COMITÉ ESPAÑOL DE GRANDES PRESAS
Spanish National Commission on Large Dams

TECHNICAL GUIDELINES FOR DAM SAFETY 2

CRITERIA FOR DAMS AND ANCILLARY WORKS' DESIGNS

Volume I

Update on RCC

- **Update of Chapter 4.3**
- **Inclusion of Chapter 4.7**
- **Inclusion of Chapter 4.8**
- **Update of Chapter 5.2**
- **Update of the bibliography**

June 2012

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4. DESIGN CRITERIA

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4.3. ROLLER COMPACTED CONCRETE GRAVITY DAMS

Gravity dams made of roller compacted concrete, or RCC, are considered separately, because the differences in the material and, above all, the different procedure for delivery to the worksite impose specific design constraints. Consequently, the design of a gravity dam must be substantially different in terms of the vibrated or compacted concrete technology planned for its construction.

Engineers considered the possibility of using the technology used for the construction of embankment dams in the construction of concrete dams. This requires the concrete to be very dry, dry enough to allow the compaction equipment to work on its surface. It also requires that the compaction work area have sufficient dimensions for this system to be efficient, dimensions far exceeding the approximately 15 m spacing that usually exists between block joints which are common in vibrated concrete dams. This distance is essentially limited by the shrinkage that occurs during the concrete hardening process due to the elimination of free water and to the decrease in temperature that follows the setting of the concrete. By decreasing the amount of water, which minimises the amount of free water, and by replacing a major part of the cement with pozzolanic materials, which releases a very moderate amount of heat during setting, it is possible to significantly increase the distance between the joints, resulting in a work area suitable for the compaction process. Furthermore, RCC technology allows the subsequent creation of non-formwork joints between blocks, which facilitates the creation of a compaction surface of suitable size irrespective of the restriction imposed by thermal stress.

It should be noted that the vibrated concrete normally used in dam construction is rather dry and the binder used is a mixture of cement and pozzolanic materials, with the percentage of the latter having progressively increased. As a result of this, the differences between the materials used in vibrated concrete technology and in compacted concrete have gradually decreased, and it is now clear that the key part of RCC technology is its placement procedure.

The economy of RCC technology derives primarily from the ability to use large amounts of concrete for construction in short periods of time, which significantly reduces the execution period compared to that required for the construction of the same dam using vibrated concrete technology. Therefore, the design of a RCC dam should be focused on minimising the aspects that interrupt the concreting process, which must be as continuous as possible, since otherwise the essential advantage of this technology is lost. The design should limit to the maximum extent possible any interference in the surface to be compacted, and the location and number of functional elements should be subject to the objective of the concreting being continuous. The economy derived from the lower cement content, due to the greater proportion of fly-ash, is added to that achieved by shortening the construction schedule, but this generally does not by itself justify the use of RCC technology.

The equipment and type of formworks needed to maintain a suitable rate of concreting that is as continuous as possible are expensive. Consequently, in many cases, in order for RCC technology to be economically advantageous, it requires a significant volume of concrete to be placed. However, there are relatively small RCC dams that are also very economical. An even topography is the most appropriate for this technology, as it facilitates the installation of the equipment for transporting the concrete to the worksite. This equipment usually consists of conveyor belts whose location has to be changed several times during the execution of the works. Nevertheless, there have also been RCC dams built in very narrow valleys. In these cases, conveyor belt equipment with self-climbing systems, like the one used for the La Breña II dam (Fig. 2.22A), is very appropriate. These systems allow the concreting system for the entire dam to be positioned only once (with the exception in some cases of the concreting for one of the top parts at the crest of the abutments, which might need the equipment to be lengthened, or it could be done by bringing in all the concrete at once from the concrete plant by truck). Recently, as an alternative to the conveyor belts, a simple system known as the "vacuum chute" has been used. This system is suitable if the mixture is rich in paste, cohesive and

does not segregate. This system has been used numerous times for RCC dams in China and later in other countries as well, such as Bolivia (La Cañada Dam), Iran (Jahgin Dam), Myanmar (Yeywa Dam), Costa Rica (Pirrís Dam), etc. In Spain, it has been used in Puente de Santolea Dam (Fig. 2.22B).
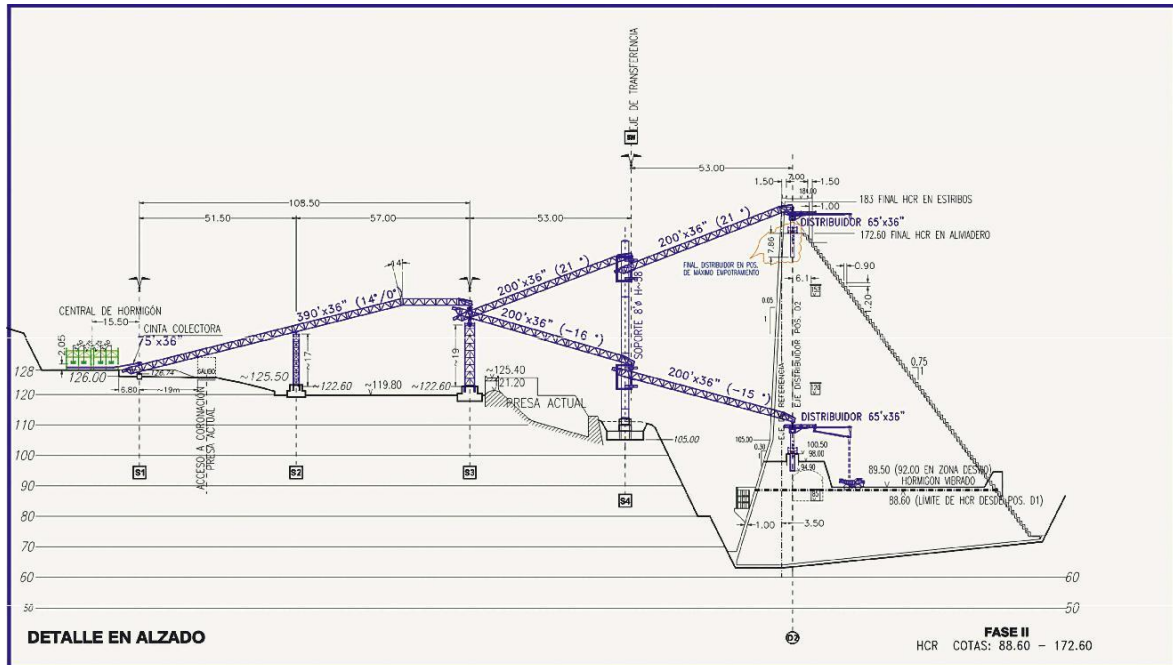
Elevation view

Fig. 2.22A – Diagram of high-speed conveyor belt transport for concrete used for La Brena II Dam (Acuasur)

Unlike vibrated concrete technology, the use of which has already been very standardised as a result of the extensive accumulated experience, RCC technology is relatively recent. As a result, relatively diverse technologies have been included under the common name of "RCC", with their common factor being that the consolidation of the concrete is obtained by means of compacting it with vibrating rollers.
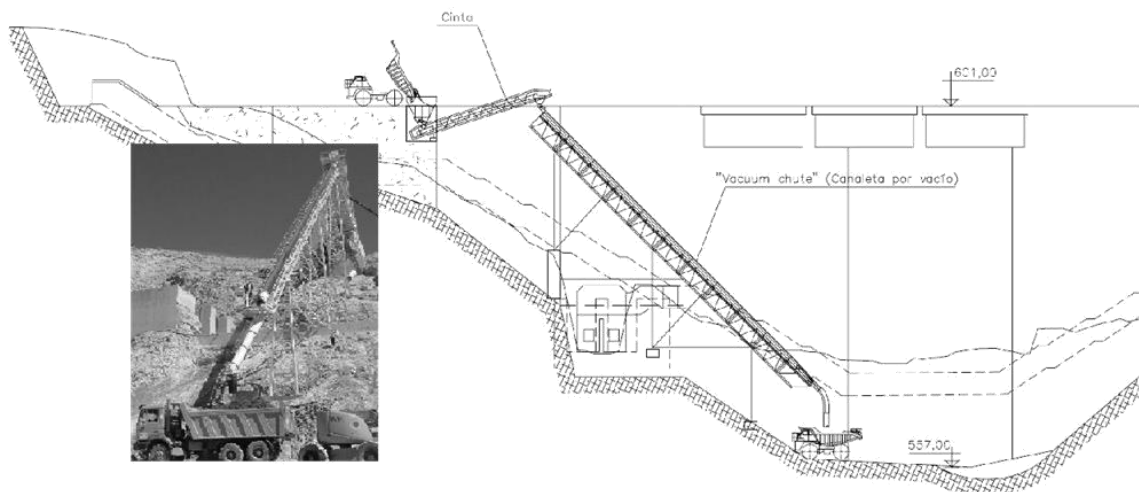
Fig. 2.22B – Puente de Santolea Dam, a 44-metre high RCC gravity dam (AcuaEbro – Ebro River Basin Authority). Diagram of the vacuum chute-type RCC transport system used for the construction of the dam.

4.3.1 Fitting the dam in the valley

The criteria for fitting the dam are similar to those of a vibrated concrete gravity dam, with certain special considerations such as:

– It is advisable to locate the outlet works (bottom outlet, middle outelts and intakes) outside the compacted concrete work area in order to increase the possibility of continuous concreting, both across a longitudinal section of the dam as well as in any cross section:

- The pipes that pass through the dam should be embedded or attached to the rock foundation, and housed in a vibrated concrete structure together with the control room.
- Intake towers should be attached to the upstream supporting dam face and built either before or after the construction of the RCC dam body, or completely detached from it.

