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RCC dams in Spain. Present and future

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ABSTRACT: This paper briefly reviews the essential characteristics of the Spanish dams in RCC, both in their typology and their design and construction, as factors relative to materials, mixtures and mixing.
The Spanish RCC dams have had a satisfactory behaviour, similar to the numerous dams of conventional concrete existing in Spain. It is believed that the use of concrete with a high content of paste has had a great influence in this performance.

1 INTRODUCTION

The peculiar location of Spain, to the South West of Europe and to the North of Africa causes that climatology of Spain has some very specific and varied characteristics, which produce rainfall patterns and river flows with a very high irregularity and an unevenly geographical distribution of the water resources.

The flow regime of the rivers presents a high irregularity, with pronounced interannual variations which can give rise to long periods of drought, and also very important seasonal variations with low water levels during the summer months. In and of itself, the available water resources in to natural regime are very scarce, with a total of 9,200 hm³/year (8.3% of the renewable resources), what would take place, to mean per-capita availabilities of only 240 m³ / year, as compared with the 1,000 m³ / year considered basic on a world level in order to cover the supply needs.

These basic data of the water resources in Spain, together with the specific circumstances of water supply, are clear indicators of the Spanish situation, in which in order to be able to attend the water demands it has been necessary to construct many large dams and reservoirs. The construction of dams in Spain began in Roman times, of which still remain in operation the marvellous Proserpina and Cornalvo dams. At the present time there are 1,200 large dams in Spain, and 25 under construction, with a total reservoir capacity of 56,500 hm³ which have made possible to pass from a natural regulation of only 8% of the renewable water resources, to a real availability of more than 40%, which has situated the country in the setting of the mean natural regulation of the European countries. With this number of large dams Spain occupies the first place among the European countries, and the fourth in the world ranking. Dams in Spain produce important economic and social benefits and have been a determining factor in the development reached during the last decades.

The greater part of the Spanish dams are made of concrete (72%), due to the fact that in general the good quality of the foundations, and that in Spain the rivers could present extreme floods, in face of which concrete dams are less vulnerable. For all this, when in the decade of the 1980's the technique of dam construction of roller compacted concrete (RCC) was developed and there was in the country a great activity in dam construction, in Spain this new technology was rapidly implanted, and so in the year 1984 the first RCC dam was completed (Erizana dam).

At the present time there are 24 RCC dams in operation, 21 being large dams, with a height superior to 15 meters (see Table I at the end). These dams have been constructed in locations of diverse climates, and their objectives cover all de purposes: Water supply (10), Flood control (9), Irrigation (3) and Hydropower (2) (see Figure 1). Spain occupies the first place among the European countries wit relationship to the number of RCC dams, and the fifth place in the world ranking.

The advantages that have supposed the RCC dams refer mainly to the economy in the costs and to a bigger speed in the construction. Also the RCC dams suppose a bigger hydrological safety, issue that has a special importance in Spain.

The main characteristics of the Spain RCC dams, which are described more in detail in the several tables of the paper, are the following:

- ??Height: Average 42.38±25.82 m, with a maximum of 101 m (Rialb dam).
- ??Volume of concrete: Total 4,218,600 m³, with an average of 175,800 m³ per dam, and a maximum of 1,325,000 m³ in Rialb dam.
- ??Volume of RCC: Total 3,608,300 m³ with an average of 150,350 m³ per dam, and a maximum of 1,200,000 in Rialb dam.

- Percentage of RCC over the total of the concrete: 86%.

In this paper the principal characteristics of the RCC dams in Spain are described, analysing their typology, the material employed and the mixtures, the waterproofing, the upstream faces, the joints and their treatment, the lift joints, the stepped spillways, and the construction methods usually employed (mixing, transport, placing and curing of the concrete). Finally some features of the Spanish RCC are presented.

2 TYPOLOGY

All the dams constructed up to the present time are of a straight gravity type (PG), except one of curved plan, with a standard section (which adjusts to the Pigeau profile) with slight adaptations in order to favour the new technology of continuous placing of the concrete; at times the triangular profile comes close to being trapezoidal.

