times, and therefore obtain full advantage of the RCC method of construction. However in less efficient RCC dams like in Rialb, this advantage does not exist and the RCC solution might not be the best option.

5 COSTS

As a general rule, the RCC dam is more economic than the CVC dam. To fulfill this statement it is required the RCC dam to be designed and the construction planned in a way that advantage can be taken of the speed of the RCC method of construction (as mentioned above).

The magnitude of the direct costs involved in the RCC usually is in the range shown in Table 3.

Table 3. Cost range normally adopted for RCC dams construction (in percentage)

Item	Sub-item	Cost range (%) related to content of cementitious materials [125 kg/m^3	>125 kg/m^3
Materials		*43 to 70%*	*56 to 68%*
	Cement	15 to 28	15 to 17
	Pozzolanic material	2 to 5	11 to 14
	Admixture	1 to 2	0 to 2
	Aggregates	25 to 35	30 to 35
Production		*15 to 21%*	*14 to 18%*
	Batching & mixing	8 to 11	8 to 10
	Handling-conveying	7 to 10	6 to 8
Placement		*20 to 31%*	*17 to 27%*
	Spreading & compacting	4 to 5	5 to 6
	Curing	1 to 2	1 to 3
	Clean up & joint preparation	3 to 4	1 to 3
	Bedding mortar	5 to 7	0 to 3
	Contraction joint	1 to 3	4 to 5
	Formwork	6 to 10	6 to 7
TOTAL		*100%*	*100%*

In the costs composition above, the item for the RCC temperature control hasn't been mentioned due to the fact that it is a conditioner of a specific application, but which may come to about 5 to 8% of the RCC total costs. The cost of additional impermeable barriers at the upstream face has also not been included, that if required, might mean between 10 and 15% of the total cost of the RCC.

The ranges of percentages are usually wider for RCC dams with low content of cementitious materials due to a more number of different concepts among these types of RCC dams. The cost ranges for higher contents of cement and pozzolanic materials usually bring less variability to the percentage distribution of the individual direct costs.

Some of the most relevant differences between those two concepts are on one hand the extreme limits of the cost of the materials for the RCC (43% instead of 68% for lowest and highest limits of the low and high-cementitious content respectively). On the other hand this is compensated by the cost of the other two groups, the concrete production and the placement. The weight of those two in the total direct cost of the RCC is usually lower in the high-cementitious content RCC than in the low content one. It is remarkable the difference between the cost of horizontal joints treatment (including curing, joint preparation and bedding mixes) with upper and lower extreme limits between 13% and 2%, for the low and high-cementitious content concepts respectively.

This analysis refers only to direct cost units. But the greatest differences between total costs of RCC dam Projects of similar local conditions are found when the indirect costs are included in the comparison. Following the examples of Table 2 of three concrete dams with the same volume, it is easy to understand that the indirect cost of an RCC dam like Olivenhain (RCC in 9 months) has been much less than in Rialb (RCC in 49 months), in which probably similar indirect costs have been supported as in Alqueva (CVC in 51 months) and even higher than in ?, a CVC dam (CVC in ? months).

Of the direct costs mentioned in Table 3, the ones with a greater incidence refer to:

– Cement and pozzolanic materials,
– Aggregates,
– Batching + Handling-Conveying, and
– Placement.

Over these items is where it is worth to apply an engineering effort in order to achieve economic benefits. Also, not leaving behind indirect costs (which may be changed depending on the construction speed). This is why the optimization of the cement contents, or rather, of the cementitious content, in order to attain the mechanical and elastic properties, thus minimizing the worries on the need of temperature control and extensive joints tretament, is a first technical-economical and quality goal. This optimization should attend also the impermeability function of the RCC.

The cost of the aggregates is relevant, exactly as it is in CVC dams, due to the dimension of its usage, since it corresponds to about 75 to 80% of the concretes unitary volume.

Handling and conveying system of the RCC must be optimized, taking into consideration the concrete planning, stages of construction and local conditions (topography and access).

The formwork system to be used may be attuned with the continuity of the RCC placement.

The RCC placement in layer thickness mainly around 30 cm allows the use of less high formworks (the standard being around 60, 90 or 120 cm), leading to a higher number and re-usages and the option of a more economic fixation system.

6 COMBINATIONS AND ALTERNATIVES

The combination of the materials availability and alternatives development is broad, but is discussed in Table 4 as an exercise for different options.

In order to simplify the analysis, only three aspects has been looked at in the combination of design alternatives: the content of cementitious materials of the RCC mix, the formation of the upstream face of the dam (associated with the watertightness system of the structure) and the treatments of the horizontal joints between layers of RCC. As shown at the bottom of the Table, different levels have been considered for each of those parameters.