In the case of hydroelectric power plants, it is preferable to either site the power generation building in an underground cavern in one of the abutments, or attach it to the downstream toe of the dam. There has been one case in which it has been placed under the spillway flip bucket (Platanovryssi Dam in Greece).

Designing the outlet works differently can lead to an optimum fit of the whole construction that is different to that which would be adopted if the dam were vibrated concrete.

– Any other structure: piles and the bridge over the spillway, the spillway side walls, the slab lining for the spillway's discharge channel (when needed), etc., must be designed so that they can be built without affecting the most continuous as possible placement of the RCC.

4.3.2 Typical cross section

All gravity dams must meet the same conditions of static and elastic stability, regardless of whether they are built with vibrated or roller compacted concrete. Both concretes have similar specific weights and stress-strain behaviours, with the differences indicated in Section 5. Consequently, the slopes that vibrated concrete and RCC concrete dams require are also similar. However, RCC dams have some peculiarities that must be taken into account when defining the typical cross section that entail variations from the section that would be used for a vibrated concrete dam:

– The number of lift joints, where the tensile strength is lower and varies depending on the efficiency of the construction process, is in the order of six to seven times greater than in a vibrated concrete dam. Therefore, the probability of exceeding the tensile strength in a lift joint and that the corresponding crack produced is greater when the dam is made of RCC, and thus complying with the condition of limiting tensile values must be especially ensured. In cases where deemed appropriate the dam can be dimensioned so that tensile stress does not occur even in accidental or even extreme situations, thereby ensuring a reserve of compressive strength in normal situations. A minimum reserve of compressive strength to be to maintained in normal situations could also be established. A state of compression in the upstream dam face reduces water seepage through the lift joints, even in the event that the bonding at the joint is defective.

– The layout of a two slope upstream dam face may entail a noticeable reduction on the upstream toe of the stress in the direction of the dam face in comparison with that produced vertically, as shown in Section 4.2.1. This should be taken into account in order to prevent the appearance of tensile stresses.

- The width of the crest must be sufficient enough to allow compaction to be successfully carried out. In general, widths of greater than 8 m (in large dams they are usually 10 m wide) facilitate construction. (Fig. 2.22C)
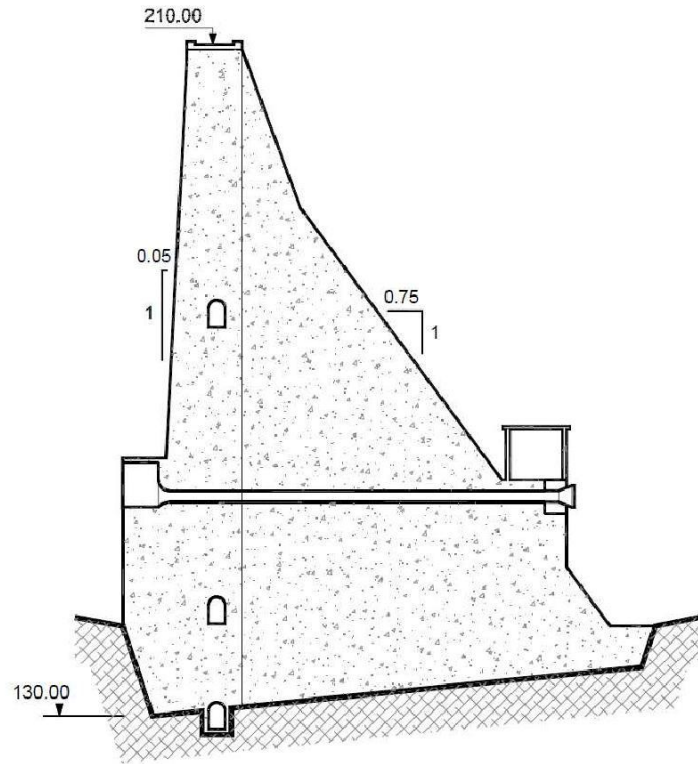

Fig. 2.22C - Santa Eugenia Dam, an 87-metre high RCC gravity dam (Sociedad Española de Carburos Metálicos). Note the kink at the downstream face used to get widths on the crest that are compatible with the compactors' ability to move about.

- Downstream dam faces which, initially, were designed flat imitating vibrated concrete dams, are now being designed stepped, with a step height multiple of the thickness of the concrete lifts, which is more in line with the building process and facilitates carrying out formwork. This has opened the door to the solution of spillways with a stepped chute in many dams. The advantages and limitations of this solution will be discussed later in Section 4.3.6.

- In some RCC dams waterproofing is done with devices attached to the upstream dam face, such as panels that serve as permanent formwork, or with waterproof linings installed subsequent to the dams' construction. This allows concrete with a minimum content of binder to be used. Nevertheless, the use of waterproofing

systems in the upstream dam face, although it is able to solve the problem of permeability, does not solve the need for proper bonding between concrete lifts, and this may leave the monolithism of the structure in danger, a particularly sensitive issue in seismic areas. For this reason, concrete with high paste (cement + fly-ash + water) content has been frequently used in Spain as these *per se* ensure the watertightness and durability of the concrete.

– The distribution of concretes in the dam's cross section is currently being developed, with a tendency towards the maximum of simplicity and the minimum of interference with the area under execution. The working stresses of a gravity dam are generally low, except on the downstream toe of very tall dams, and thus conditions related to weight and watertightness prevail over strength-related conditions. The problem is caused by the anisotropy introduced by the numerous lift joints, one approximately every 30 cm, in terms of their bonding and waterproofing. The bond is ensured if the paste/mortar ratio is correct and the placing of the successive lifts is accomplished by maintaining a sufficiently low enough maturity factor (see Section 4.3.3). The other condition – watertightness – has been a decisive factor in the evolution of the types of concrete used. Limiting ourselves to the Spanish experience, we can establish the various steps followed in the evolution of the distribution of concretes:

a. Initially, conventional vibrated concretes (CVC) were used to build the upstream dam face using thicknesses of 1 to 4 m, with the mistaken idea that the area of vibrated concrete would act as a waterproof screen that would prevent seepage through the joints between the RCC lifts should the bonding between the two of them be defective, in addition to giving a good aesthetic finish to the dam face.

This layout creates functional and construction drawbacks.

Functional drawbacks: The long exposure time allowed by hot joints between RCC lifts, which may vary (depending on many factors, the most important of which is the ambient temperature) from 8 to 24 hours, is not compatible with the exposure time for CVC, which is usually 1 to 3 hours. Consequently, all the joints between CVC lifts are cold joints, the treatment of which is not very compatible with the speed of progress for RCC lifts. To this must be added the

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contamination generated on the adjacent RCC, due to which they potentially have a significantly higher permeability than that of the hot joints for properly executed RCC. Additionally, the greater spacing of transverse joints generally used in RCC dams, typically between 20 and 40 m, is not suitable for the CVC lining, especially given its two-dimensional character, resulting in the not infrequent appearance of random vertical cracks, typically separated between 5 and 10 m (depending on the mixture proportions and the weather). This causes what was planned to be a waterproof face to become what is actually a lining with a grid of preferential pathways for seepage, whose vertical cracks can spread to the RCC, generating spontaneous transverse joints in the middle of a block, reaching the galleries, and even reaching through an entire block of the dam.

This solution also has several construction drawbacks:

- difficulty in adapting vibrated concrete works with roller compacted concrete works, with one being subordinate to the other to the detriment of the need for continuous compaction
- as a result of the increase in the exposure times between RCC lifts, the quality of the bonding between them decreases and, therefore, the potential watertightness of the dam is also reduced (additional functional drawback)
- in some cases separate facilities are required to produce the two types of concrete, with the corresponding increase in costs.

The drawbacks mentioned are extended to the interface concrete that is in contact with the rock slopes.

b. To overcome this drawback, one alternative is to dispense with vibrated concrete, except in contact with the foundation, and use two compacted concretes, with the richer one used for the upstream area. However, experience has confirmed that it is more advantageous overall, in terms of speed and economy, to build the entire section with the concrete that is richer in paste. (Fig. 2.23)
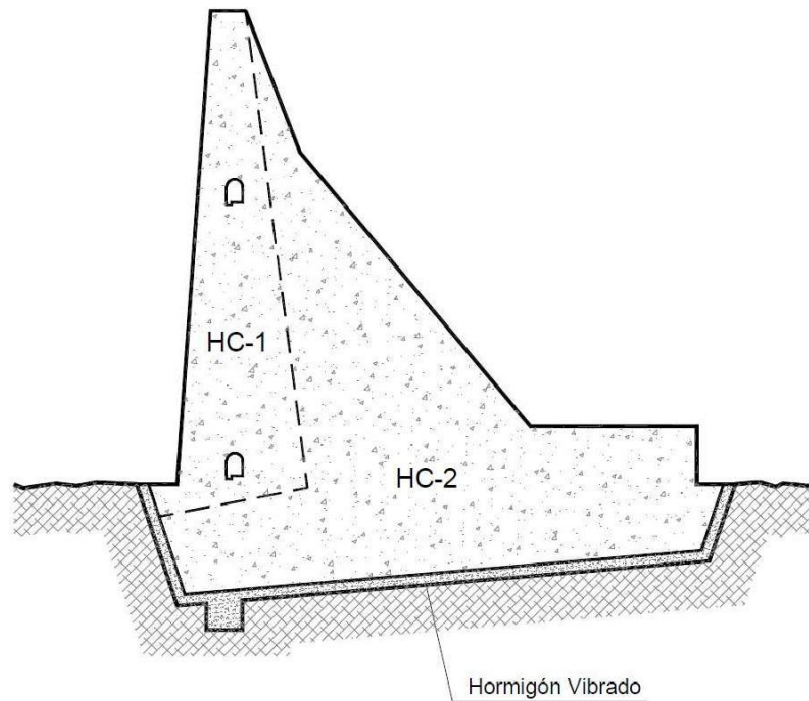
HV: Vibrated concrete