It is obvious to point out that both the quality and the geotechnical characteristics of the foundation affect the width of the structure (Puebla de Cazalla and Rialb Dams). The seismicity of the Iberian Peninsula has generally very little influence on this.

The experience in construction of RCC dams has shown that the design of a dam should simplify the structure, eliminating all that is superfluous, that is to say, that which is not detrimental to it safety and its functional character. So:

- The conduits of intakes, outlets and diversions are usually concentrated in one same section or block. Their valves and operating mechanisms are situated next to the downstream face and their inlets, if it is possible, in a tower backing on to the upstream face.
- The inspection and drainage galleries should be reduced in number to the essential minimum. In the case that only one gallery is utilized, it will be attempted to ensure that it be "perimetric" as it permits the carrying out of corrective ground works, waterproofing and drainage, in a more rational manner and with greater efficiency. These perimetric galleries have been carried out in various ways: embedded in a trench in the ground, encased in the conventional concrete of the foundation or formed with prefabricated elements. In the Puebla de Cazalla Dam the perimetric gallery was formed with corrugated metal tubing, with very successful results.

It has to be pointed that it has not always been possible to make a simplified design for which, in some cases, a part of the inherent constructive advantages of the RCC has been lost.

In addition, it should be mentioned that in the new rockfill Tous Dam, RCC was extensively used to protect the outlets.

Figure 1. Situation of the RCC dams.

Figure 1 shows the location of all the twenty-six RCC dams and in Figure 2 some standard sections which can be considered to be the most representative are shown. The Tables I to IV (see end of document) describe the geometric and constructive data and the materials employed in the twenty-four RCC Spanish Dams in operation.