Regarding the cementitious material content, it should be considered that unless the dam is constructed slowly, options C2, C3 and C4 in the Table are selected even when they might require any kind of temperature control of the concrete. When two options of cementitious materials content are included together as an alternative, the decision is mainly dependant on the strength requirements derived from the thermal and/or seismic analysis.

The option selected in the design of the RCC mix will highly condition the other two design parameters under discussion in this Table. For example, when a mix with a high cementitious content is selected, the probability of having an impervious RCC (option F2) is higher than if a low-cementitious content mix is selected. In that last case, an upstream impermeable barrier is required (either option F1 or F3). Also the requirement of bedding mixes at the horizontal joints between the layers is interrelated with the mix concept. Bedding mixes are generally less required when working with higher cementitious materials contents.

The speed of construction will determine the level of treatment required at the horizontal joints. In all RCC dams a less treatment is required as the speed of construction is raised.

Finally, two heights for the dam are discussed in the Table, 100m and 200m. The implications of the higher dam are mainly on the strength and impermeability requirements.

Table 4. Discussion on the combination of alternative design parameters with the availability of materials for RCC dams

Material availability and quality		Particular conditions of the dam		Design alternatives		
Pozzolanic material	Aggregate	Speed	Dam height	Cementitious materials content	Upstream face	Joint treatment
Near available Good quality	Any type	High or Low	100m or 200m	C2	F2	J4
Far available Acceptable quality	Crushed	High*	100m	C1/C2	F1/F2	J3/J4
	Natural & good fines			C1/C2	F1/F2	J3/J4
	Natural & bad fines			C2	F2	J4
Near available Poor quality	Crushed	High*	100m	C2/C3	F2	J4/J2
	Natural & good fines			C1/C2	F1/F2	J3/J4
	Natural & bad fines			C2/C3	F2	J4/J2
Far available Poor quality	Crushed	High or Low	100m	C1/C3	F1/F3	J3/J1
	Natural & good fines			C1	F1	J3/J1
	Natural & bad fines			C3	F1/F3	J3/J1
Far available Acceptable quality	Any type	High	200m	C2	F2	J4
		Low		C2/C4	F1/F2	J1/J3
Near available Poor quality	Crushed or natural & good fines	High	200m	C2/C3	F2	J4
		Low		C3/C4	F1/F2	J1/J2
	Natural & bad fines	High	200m	C2/C4	F2	J4
		Low		C2/C4	F2	J1/J2
Far available Poor quality	Any type	High	200m	C3/C4	F1/F2	J2/J4
		Low		C3	F2/F3	J2/J1

* for low speed of construction change C1 by C3 and J3 by J2

Legend of design parameters:

C1: low cement and low pozzolanic material content
C2: low cement and high pozzolanic material content
C3: high cement and low pozzolanic material content
C4: high cement and high pozzolanic material content
F1: Impervious CVC barrier upstream against forms
F2: RCC or RCC enriched with grout against forms
F3: Any kind of impervious membrane upstream
J1: Extensive use of bedding mixes (all joints)
J2: Partial use of bedding mixes (upstream & cold joints)
J3: Extensive treatment but little use of bedding mixes
J4: Low treatment and little use of bedding mixes

7 CONCLUSIONS

No doubts if a good or medium quality pozzolanic material is available (what in fact is the most frequent case) the best option is to use it extensively in the RCC mix. That would simplify the design at least in two directions:

- The RCC can be designed to be watertight, therefore no additional impermeable barrier would be required on the upstream face, and
- The performance of the horizontal joints between the layers would be improved with a richer mix and the joints treatment, including the use of bedding mixes, could be reduce to a minimum.

Those two advantages will automatically generate further new ones. For example, as the number of activities on the lift under construction is reduced, the speed of construction can be increased, reducing the total cost (mainly because of the reduction of the indirect costs as discussed above).

Only in case that no acceptable pozzolanic materials are available within a reasonable distance of the site, different options of the design come up into discussion. In those particular cases, and depending on the speed of construction and height of the dam, alternative design methods might be adopted. The extensive use of fillers instead of pozzolanic materials to improve the aggregate gradation and the strength, impermeable CVC barriers or membranes at the upstream face and extensive use of bedding mixes on the RCC layers surface are some examples.

Based on the precedent information it may be observed that the RCC methodology makes it possible that the same type of concrete dam may allow different alternative- conceptions, considering the requisites of stability and watertightness, without affecting safety and quality.

This concept comes closer to those applied on earth-fill and rock-fill dams, with different basic materials and several watertightness systems.

In face of that, it is possible to affirm that there is no basic rule to make mandatory the use of a large quantity of pozzolanic material or a determined content routine, or a unique face molding system and/or watertightness system.

Every new Project should be studied looking through all those possibilities, bearing in mind the actual local conditions: time schedule, financing availabilities, local experience, purpose of the structure, etc. And at the end of the analysis one might come to the conclusion that the RCC dam is not (or was not) the best option for that particular site.