Fig. 2.23 - Santa Eugenia Dam, an 87-metre high RCC gravity dam (Sociedad Española de Carburos Metálicos). Concrete use by zones: HC1: 236 kg/m^3 of binder; HC2: 210 kg/m^3 of binder.

c. Good results have been obtained using a single compacted concrete with a medium paste content (approximately 180 kg of binder per m3 of concrete), supplementing each lift with additional mortar applied in an approximately 3 or 4 m wide strip parallel to the upstream dam face, in another, narrower strip (about 1 m) parallel to the downstream dam face and on the sides next to the foundation. Thus, there is no interference with placing compacted concrete, and both the upstream area adjacent to the reservoir as well as the concrete/rock contact area are closed to the passage of water. Furthermore, the flow of the mortar over the outside surfaces against the formwork allows a nice finish to be obtained for the exposed dam faces. The process's efficiency has been proven with Lugeon permeability tests performed on-site.

If this solution is adopted, it is advisable to check at the full-scale test section for the actual amount of paste in the areas treated with the mortar in order to prevent localised cracks from shrinkage. (Fig. 2.24)

Areas treated with addition mortar

Perimeter gallery — Conventional vibrated concrete in contact with the ground
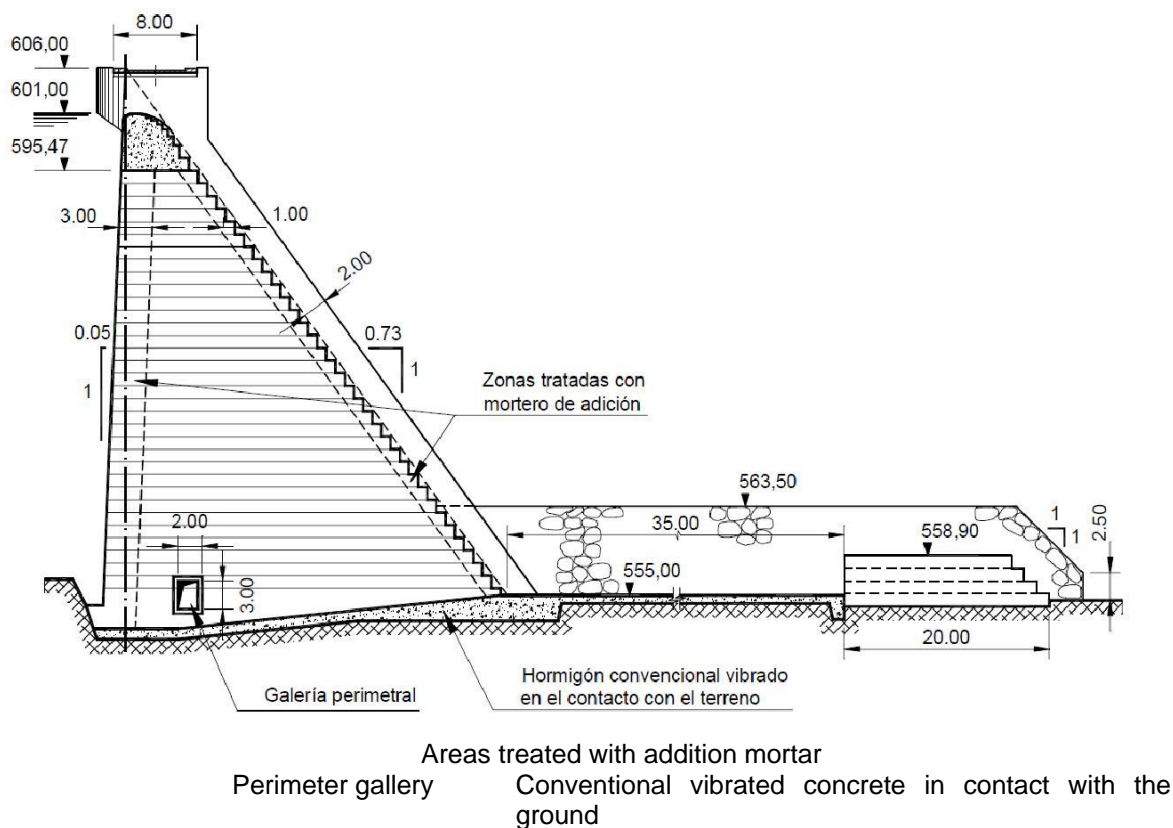
Fig. 2.24 - El Boquerón Dam, a 50-metre high RCC gravity dam (Segura River Basin Authority). The construction process described has been used for this dam. The small end sill for the spillway's stilling basin was used as the test section.

The trend in recent years (Esparragal Dam and La Brena II Dam, among others), has been to go with single-RCC dams, as commented in b) above. In English, this is known as the "all RCC dam" technique (Fig. 2.25A). To obtain an aesthetically nice finish on the dam face and to solve the problem of the RCC's contact with the rock on the slopes, a method called "GEVR" or "GERCC" (Grout-enriched vibratable RCC), which is known in Spanish by the acronym "HEL" ("HCR enriquecido con lechada"). This technique consists of applying a certain amount of grout to the formwork of the dam face and on the rock of the slopes, which will allow the RCC to be "vibratable". There are two possible methods for applying the grout: either before the RCC to be vibrated is spread, or afterwards. The former is most appropriate for wet RCCs, while the second one is best for dry RCCs. Mortar has been used instead of grout in some cases; when this occurs, the mortar is always spread prior to the RCC to be vibrated. At high temperatures, it is advisable to add a set-retarding admixture to the mortar.

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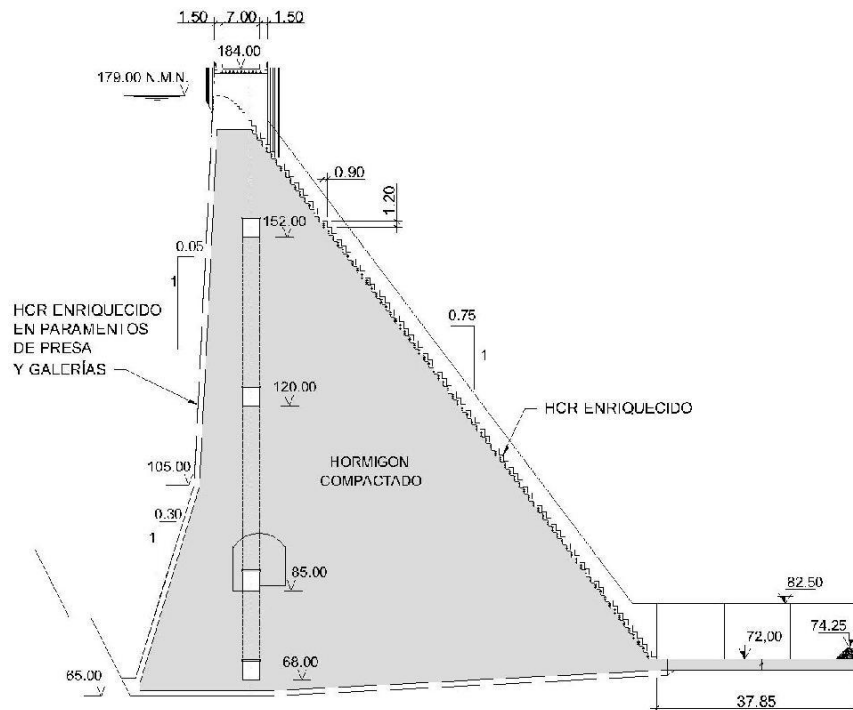
Enriched RCC on dam faces and galleries

Fig. 2.25A - La Brena II gravity dam, a 119-metre high RCC dam (Acuasur). Typical
cross section of the dam in which enriched RCC has been used on the dam faces.

An all-RCC dam body with a well-designed mixture and correctly built, with hot joint exposure times that are appropriate for the weather conditions at any given time, is a monolithic structure (between transverse joints between blocks) and waterproof per se.

Mortar applied between layers, as mentioned above in c), can improve shear and tensile strength across the joint for particular given conditions. But with a well-designed, workable RCC with suitable paste content, an equivalent performance can be achieved. In fact, the joints that have demonstrated better behaviour when cores have been tested, have all been in high-paste content RCC dams without mortar in between the layers, as it has been found that the mortar acts as a shock absorber during compaction, hindering the interpenetration of the layer being compacted with the one below it. However, in low-cementitious-content RCC dams and also in most of those with a medium paste content, applying mortar between the layers is an essential factor for improving the properties of the joint. In dams where they are working with dosages of low-paste content RCC, there has also been a tendency observed of

the mixture segregating, which adversely affects the bond between the layers and the monolithic nature of the structure in the vertical direction, and this effect cannot be controlled using mortar between the layers.

e. Lastly, it should be mentioned that in the preliminar full-scale trial carried out for the construction of the Enciso Dam, the RCC has been directly vibrated using immersion vibrators (IVRCC), without any enrichment whatsoever needed (Fig. 2.25B), as has been done recently in other dams (in South Africa, for example). This has been possible thanks to the use of a very workable RCC mixture with a consistency with Vebe times of 8 to 12 seconds, the addition of a set-retarding and plasticiser admixture to the mix, and the use of a fine aggregate that meets the recommendations given in Section 5.2 of this Guideline. The method of vibrating this RCC is slightly different to that used with CVC, so prior training is recommended along with the use of vibration equipment mounted on the arms of small backhoes, supplemented with manual vibrators for hard-to-reach areas, such as around the joints.