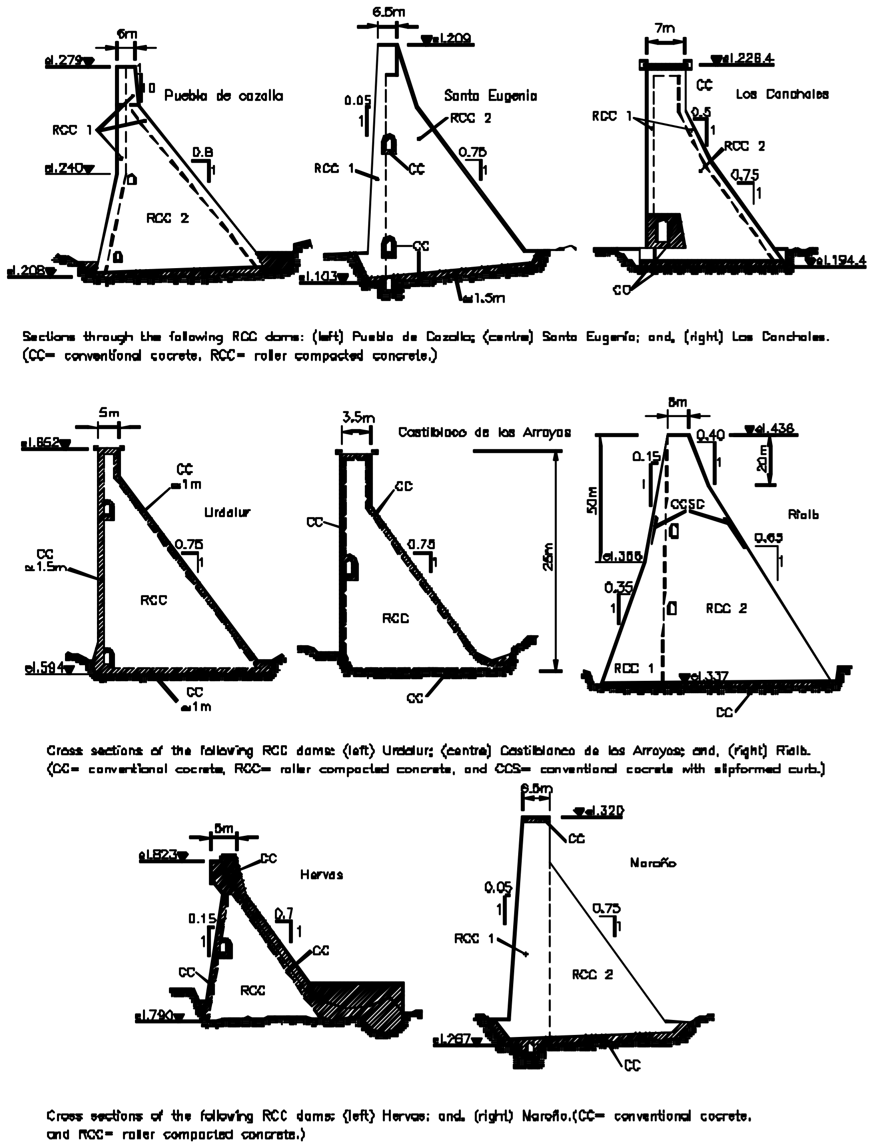


Figure 2. Most representative sections of Spanish RCC dams.

3 MATERIALS FOR THE RCC

3.1 Aggregates

In Spain, the aggregates used in the RCC dams have been practically of identical character to those employed in conventional concrete. Of crushed stone or of natural deposits, of calcareous or siliceous origin, are employed without distinction, depending on their cost.

The aggregates are classified in coarse aggregates (> 5 mm) and fine aggregates or sands (< 5 mm). The first ones are separated, in general, in three fractions and the second into one or two fractions, depending on their maximum size.

The maximum size of aggregate (M.S.A.) has been of 80 mm, only being greater in Erizana and Sta. Eugenia dams where it was 100 mm. When the upstream face has been constructed with RCC, the aggregate of 80 mm has been reduced to 40 mm or 50 mm in this zone.

In the Spanish RCC the advantages of using aggregates of a greater size (greater resistance, lesser shrinkage, lesser quantity of water and paste), have been subordinated to the interest of avoiding segregation.

When the aggregates have been of quality, the fines of the sands have formed part of the paste. If they are of a calcareous nature, these fines ($\leq$ 80 μ) can reach a 12% of the total of the sand. In the Urdalur Dam it was of 8%.

In Table IV (see end of document) the quantities of aggregates utilized in the concrete of different dams are indicated.

3.2 Cementitous content and additives

The binding material used in Spain for the compacted concretes is generally a mixture of Portland cement and fly ash, class F type silica-aluminous, with a content of the latter very superior to that of the cement. Other additions such as blast-furnace slag have been used only in Urdalur dam and in the auxiliary compacted concrete of the New Tous Dam. In these cases the cementitious material has been a composite cement supplied by the cement factory.

To date, it has been preferred, due to its greater flexibility, to make the mixture on the work site.

The characteristics of the fly ash are regulated by the UNE-83-415-87 Standard.

In general at the beginning of RCC dams construction, admixtures were not used for RCC. In the Puebla de Cazalla Dam setting retarders was successfully used. Setting retarders and water reducers are of a more general use at the present time.

4 MIXTURES

In the RCC the mixtures are the object of special studies. It is not only valid to comply with the specifications of the design documents, which generally are limited to requiring some compressive and tensile strength. Several technologies are available in order to determine the mix design of the concrete. All these methods are grouped together by those which are based on the concrete technology and those others which depend on soil technology. Those of the first group are based on the “consistency” of the material, which is measured and determined by the “Vebe Consistometer”. The second group uses the Modified Proctor test.

In Spain, the concrete technology has been generally employed. That is to say, it starts from a grading of the coarse aggregate with a minimum of voids which are filled with a mortar, in this turn the voids of the sand being filled with an excess of paste.

In essence it consists in designing a paste of cement, active additions, fines and water, the volume of which exceeds the volume of voids of the frame formed by the total aggregate.

The combined grading of the aggregates is continuous and the consistency of the concrete is measured with the Vebe Modified consistometer. Up to the present time all the RCC dams in Spain have been constructed with mixtures with a high content of paste, it is to say, with a cementitious material dosage superior to 150 kg/m³, and in most cases, to 200 kg/m³, with a high substitution of cement by fly ash (proportions) fly ash/cement from 60/40 to 70/30 are normal). Cementitous material contents of 240 kg/m³ have been reached in some cases.

It is convenient that the content in paste exceeds that is necessary to fill the voids; the excess flows back to the surface and contributes to improving the union between successive lifts.

In Table IV the characteristics of the concretes are shown. (See end of document).

	Mean	Maximum	Minimum
C.P. (kg/m³)	78	100	70
F (kg/m³)	125	170	90
C+F (kg/m³)	200	240	185
$\frac{F}{C ? F}$ (%)	63	70	60
$\frac{W}{C ? F}$ (%)	0,49	0,54	0,42

Chart 1. Characteristics of the binders used in Spanish RCC dams.

5 IMPERMEABILITY

The impermeability of the Spanish dams of RCC has been entrusted to the body of the dam and sometimes to its upstream zone. A conventional concrete strip of a minimum width of 1.5 m sufficient to place and absorb the “water-stop” bands, has been the element in which the impermeability of our first dams has been entrusted. In later constructions, the whole section has been carried out using RCC, although of two types, RCC 1 and RCC 2. The first is placed on the upstream face in a strip of a minimum width of 3 m but increasing with the head of water. This concrete, of greater quality, has a smaller M.S.A. in order to reduce or avoid segregation; this measure is accompanied by a paste slightly richer in cementitious material

Presently the technique is orientated to the use of only one RCC type in the body of the dam, using all possible measures in order to minimize the problem of the segregation. This is possible by the use of a concrete rich in paste. This procedure presents some advantages: rapidity of construction, reduced cost and no technical problem of the union of the different concretes.

In the Spanish dams no other elements have been incorporated, close to the upstream face, in order to improve the impermeability, as it has been done in many other dams (synthetic sheets, prefabricated panels, etc.).

If this has been possible, it is due to the use of RCC with high quantity of paste in the Spanish dams.

If in the dams of Puebla de Cazalla and Cenza a strip of bedding mortar, 80 cm wide, was placed between layers, its main purpose being to improve the aspect of the faces.

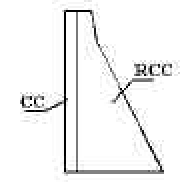
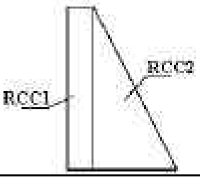
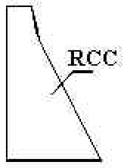
TYPE	No. OF DAMS	REMARKS
	6	
	7	1 with slip formed curbs
	11	3 small size dams 1 with slip formed curbs

Chart 2. RCC dams in Spain – upstream face.

6 JOINTS

6.1 Vertical contraction joints

Their placing is mainly based on thermal considerations. The importance of a thermal study is obvious in order to determine their distance and the convenience of cooling the concrete.

The RCC dams are divided in blocks by way of joints which are materialized by means of conventional formworks or with inductors.

6.1.1 Joints with formwork

In the beginning all the joints were of this type and they were 40 to 60 m apart. These blocks permitted the placing of the formwork of the face in one of them, whilst the other was being concreted. Its inconvenience was the passage of the machines from one block to another, overcoming the difference of height of the formwork, which has been solved in many diverse ways. When the concrete of the upstream face was vibrated, initiated joints were left every 15 or 10 m. (See Figure 3).

6.1.2 Driven joints

Later, the blocks were made longer, or they were concreted in a continuous manner from side to side, this depending on the size of the installations (production) and on the maximum temperatures.

In both cases the blocks have to be divided in other intermediate blocks in order to avoid cracking due to the hydraulic and thermal shrinkage. This division of the blocks can be done by sawing the layer with a disc saw or otherwise by driving in a plate or sheet. The first procedure has only been carried out in the Maroño Dam. The second procedure has been used in all the remaining dams by way of an equipment which inserts by vibration a synthetic film or a galvanized sheet.