Fig. 2.25B – Test section for the 100-metre high Enciso Dam (Ebro River Basin Authority. Dam face execution and finishing with RCC vibrated using immersion vibrators without adding grout (IVRCC= 'HCRV'). As a comparison, GEVR ('HEL') – i.e., with added grout – was tested.

Regarding the use of vibrated concrete at contact points with the support rock, this is necessary only for creating a smooth surface suitable for compaction. If the surface of the foundation allows compaction to begin without any vibrated concrete for smoothing it, the dam/foundation bond will be at least as good, and possibly better, than if it is

included a layer of vibrated concrete. In some cases, the concrete/rock contact on abutments, whose slope hinders the use of vibrated concrete, has been solved by adding a 1-to-2 m strip of mortar over the previous lift of RCC, along the concrete/rock contact line, similar to that described in c).

However, the trend in recent years has been to use GEVR – or even IVRCC – as an interface at the RCC's contact with the rock, as mentioned above.

4.3.3 Joints

The roller compaction process involves substantial differences to that of vibrated concrete with regard to the joints that must be included in the dam's design.

VERTICAL BLOCK JOINTS

As mentioned in 4.3, in RCC dams, transverse joints can, in general, be distanced more than in a vibrated concrete dam, as a result of its reduced shrinkage. Distances of 20 to 40 m are common. Furthermore, using RCC method for the construction allows for the subsequent creation of transverse joints, dividing the block whose size was defined based on considerations related to the capacity for delivering RCC to the worksite into several sub-blocks of a length suitable to avoid cracks due to shrinkage. The joints that separate sub-blocks from a single construction block are created as each lift is compacted. There are several ways to do this, and the joint is named based on the procedure used to create it:

> a) induced joints are created either by inserting metal sheets into each lift or by creating a slot and then (or simultaneously) inserting a plastic sheet
> b) cut joints are created by cutting through each of the lifts with a radial saw and then introducing, for example, asphaltic emulsion into the slot created. In Spain, this system was used only for the Maroño Dam and has fallen into disuse.

With both processes, as compaction progresses, the joints are made between the sub-blocks. Thus, RCC dams are divided into one or more blocks of lengths defined in terms related to the capacity for delivering RCC to the worksite, and separated by

formwork joints sometimes reaching lengths of more than 500 m. Blocks that are too long in relation to the expected shrinkage of the concrete must be, in turn, further divided into several sub-blocks by means of joints that are induced, cut or created by some other process. (Fig. 2.26). The ideal scenario is to build the dam from slope to slope using a single working block, avoiding formwork joints and making all the transverse joints by inserting crack inducers, but this requires excellent resources for the production, transport and placement of the RCC, appropriate for the size of the dam.
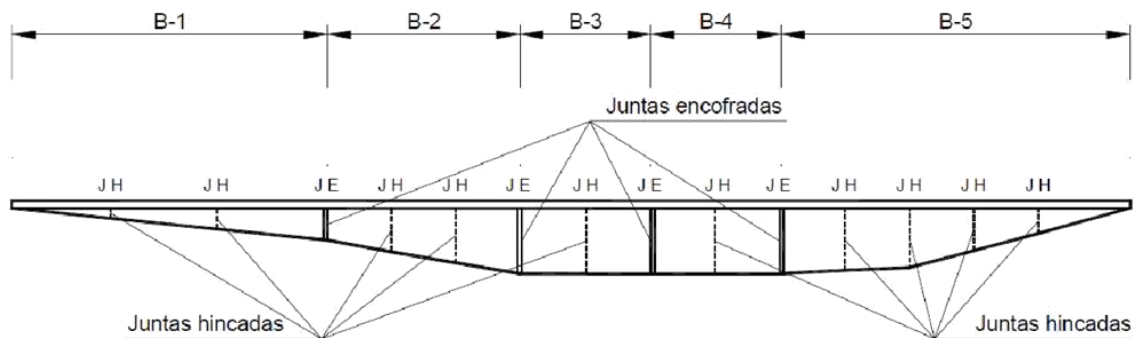
Top: Formwork joints, below: Induced joints

Fig. 2.26 - Sierra Brava Dam, a 54-metre high RCC gravity dam (Guadiana River Basin Authority). Elevation view of the layout of formwork and induced joints.

The waterproofing of transverse joints can be done by using plastic water-stops like those used in vibrated concrete dams. The creation of formwork-created spaces around the joints should be avoided so as to use traditional vibrated concrete. The construction process suffers less interference if the RCC is made "vibratable", by applying one of the techniques mentioned earlier in the subsection on the typical cross section.

Minimum interference with the compaction process is obtained using waterproofing devices attached to the dam face that are installed afterwards, but the cost and complexity of these are higher. (Fig 2.27)
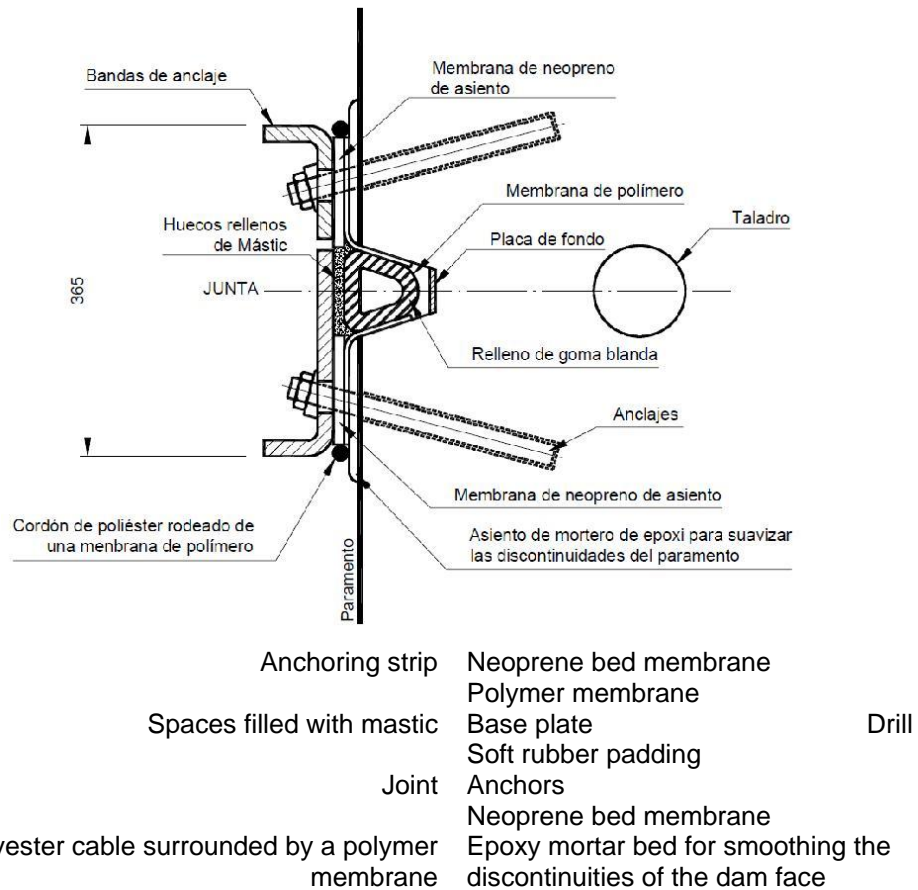
Anchoring strip   Neoprene bed membrane
Polymer membrane
Spaces filled with mastic   Base plate   Drill
Soft rubber padding
Joint   Anchors
Neoprene bed membrane
Polyester cable surrounded by a polymer membrane   Epoxy mortar bed for smoothing the discontinuities of the dam face

Fig. 2.27- Water-stop attached to the upstream face, as studied for the New Victoria Dam in Australia.

HORIZONTAL LIFT JOINTS

The height of the lifts is determined by seeking out the optimum technical and economical outcome based on the type and weight of the compaction equipment chosen, usually vibrating roller compactors, and on considerations related to the capacity for delivering RCC to the worksite. Lift height is typically about 30 cm. Therefore, in a RCC dam, the number of lift joints is some seven times higher than in a vibrated concrete dam.

To avoid the occurrence of cold joints, which must be treated by flushing with water and air and applying a layer of bedding mortar, the flow of paste to the surface must be ensured, and the time that can elapse between the placement of each lift and the next one must be limited.

The proper vertical continuity of the structure requires the bond between lifts without subsequent separation. This requires the paste to flow after compaction. This is achieved if the paste/mortar ratio (by volume) is 5% greater than the void content of

the compacted sand. However, when an elevated level of strength and watertightness across joints is required, the paste/mortar ratio can be as much as 15%, or even more, greater than the void content of the compacted sand. The value of this void content is generally between 26% and 33% (it is recommended that it does not exceed 30%), so it is common to design RCC mixtures with paste/mortar ratios of 0.36 to 0.44 or, in some particular cases, as much as 0.46. The importance of the concept of paste in the RCC is defined below in Section 5.2. With the paste/mortar ratio indicated, there is enough paste to fill in the spaces between the grains of fine aggregate as well as some additional amount, so that, due to the effects of the compaction, it flows to both the surface of the lift as well as to its bottom section, serving as a bedding mortar that facilitates bonding between the lifts. Each case will require an analysis of the parameters for the paste/mortar ratio and its effect on the watertightness of the joint to be carried out on the full-scale test section.