Whatever the type of transverse joint employed, it has to be made waterproof next to the upstream face. Normally it has been done with two bands of synthetic material ("water-stop"). Between them one or two conduits are left moulded in the joint, one of them connected to the inspection and drainage gallery. In the Atance Dam an exterior

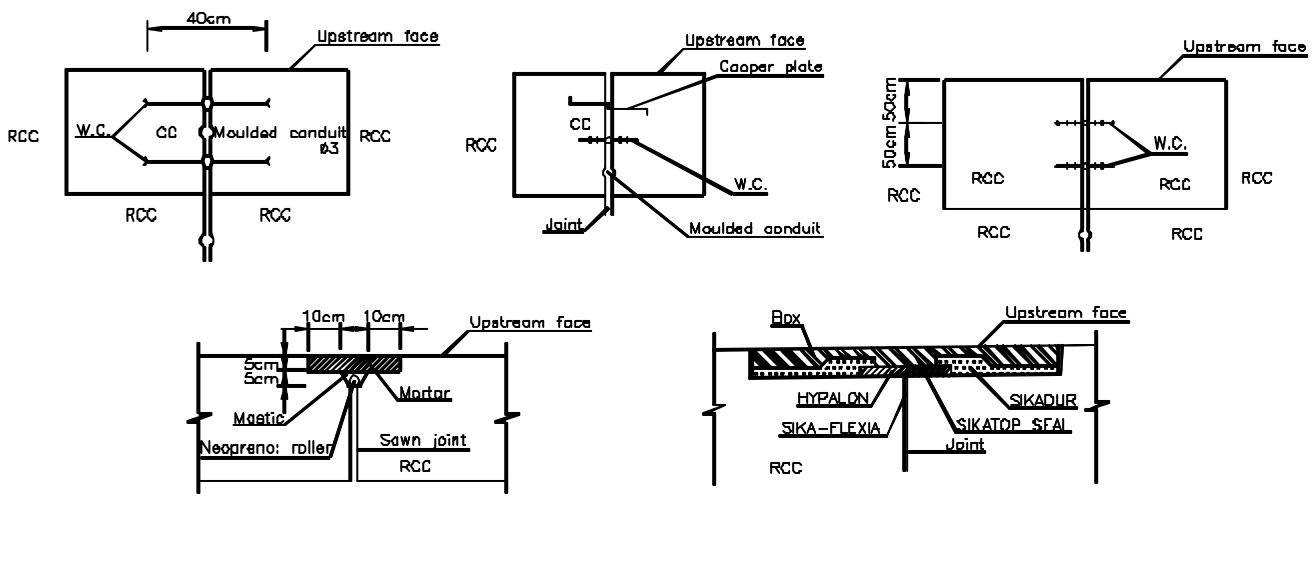


Figure 3. Waterproofing of vertical joints (formworked)

device has been installed the upstream face, which undoubtedly allows the placing of the RCC with greater speed and quality. Its efficiency has not been proved up to now due to the low water level in the reservoir.

In Table III (see end of document) data of the transverse and longitudinal joints of the blocks are given. In Figure 3 the details of the impermeabilization are shown.

In Sierra Brava Dam with formworked blocks 90 m long, a driven joint has been inserted in their center (final blocks 45 m long). In the Maroño and Cenza Dams, with continuous concreting, joints have been sawn every 40 m in the first, and plates have been driven by vibration every 20 m in the second. In the Val Dam joints have only been formworked every 60 m.

6.2 Horizontal joints between layers

These joints are the weak points and most controversial in the RCC dams, similarly to dams of conventional concrete. The difference is that in the first case, these joints are spaced 0,30 m (thickness of the layer) and in those of the second case they are spaced between 1,50 m to 2,50 m. The great number of the first demands greater attention.

The surface treatment of the layers is a point of discussion in our country, at the time of classifying a joint as "hot" (not needing treatment) or "cold" (needing treatment).

There exist several criteria in order to determine if a joint can be considered as cold or hot. One of theme is the Maturity Factor (M.F.), defined as the product of the mean hourly temperature, measured on the surface of the layers in Centigrade degrees, by the time transcurred in hours between the placing of two successive layers. At first this M.F. factor was fixed between 150 - 250? Cxh. In many cases these values make it necessary to divide the dam in blocks by way of formworked joints, due to the size of the installations. These inconveniences and the experience accumulated have brought about that many engineers apply this criterion with flexibility. Every dam is a prototype and has an M.F. of its own variable in time according to the environmental conditions of temperature and relative humidity. It must be the experimental data, obtained on the test slab, that will provide an M.F. which is applied as a practical control of the constructive process.

$$T(h) \times t\ (?C) = M.F.$$

Depending on the cases this factor has varied in reality between values of the order of 80 and 300, which shows its lack of representivity. In Spain it has been used with maximum times between layers from 6 to 9 hours, although in Puebla de Cazalla dam a time of 16 hours was reached, due to the use of a setting retarder.

These criteria appear more appropriate for low paste contents (< 120 - 150 kg/m³ of cementitious material) and require to use mortars in the cases of cold joints (time between layers superior to that marked).

With richer contents (> 200 Kg/m³) it goes up to 24 hours (Upper Stillwater, New Victoria) and with the following treatment of joints, recommended by some experts:

1 Joint less than 24 hours: " Hot Joint ". It does not require any treatment, if the surface has not been damaged. Simply remove the water and the detritus by way of a vacuum equipped truck.
2 Joint between 24 and 48 hours (with favourable climate up to 72 hours): "Prepared joint". It is sufficient to rake the surface with a steel wire brush and remove the detritus (vacuum equipped truck).
3 Joint more than 72 hours (with unfavourable climate 48 hours): "Cold joint". Sandblasting and water at pressure. Same completion as the previous case.

In the hot joints no treatment is necessary, if we exclude their cleansing and maintaining the humidity of the surface, by aspersion of water.

The cold joints are treated similarly to that of the conventional concretes, applying a jet of air and water at pressure, cleaning with sweeper and suction and always placing a thin layer of mortar. The aspect of their surface should be identical to that of the conventional concrete dams. The cold joints programmed coincide with the upper face of the curbs (Burguillo and Sierra Brava dams,....) or else with the edge of the formwork (dams of Maroño, Santa Eugenia, Canchales, etc.). Some people discuss the necessity of bedding mortar, if the concrete is rich in paste.

In this important theme of the union between layers, one must be pragmatic, that is to say, the previously mentioned criteria should be considered as an orientation. It will be the daily practice which determines the time of covering. Samples obtained by drilling during the work will provide useful information about the quality of the union.

7 CONSTRUCTION

7.1 Mixing, Transport and Placing

The mixing of the concrete has been usually carried out in tower-plants with several batch mixers, with a capacity such that makes possible its continuous placing although the mixing is not continuous. The only dams with continuous mixing have been those of Castilblanco and Rialb.

Conventional trucks with pneumatic tyres and high speed belt conveyors as well as their combinations, have been, in the Spanish dams, the only means of transport of the concrete from the mixing plant up to the point of placing. Belt conveyors up to the entrance to the works and interior distribution by trucks in Sierra Brava; all the transport by trucks in the dams of Los Canchales, Puebla de Cazalla, Santa Eugenia; high speed belts and trucks in the works in Maroño, Rialb, Val, Boquerón and Atance.

Every system has advantages and inconveniences. If the transport is carried out only using trucks, providing accesses at different levels, if the ground is very abrupt, is difficult and costly; in these cases the access should be made upstream in order not to affect the stability of the abutments nor causing damage to the landscape. The placing of the concrete with belt conveyors and spreaders is the procedure which least affects the quality of the mix already placed. In the high zones of the dam, the transport trucks are obliged to manoeuvre and make tight turns which can damage the recently placed concrete. The high speed conveyors, in spite of their cost, are very interesting for the dams of large dimensions, and also in the case of very steep slopes, with the inconvenience, with respect to trucks, that a breakdown of the belt paralyzes all the process of the job until it is repaired.

The transport of the concrete is an important decision which the constructor must take, as it affects to a great degree the quality and the cost of the work. It should be taken in function of the topography of the site, of the rhythms of production and of the existence or not of shuttered blocks.

Once the concrete mix is poured on site - either with belts or trucks - in small mounds it is immediately spread by bulldozer in longitudinal strips parallel to the axis of the dam. In very few occasions, a grader has been used. It is normal to advance the strip from the downstream face to the upstream face with a slight slope towards the latter.