If the time elapsed since the completion of the lift exceeds a certain limit, which depends on the temperature, the joint must be treated so that it will attain an adequate bond between the lifts. If so, the joint is referred to as a "cold joint". Otherwise, it is a "hot joint" and a new lift can then be placed without any need for a treatment to ensure bonding. In the project design, the so-called "maturity factor" can be used to determine whether a joint is "hot" or "cold":

$$t_m(\text{hours x }^oC) = t(\text{hours}) \times T(^oC)\ [1]$$

where:

t_m: maturity factor

t: time elapsed since the completion of the lift

T: average daily ambient temperature on the surface of the lift

No absolute values can be set for the maturity factor limit, as in each case it will depend on a many variables, such as: the dosage (water content, amount of paste, types of cementitious materials, use of a set-retarding admixture, etc.), its workability, tendency to segregation, compaction methods and machinery, the effectiveness of the curing process, whether or not pre-cooling systems are used in hot weather and, in general, anything that may affects the initial and final setting times. It is advisable to obtain the maturity factor for each dam to be built from a well-planned test section. It

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1 The ratio between the temperatures in °C and °F is not strictly proportional (in fact T (°C) = (T (°F) – 32) /1.8), and thus neither is the ratio between tm(hoursx°C) y tm(hoursx°F).

is, however, much more operationally practical for on-site monitoring, to set a time limit for the exposure time for each month of the year by deducing these times from the aforementioned maturity factor, than to apply the maturity factor layer by layer.

The trend is to define three types of joint treatments for which suggested values (with all the provisos mentioned above) are given for the limit maturity factor time limit for the case of paste-rich RCC mixtures (for low- and medium-rich mixtures, it would be necessary to significantly reduce the maturity factors listed below):

– Hot or fresh joint. Maturity factor < 300 °C x h. Treatment: only a good curing and cleaning of the surface of the lift. This limit may reach 400 or 500 °C x h when set-retarding admixtures are used that increase the initial setting above 20 hours (Yeywa Dam in Myanmar, Ghatghar Dam in India, Jahgin Dam in Iran, Pirrís Dam in Costa Rica, Changuinola Dam in Panama and, recently, Puente de Santolea Dam in Spain).

  In fact, in these dams the maturity factor criterion has been replaced by the initial setting time. In this case, which is more conservative, the time between layers with hot joints between them is limited to the time at which the setting of the lower lift of RCC begins, measured in accordance with the UNE 83311 Standard.

– Warm or prepared joint. This is halfway between a hot joint and a truly cold joint. Maturity factor 300 to 800 ºC x h. Treatment: brushing the lift's surface and/or spreading bedding mortar prior to placing the next lift.

– Cold joint. Maturity factor > 800 °C x h. Treatment: green cutting of the lift's surface until the aggregate is exposed and spreading bedding mortar prior to placing the next lift. Some experts prefer to dispense with the bedding mortar and enrich (or not) the first lift of RCC on the cold joint with more paste. Others prefer grout instead of mortar as the interface on the bedding.

When considering two successive lifts, in order for there to be a correct bond between the two it is necessary to begin placing the upper lift across the entire surface of the joint before the maturity factor limit is exceeded or the setting of the concrete begins, depending on the approach adopted. For the purposes of monitoring the work, a limit value should be set that is close to the value at which, in practice, a correct bonding

between lifts would not occur. Setting too-strict maturity times in the project design aimed at creating a safety margin is detrimental to the continuity of the concreting and, hence, also to both the economy of the work and its quality, since the bond that is made in a hot joint is better than the one that can be obtained by treating the joint. We reiterate here the need to design the RCC dam facilitating continuous concreting, with the least possible number of cold joints. Formwork procedures involving the creation of cold joints, like the use of slipforming machines when they are not appropriate for the nearly-continuous concreting process, must be avoided, since they give rise to the systematic appearance of cold joints spaced at equal distances at the height of the slipformed facing element, since compaction must be stopped in order to create the facing element, which remains as permanent formwork.

However, in wide valleys, and when both the slipformed facing elements as well as their sequence of execution with the RCC lifts have been properly designed (see example in Fig 2.27A), the use of a slipforming machine to form the faces of the dam has been a very suitable solution that does not lead to any cold joints nor does it delay the rate at which the RCC is placed (except in areas of the dam where the layers have very little volume, such as at the crest of the abutments, but in that zones also there is an inevitable slowdown in placing the RCC when formwork is used instead of a slipforming machine). Examples include Upper Stillwater Dam (USA), Platanovryssi Dam (Greece) and Porce II Dam (Colombia), among others.

upstream face   downstream face
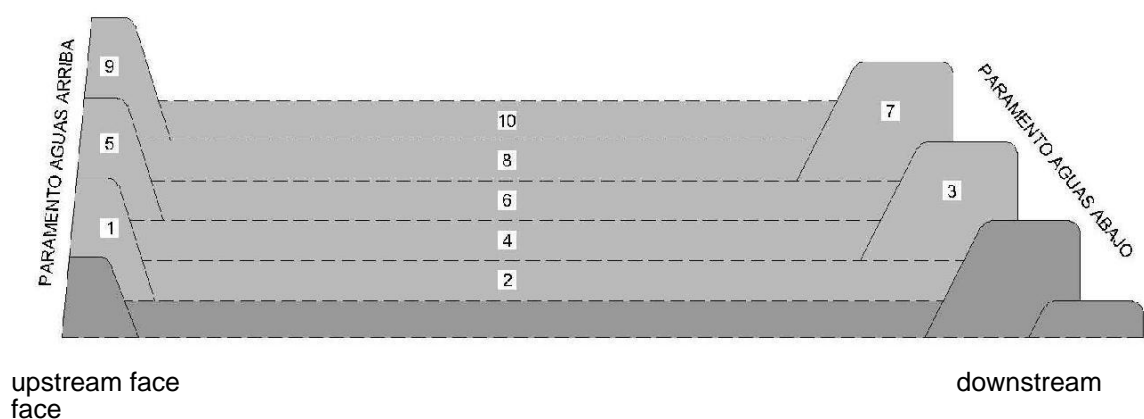
Fig. 2.27A - Diagram of the execution sequence of the slipformed facing elements and RCC used in the construction of Porce II Dam (Colombia)

LONGITUDINAL JOINTS

They are usually not necessary, but they are easily created using formwork, crack inducers or cut joints. The latter two have the disadvantage of hindering any subsequent injections, due to the conduits that it is necessary to leave installed.

4.3.4 Galleries

The following recommendations are made with regard to galleries in RCC dams:

- The number of galleries should be limited to the minimum necessary. If outlet works are located outside of the dam body, neither valve rooms nor galleries to access them will be needed. In low-height, B or C category dams it may even be appropriate not to have galleries of any type. In general, the main gallery for drainage is the lower gallery, which is where the dam's drains end.

- As the lower gallery is near the foundation, it can be included in a wide vibrated concrete plinth in order to facilitate the continuity of the compaction and should be built before this process begins. (Fig. 2.28)
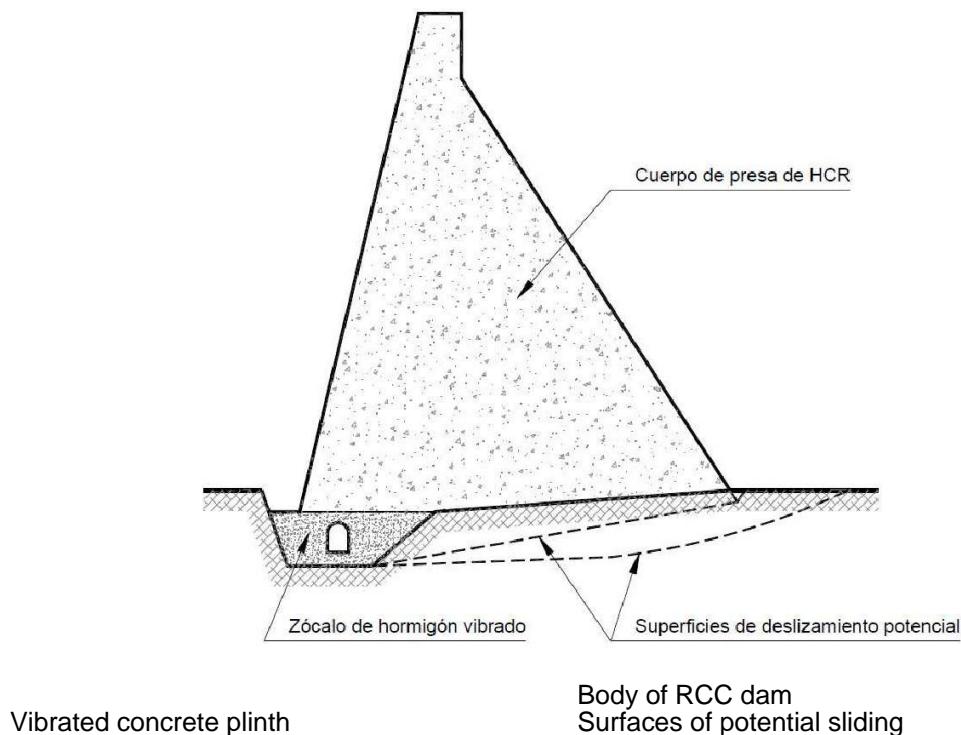

Vibrated concrete plinth

Body of RCC dam
Surfaces of potential sliding

Fig. 2.28 - Gallery incorporated into a heel-shaped part of the base located at the upstream toe of an RCC gravity dam.