The extension of the mixture close to the faces should be carried out carefully since they are the zones more susceptible to segregation, for which they require greater attention and the presence of workmen for manual corrections.

The compaction of the concrete is always carried out with self propelled smooth vibrating tandem rollers of 10 to 16 t. Other light units of some 3 t or pneumatic plates and tampers are used close to exterior faces and contacts with galleries and conduits. For a thickness of a normal layer (? 30 cm) the number of passes of the roller is usually 6, back and forth, the first and last without vibration and the rest with vibration.

7.2 Faces-Formworks

It is usual that the upstream face of a dam is smooth and that of downstream is stepped.

The first Spanish dams have been constructed using conventional travelling formwork, the design details of which depend on the number and type of the joints, on the rhythm of the construction and on the covering time. The height of the panel is a multiple of the thickness of the layer (2 to 2,40 m) and on its upper edge it will form a cold joint. This type of formwork is especially indicated when the dam is divided in shuttered blocks, as when one goes up the concrete is placed in the other. In the Cenza Dam a special formwork, travelling-hinged has been used, which allows greater speed of placing and, in this manner, the layer can be continuous from side to side avoiding the cold joint.

Concrete curbs have been employed in the dams of Burguillo and Sierra Brava. They were constructed with slip form equipment. In order that the formwork with curb results economical it is necessary that the dam will be long enough, that it be employed on both faces and that due to its shape it can be considered as a part of the resistant section of the dam. In the first projects this solution resulted attractive to the constructor, today their opinions do not always coincide.

If the downstream face is smooth, conventional formwork or slip formed curbs are employed. If it is stepped, as occurs in the majority of the Spanish dams, panels of the height of the step are employed; their fixing with anchorages and brackets is not easy, for which it is convenient that the height of the step is not small both for its fixing or as also its æsthetic outlook.

In the Spanish dams no other type of formwork has been employed other than the ones described.

Faces without formwork have been carried out in the Guadalemar Dam (isosceles section). In the Los Canchales Dam formwork has not been employed on the lower part of the downstream face since it was then covered by an earth fill.

7.3 Curing of the concrete

Immediately after its compaction and until the spreading of the following layers the surface of the layer has to be maintained humid.

This curing must be more carefully performed when the temperatures are high, avoiding the drying out. The treatment finishes on commencing the spreading of the following layers, simply cleaning the surface with a truck with vacuum equipment. It is important not to leave any puddles.

7.4 Contact surface of the ground with the RCC.

The previous treatment of the foundation is equal to that for conventional concrete. All the small voids of the rock are filled with low consistency concrete internally vibrated. Before beginning the placing of the RCC a flat surface not less than 30 x 30 m is necessary which is obtained with a levelling concrete, so that the machines for placing, spreading and compaction of the RCC can operate efficiently.

In very steep slopes (> 0.5H, 1 V) and on those slightly inclined as also in places not accessible to the compacting machine, a vibrated concrete is placed. This union must be carefully controlled. Always when possible in the dam section contacts should be avoided between conventional concrete and RCC, as described in the paper.

8 TEST SLABS

It appears obligatory that in every RCC dam, test slabs are carried out, and it has been done in the Spanish dams.

Before starting the placing of the concrete in the dam, a full size test slab should be constructed; on which the data obtained from the laboratory tests are corrected and optimized as well as those others that are imposed by the Technical Specifications of the Project. On the test slab the conditions for placing on the job the RCC will be tested: faces, thickness of layers, segregation, treatment of joints between layers and construction joints. It will serve at the same time for the personnel of the job to acquire experience. The dimensions of the slab have to be generous and not less than 10 layers in height and an approximate volume of RCC of 1,500 to 2,000 m³. In the dams of Canchales, Urdalur and Sierra Brava, among others, it has been preferred to make two test slabs, one during a previous phase and another once the plant had been installed. In order that its cost does not affect too much that of the job, the second slab can be integrated in some zone of the dam of lesser commitment.

In the previous laboratory tests study the gradation of the aggregates, the dosification of the cementitious materials, the consistencies, and Vebe times, for diverse mixtures of the RCC are studied.