–   The galleries must be located at a distance from the upstream dam face that will allow for the concrete that is to be placed between the gallery and the dam face to be spread and compacted properly. It is advisable that there be a separation of at least 6 to 8 m, avoiding excessive separations that impede the drainage of the foundation.

–   The process for creating the galleries must be chosen based on seeking the least possible interference with the RCC placement and thus it is advisable for it to be executed as quickly as possible. Some procedures that can be used for this purpose are:

a)   Precast panels used as permanent formwork. They provide a nice finish. They have the disadvantage of reducing the efficiency of the galleries in terms of dissipating the heat from the setting process, which is significant, and of masking possible defects in the dam's concrete. This procedure has hardly been used in Spain.

b)   Metal pipe used as permanent formwork, with the same disadvantages as those described in a). This system is obsolete.

c)   Occasionally, sand has replaced concrete in the area of the gallery in order to allow for the compaction process to continue, with the sand being subsequently removed. The finishing of the galleries is very poor. This system is obsolete.

d)   Formwork for the vertical faces and a precast slab for the roof, which has sufficient load-bearing capacity to withstand compaction. Unlike the way formwork is placed in vibrated concrete dams, in RCC dams it must be installed horizontally over one lift. To provide the necessary longitudinal slope for the gallery ditches, both they and the gallery floor slab are made of conventional concrete in a second stage (Fig. 2.29).
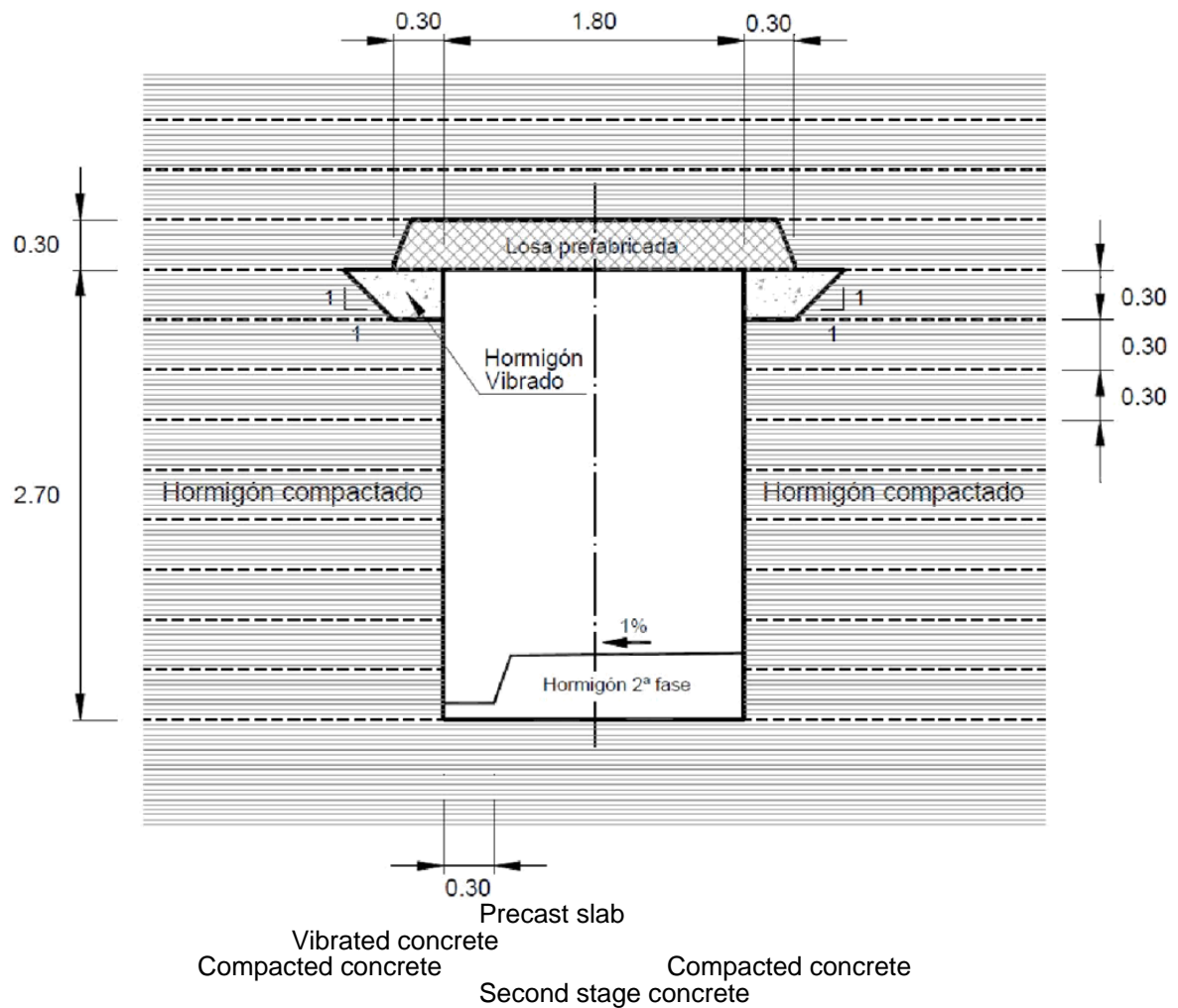
Fig. 2.29 - Typical cross section of a gallery with a precast slab to form the roof.

The methods used for building galleries should be consistent with their purposes. A gallery whose sole mission is to provide access to the interior of the dam can be built using any method. By contrast, procedures that mask the RCC, e.g., precast panels, metal pipes, etc., in the event that they are left as permanent formwork, should be avoided in galleries whose main missions include the inspection of the performance of the RCC.

The shape of the galleries is somewhat dependent on the procedure used to create them. Considerable freedom exists in this regard, as discussed when referring to vibrated concrete gravity dams.

In terms of the procedures for the construction of the sloped sections of the perimeter galleries, or of sections connecting different levels of horizontal galleries, the most frequently used are:

a) Those done with vibrated concrete in a trench dug into the rock of the abutment slopes. This is generally a more expensive solution, but it avoids interference with the subsequent placement of the RCC (similar to what was mentioned above for the lower section of the perimeter gallery, Fig 2.28).

b) Those done simultaneously with the RCC. In this case, they must be far enough from the abutment slopes for the RCC to be comfortably spread and compacted between the gallery and rock. It is advisable to standardise the slopes of the different sections as much as possible. Complicated junctions between horizontal and sloped sections can be solved by specially designed precast elements. In some dams, the horizontal and sloped galleries have been included on the same plane, greatly facilitating the simultaneous construction of the junction and he RCC, and solving the issue of connecting them using stainless steel stairs and walkways (La Brena II Dam).

c) Some designers are in favour of using only horizontal galleries in RCC dams and connecting them with vertical shafts. Spiral staircases, either precast or made of stainless steel, are installed in these shafts. A shaft is always left without a staircase in order to be able to use it to move machinery and equipment, or the spiral metal staircases are designed so that they can be easily assembled and disassembled from the upper level. (Platanovryssi Dam in Greece).

4.3.5 Drainage of the dam body

In RCC dams, the drainage courtain should be made by drilling, thus avoiding interference with the RCC placement. The drainage of the dam is of greater importance than in vibrated concrete dams, as the number of discontinuities defined by its lift joints, through which seepage may occur, is considerably higher. The distance from the drainage courtain to the upstream dam face depends on the distance of the galleries, from which the drilling must be done, to this face.

4.3.6. Spillways

The spillway designs used for vibrated concrete dams are also valid for the RCC dams. In the latter, the most common spillway shape is the uncontrolled overflow profile, due to its economy and ease of construction. However, RCC dams with gated spillways over 20 m in height have also been built.

With regard to the discharge channel, the stepped shape of the downstream face typical of RCC dams is very suitable for this use, with the advantage that the high level of energy dissipation obtained from this, leads to stilling basins of very limited length, in addition to the saving on the lining of the stepped face, using a slab of reinforced concrete anchored to the downstream dam face. While there is a reasonable limit for this type of stepped spillway channel, the limit being that the unit flow should not exceed 20 m^3/s/m, in some cases they have been designed for units flows of up to 30 m^3/s/m. More than 30% of RCC dams built world-wide have adopted the stepped spillway solution, including several of those built in Spain.

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4.7. RCC ARCH DAMS

The typology of arch dam built with RCC has been developing progressively, mainly in China, and with both single- and double curvature. The specific aspects of the structural design and considerations regarding the foundation of this kind of dam are similar to those mentioned in the sections relating to conventional concrete dams.

Nevertheless, there are some characteristic features in the design of RCC arch dams that derive precisely from the speed with which they are built. In particular, thermally generated stresses become more marked than in conventional arch dams, as the heat generated during hydration process does not dissipate as readily as it does in conventional concrete dams. This is even more critical when also considering the need to fill the reservoir before getting the internal temperature to drop to levels approaching the dam's final stability temperature. This has been the most frequent case with the RCC arch dams built to date in China that have reached heights above 100 m.

This has created a new field of research and development related to RCC dams that focuses primarily on four aspects:

- more detailed three-dimensional thermal-stress studies, the determination of the optimal distance between joints and foreseeable openings in these that would allow for grouting in a timely manner so that they give the arch effect to the structure.

- the design of specific post-cooling systems compatible with RCC dam construction systems.

- the design and construction of grouting systems for transverse joints that allow for a potential subsequent regrouting during cooling stages or loading/unloading cycles after the initial impoundment. These systems must also be compatible with the placement procedures of the RCC, without limiting its placement from one slope to the other, in a single block, which is the usual practice in the geometries of the valleys where this kind of dam is built, and

- the use of high-performance RCC mixtures, with a high paste content and with high

percentages of the cement being replaced with pozzolanic materials/fly ash.

With regard to thermal control and the thermal stress analysis, it is necessary to have available not only powerful tools for numerical calculation but also the proper knowledge of the development over time of the RCC's tensile properties and of the environment where the dam is constructed. Three-dimensional finite element models are required for the design of this type of dam. The experience of the design team is also important.

When manufacturing the RCC for these dams the use of pre-cooling facilities is common; these make it possible to cool the aggregates, chill the mixing water and to use flaked ice. The cost of these facilities is usually more than offset by the benefits of commissioning the dam ahead of schedule. To date, when they have been used, post-cooling systems for RCC arch dams are similar to those used in traditional dams, such as coils embedded in the concrete through which cold water is circulated. However, more research is needed on systems that interfere less in the placement of the RCC. In these dams, the contribution of inspection and drainage galleries as cooling elements is very beneficial.

Transverse joints are created by inserting joint inducing elements (metal sheets, plastic, etc.) after compaction of the layer. The systems for the grouting of these joints and for the creation of compatible grout compartments compatible with the RCC placement is a chapter that is still under development. In South Africa and China, different methods have been researched with varying success. The introduction of grout-enriched RCC allows for the relatively easy embedding of these elements close to the dam faces and on the horizontal planes that separate the compartments. Recent experiences in China show, however, that more detailed work needs to be carried out on the design, manufacture and installation of grouting lines and of the re-grouting valves, in order to ensure their operation and that they are not damaged by the equipment used to place the concrete.

In some recent constructions of RCC arch-gravity dams (Changuinola, Panama and Portugués, Puerto Rico) neither post-cooling nor transverse joints grouting were used. In these dams, the thermal state of the core itself maintains the joints closed, giving sufficient continuity to the compressive force in the horizontal arches.

Given the high quality that is required of the material, the mixture proportions used in RCC arch dams are exclusively mixes with a high content in pozzolanic material and a total cementitious material dosage of over 200 kg/m^3. Depending on the quality of the fly ash or natural

pozzolans, their percentage may reach 70%. The maximum aggregate size, preferably obtained by crushing, should not be more than 40-50 mm in order to control any possible indication of segregation. Work should be done with concretes that have a very workable and cohesive consistency with Vebe times of approximately 10 seconds. In addition, set-retarding admixtures should be used that permit the time of activity (initial setting) of the lower, compacted lift to be prolonged until it is covered with the next lift. This is the only way in which to guarantee the monolithic character of the structures' vertical cantilevers. The water/cementitious ratio of the RCC mixtures used in arch dams is typically between 0.50 and 0.65. The percentage of fine aggregate (sizes of less than 5 mm) on total aggregate must be approximately 35%. The quality and quantity of fine sand passing through the UNE Standard 0.080 mm sieve, which may exceed 5% in the combined curve of aggregates, are very important in these mixtures.

4.8. OTHER USES OF RCC IN DAM CONSTRUCTION

Following is a summary of the most important applications of the RCC technique in other works related to the construction of dams.

- Construction of cofferdams. This solution is especially interesting when they are of significant volume and are needed within a short period of time, or when the risk of overtopping during its operational period is high (e.g., Three Gorges Dam in China).

- The construction of stilling basins of spillways and outlet works for embankment and concrete dams (e.g., El Atance Dam and El Boquerón Dam, where part of their stilling basins were executed using RCC and these were also used as test sections). This is a particularly appropriate solution when large volumes of poor quality soil must be replaced.

- Refurbishment of stilling basins of spillways and outlet works for embankment and concrete dams that have been eroded by floods (e.g., Tarbela Dam in Pakistan).

- Protecting river banks downstream of spillways (e.g., Platanovryssi Dam in Greece).

- Protecting against overtopping in embankment dams, by coating the downstream face with RCC (over 50 applications in small dams in the U.S. to have the dams comply with new, stricter, regulations on flooding).

- Protecting against overtopping during the construction of embankment dams, in cases where there is a high risk of this occurring. (e.g., Xingo Dam in Brazil).

- Reinforcement of concrete and masonry dams by building buttresses on the downstream face (several dams in the U.S., in order to adapt the dams to seismic stresses greater than those for which they were originally designed).

- As a backup dam against the failure of another dam in service but in precarious conditions in order to comply with new, stricter regulations (e.g., Saluda Dam in the U.S.).

- The coating of the downstream face of concrete dams in order to protect it, or to replace concrete damaged by the action of freezing and thawing (e.g., Santa Cruz Dam in the U.S.).

- Foundations for large conventional concrete hydraulic structures (e.g., Tous New Dam).

- Raise of concrete dams (e.g., San Vicente Dam in the U.S.).

5. DEFINITION OF THE CONCRETE MIXES IN THE PROJECT DESIGN

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5.2. CONSIDERATIONS REGARDING ROLLER COMPACTED CONCRETES

Much of what has been said about vibrated concrete (CVC) is also valid for roller compacted concrete (RCC). Therefore, in order to avoid repeating information, just a few considerations about the particularities of RCC will be mentioned here.

When considering the materials and dosages for an RCC dam, the designer must always bear in mind that they are in-situ properties, including most especially those of the horizontal joints between lifts, that are important and not the ones that can be reached in the laboratory.

In both CVC and RCC technologies, a part of the water in the fresh concrete has no purpose other than to facilitate its consolidation. The amount of water required for doing this using vibration is much higher than if the same thing is achieved using the roller compaction process. The essential characteristic of fresh RCC is its relative dryness, with a moisture content that allows it to be consolidated using vibratory rollers. The water/cementitious ratio is in the range of 0.50 to 0.70 and the consistency of the RCC received on the worksite has Vebe times of 8 to 15 seconds. Fresh RCC should look cohesive and show no signs of segregation. Hardened RCC is similar to hardened CVC, though its density, if compaction is performed properly, is superior when the component materials are of the same origin.

The percentage of fly-ash, or in general pozzolanic materials, in the total amount of the cementitious materials (cement+fly-ash) cannot be considered characteristic of RCC, as evidenced by replacement percentages of up to 70% for vibrated concretes. What can be said is that, for RCC dams where the delivery of concrete to the site is done at a fast rate, the adoption of high ratios between the fly-ash content and the cement is obligatory.

In addition, the variety that characterised the composition of the concretes of the different RCC dams built in the early times of this technology has been decreasing and has become increasingly concentrated on two distinct trends. On the one hand are the mixtures incorporating a high content in pozzolanic materials, between 100 to 160 kg/m^3 and on the

other, the mixtures which leave it out entirely or use a minimum amount, between 0 to 30 kg/m^3. Each of these trends entails consequences that affect the design of the dam. Generically, we can say that the former correspond to mixtures traditionally called "high-paste" and the second to "lean" or "low-paste" mixtures. The proportion between these for RCC dams currently being designed and built world-wide currently is approximately 80-20%. Given the availability of fly-ash and the required levels of quality, in Spain 100% of our RCC dams have a high content of pozzolanic materials and thus fall into the former group.

Concrete is composed of a skeleton of aggregates whose holes are completely filled by the paste. The total volume of the paste in the mixture should be such that it also provides an excess of paste on the surface that will enable bonding between successive layers.

AGGREGATES

The following aspects of the aggregates used for manufacturing RCC stand out:

a) The objective to achieve an aggregate structure that is as closed as possible is the same as for a concrete to be vibrated, and thus the dosage of the aggregates can be done based on the same procedures used in vibrated concrete technology. Dividing aggregates into fractions can be carried out with the same criteria as for those used in CVC.

Nevertheless, there are specific methods for determining the dosage of the skeleton of aggregates in an RCC. Also, for fine aggregates used in RCC, a greater proportion of fines is generally allowed, provided they are not plastic, which can increase the compactness of the mixture and reduce the content of cementitious materials. The void content of the compacted sand fraction must be below 30%. The grading curve of the sand for RCC must conform to the following ranges:

	% by weight passing through each sieve						
Mesh opening (mm)	5.00	2.50	1.25	0.60	0.30	0.15	0.08
Upper limit	100	85	68	52	35	25	18
Lower limit	90	65	42	25	15	10	5

b)   The quality requirements for aggregates (strength, durability, density, shape, etc.) must be the same as for those used in CVC dams. Only in dams with a low content of pozzolanic materials, or in small dams and weirs may the use of materials with poorer physical and chemical characteristics be allowed.

c)   The maximum aggregate size is usually smaller in RCC than in CVC, mainly due to its greater tendency to segregation and to the reduced height of the lift to be compacted. In current practice, common maximum sizes are approximately 50 – 60 mm for crushed aggregate and 40 – 50 mm for rounded aggregates.

d)   As mentioned above, in general, the content in plastic fines must be limited. The incorporation of non-plastic fines in a proportion of between 5% and 18% of the fine aggregate has the beneficial effects mentioned in section a). In some cases, the water demand increases with the increase in fines in order to achieve the correct degree of workability and consistency. In many cases, this increase in water is justified by the increase that occurs in the volume of paste available on the surface of the lifts, which improves the joints' strength and watertightness to the detriment of the strength in the parent concrete.

CEMENTITIOUS MATERIAL

Unlike what has been said about vibrated concrete, the fast rate of placement requires that the content in mineral admixtures be high, approximately 60% – 70%.

The term "mineral admixtures" comprise different classes of materials that demonstrate a binding activity and that act as active replacements for the cement. Some important admixtures include blast furnace slag, fly-ash with low and high content in lime, natural pozzolan, some limestone fillers and calcined clay. All these and more have been used in RCC dams. Their performance depends largely on the quality and uniformity of the source, and on the control of the preparation process until they are incorporated into the mixture.

Subject to their availability at a competitive price, the use of mineral admixtures that partially replace cement free of admixtures provides both technical and economic advantages in RCC dams. In these cases it is common to employ ratios of up to 70% of these pozzolanic materials.

Some of the main advantages of their use are as follows:

- they reduce heat of hydration
- depending on their shape, they can improve the workability of the mixtures (this is true for many of the low-lime fly-ashes)
- in general, they decrease the water requirements for a given consistency
- they fill voids and increase the compactness of the mixture, reducing its porosity and increasing the density and watertightness of the RCC matrix
- just as in CVC concretes, concretes with a high content in mineral admixtures are usually less susceptible to the alkali-aggregate reaction

they slow down the setting process and improve the bonding between layers with the same exposure time

- with some of them (as is the case of fly-ashes in general) higher long-term strengths are obtained
- they reduce costs, because they are usually cheaper than cement free of admixtures

PASTE

The design of the paste is one of the aspects with the most influence on the final, on-site quality of the RCC. The volume of the paste in the mixture also directly defines the orientation of the RCC dam design adopted, which moves between the two conceptual extremes: a high or low paste content.

In order to unify criteria and in accordance with international practice, the RCC paste includes the cementitious materials, water and admixtures. 'Cementitious material' means the cement and any active mineral admixture like those mentioned in the previous section. When considering any RCC mixture, the amount of paste must be enough to ensure, at the very least, that the spaces left by the compacted fine aggregate will be filled, i.e., those spaces from the fraction of aggregates less than 5 mm, including all fines which are not cementitious materials.

However, as indicated in Section 4.3.3, the design of the paste that must be incorporated into the RCC mixture is a function of the behaviour required in the joints between lifts that have not been treated or that have no mortar between them. In these cases, the amount and dosage of the paste depends on the degree of watertightness required in these joints and on their shear and tensile strength. This criterion is always stricter and more constraining for a design of RCC mixtures than is strictly necessary for the design of its own matrix (the parent concrete of the lift).

The design of the paste is governed by three main parameters of the RCC mixture itself: its consistency, strength and setting time. In practice, for the purposes of design and control, what is done is to relate the properties of both the RCC matrix and those of the joints between lifts with these three parameters. That is to say, a well-designed RCC mixture allows for the joints between lifts to perform well without treatments or mortars. This is directly related to the design of the paste, since it directly influences the properties of the mixture, both in fresh and hardened states. The paste contributes directly to fresh RCC not segregating, to it being dense and cohesive, and to its compacted surface maintaining its activity (chemical and physical binding capacities) during a prolonged period of time until it is covered with the RCC for the next lift. The paste also influences the evolution over time of the RCC's elastic and thermal properties and its watertightness and durability.

The final criterion for the optimisation of the design of the amount and dosage of the

paste is that of the least cost from among the ones that meet the design's most limiting criteria which, as already mentioned, are usually those related to the joints between untreated layers and not the criteria for the RCC's matrix itself.

Generally, mechanical strength requirements also require low cementitious material content, so that in the event that there is not any fine aggregate with suitable fines available, an appreciable amount of cementitious material (normally the mineral admixture due to reasons related to heat of hydration and costs) will serve exclusively as fill.

When dosing the concrete, the technically and economically optimum combination of the various components must be sought; mixtures with a lower content in cement and water, which result in concretes with less shrinkage and less setting heat, are generally considered preferable. In addition, they must have a suitable workability that will enable compaction to be effective.

CHEMICAL ADMIXTURES

One of the common components of the RCC mixture is the set-retarding admixture. Its purpose is to keep the initial setting of the mixture under the exposure time between consecutive lifts to ensure they are bonded together and, consequently, the monolithic character of the structure in the vertical direction. In many cases set-retarding admixture have a very positive secondary effect as water reducers and, therefore, of increasing strengths, not only over the short-term but also over the long-term.

Nowadays, set-retarding agents are a common component in high-paste RCC dams. Depending on the commercial product, the other components and the weather conditions, the dosages used generally vary between 0.6% and 2.0% (by weight) of cementitious material content, and work has been done with mixtures with initial setting times of up to 20 – 24 hours.

When working with these high levels of delayed setting, it is necessary to use well-controlled products and to check to make sure that they do not produce negative secondary effects (influence on the strength and stability of the mixtures, the performance of the mixture during compaction, possible Vebe time test distortion, etc.). Some

admixtures work well with certain cementitious materials and not as well with others. Given the above, it is imperative to test the admixtures to be used both in the laboratory as well as in a full-scale trial on a test section. In addition, the lower initial strength of the RCC with a retarder must be taken into account in the design of the formwork for the dam faces.

In some countries (mainly the U.S.) air-entraining admixtures are frequently used, but more to improve the workability of fresh concrete than to increase its resistance to freeze/thaw cycles.

FRESH CONCRETE CONSISTENCY

The consistency of the RCC should be that which enables its transport, spreading and compaction using standard earthmoving equipment without causing segregation. For an optimised particle size distribution, adequate consistency is more easily achieved the wetter the mixture is, with the limitation being that it must be able to be uniformly compacted by vibratory rollers with a static weight of 10 to 12 tonnes. These constraints prevent defining its consistency using the traditional Adams slump cone procedure. There are various methods of measuring the consistency of compacted concretes, such as the Vebe method, or the UC method developed at the University of Cantabria. Either one is valid when used properly and its particularities are taken into account.

When using the Vebe test, the consistency of the RCC as measured according to the UNE-EN 12350-3 Standard, but using a mass of 12.5 kg (instead of 2.75 kg as indicated in the Standard), should be between 8 and 15 seconds under laboratory temperature conditions (20 °C). Some standards often used in other countries use masses other than the aforementioned 12.5 kg masses in the Vebe test, which must be taken into account when comparing results.

FULL-SCALE TESTS

Full-scale tests, commonly called "test sections ", are blocks that are built prior to starting to place the RCC in the dam. They are made with the materials and resources that are planned for the dam, and full-scale tests are carried out on them using the mixture

proportions that have been previously tested and optimised in the laboratory. Depending on the size and needs of each project, the total volume of the test section or sections may vary from a few hundred to several thousand m^3. The main objectives for constructing them are:

- training of the contractor's staff and the worksite control team
- testing of the equipment and procedures for concrete placement proposed by the contractor
- confirmation that the mixture does not segregate when it is manufactured and placed using industrial production equipment and
- confirmation of the strength parameters across the joints between layers for different types of treatment and degrees of maturity. In order to consistently obtain this valuable information, it is advisable to carry out tests for the aforementioned three objectives on previous small test sections that are no thicker than two layers.

The need to do this is debatable for cases in which the performance of the mixtures is well-known from prior experiences and studies and in cases where the staff and equipment are experienced. Otherwise, especially in countries or environments where RCC is new, it is very advisable to carry this out, as it avoids unnecessary stops and delays in the initial stage of the RCC placement in the dam.

In order to save costs, for some RCC dams, the test section has been made in a temporary or permanent structure that is large enough for its intended purpose: cofferdam, the slab and end sill for the stilling basin, the dam abutment blocks, etc.

PROPERTIES OF HARDENED CONCRETE

The higher the content of the fly-ash-to-cement ratio, the slower the development of mechanical strengths. The characteristic strength of the concrete should be established so that the concrete reaches the required strength before the corresponding stress can take place and so that an adequate safety margin is maintained. Stresses corresponding to the construction phase and, if possible, to the early impoundment of the reservoir, must be taken into account. Linking the maximum predictable stresses to its strength at 90 days must be avoided, as this is arbitrary and may lead to an unnecessary strength requirement or, in other cases, the acceptance of situations in which adequate safety margins are not maintained. It is common nowadays to employ a design-age of 180 to 365 days.

In many cases, the critical design parameter is usually the in-situ direct vertical tensile strenght across horizontal joints, especially in seismic areas and/or under conditions in which significant thermal loads occur. In these cases, the strength of the RCC's matrix, which is the value monitored in laboratory specimens, is a secondary aspect; the important thing is to ensure the strength of the dam's joints. There are experience-proven procedures for correlating both parameters, so in practice what is done is to design the RCC mixtures so that they reach an in-laboratory compressive strength that guarantees that it will meet the in-situ strength requirements for the joints at the design age. To do this, it is essential that the RCC mixture includes enough excess paste that it flows back to the surface during compaction.

RCC's compressive strength is usually measured using cubical or cylindrical test specimens. The specimens are prepared using a vibrating table, which is the most suitable method for high-paste RCC mixtures. For low-paste mixtures a vibrating hammer with a tamper is also used, but in some cases it has been found that this leads to elevated strengths at early ages that are unrealistic.

From the data available to date, it appears that, in general, RCC reaches over the long-term strengths greater than those of CVC, its elasticity modulus is lower and its density slightly greater.

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**Chapter 4: Design criteria
and Chapter 5: Definition of the concrete mixes in the project design**

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