From the test slab, cores will be obtained by drilling in order to measure densities, observe the unions between layers and the " in situ " permeabilities by filling the borehole with water.

9 MAIN CHARACTERISTIC OF THE SPANISH RCC DAMS

The main characteristics of the Spanish RCC dams can be summarized as follows:

1. All the dams are of straight gravity type, except one which is curved. Their standard section responds to the classic Pigeaud profile with adaptation to the technology of continuous placing.

2. In the design of the outlets and intakes, as also in that of the galleries, efforts have been made, at times insufficient, in order that the design is in agreement with the philosophy of a faster and economic construction.

3. The aggregates are of the same quality and similar granulometry as those utilized in conventional concrete. Their maximum size (M.S.A.) oscillates between 100 and 40 mm, the most normal being 80 mm.

4. Percentages in volume of the compacted concretes (RCC) with respect to the conventional concretes (CC) which the dams contain are very high. Values of (RCC):/(RCC+CC.) superior to 80% can be interpreted as a design of dam well orientated towards the new technology.

5. The cementitious materials are a mixture of Portland cement and fly ash class F. The substitution of cement by the fly ash reaches percentages of 70%. In two cases the cementitious material has been a composite cement available in the market.

6. The concretes of all the Spanish RCC dams are of " high paste content ", that is to say, the quantity of cementitious material is superior to 150 kg/m³. Their dosifications between 200 kg/m³ and 240 kg/m³ situate them among the dams with greater quantity of cementitious material.

7. All the dams have been divided in blocks by way of formworking the transverse joints. Exceptions are the dam of Guadalemar, which does not have joints, and Cenza, with a joint that only affects the uppermost 20 m.

8. The blocks of length superior to 60 m have been divided by way of driven joints in the majority of the cases.

9. The waterproofing of the vertical joints is obtained with two PVC water-stop bands, in the majority of the cases with a moulded conduit between them.

10. The Spanish dams of RCC do not incorporate in their interior any material that is not concrete or mortar. No material of the market is incorporated to reinforce the union between layers; no material (synthetic sheets or others) in order to increase the impermeability in the upstream zone; no prefabricated material for the drainage of the dam (only boreholes with drill or moulded conduits in the vertical joints).

10 INVESTIGATION

Together with this large experience in the use of RCC dams, extensive research has been conducted on a number of particular topics of this technology. Some recent findings are summarized in the next paragraphs.

10.1 Stepped spillways

Tests have been performed on scale models to characterize the pressure field over a stepped spillway, providing information about the maximum and minimum pressures registered and the cavitation risk. For all the tested discharges a fully developed skimming flow regime occurs over the chute. The pressure along the symmetry centers of the horizontal faces shows a wavy pattern: some steps are in a peak and some others in a valley of that wavy behavior. Moreover, two different zones on the step have been identified: the outer edge, governed by impact with the upper jet, and the inner region controlled by the recirculating internal eddies.

There is not much information about the behavior of gated stepped spillways. For this reason some dams built in RCC are designed with a smooth spillway instead of a stepped one. To provide a better insight into this topic, the interaction of a Tainter gate controlling the flow over a stepped spillway has been analyzed with a scale model. Several scenarios have been tested: the discharge under a partially raised Tainter gate and two emergency situations characterized by the gate overtopping and a combination of flow over and under the gate. It was observed that to make compatible the flow through the gate (over and/or under) with the hydraulic behavior of a stepped spillway, the stepped channel should begin downstream the ogee profile.

Current social and political trends dominant in the world seem to favour building new dams of heights below 50 m, their impact being smaller than that of higher dams for large reservoirs. Most studies performed on stepped spillways refer to higher dams, even if the results are extrapolated and applied to lower dams. To obtain more precise information, a research work was done on models of a scale that makes them representative of dams not higher than 50 m. The results indicate that a significant reduction of basin works can be obtained with stepped spillways instead of flat ones, even in the case of dams of an average/low height. For curved dams, savings in the stilling basin are lower than those obtained in the case of straight ones, but still significant.

10.2 Thermal behavior

A lot of computation time is required for the analysis of the long-term thermo-mechanical behavior of RCC dams using 2-D models. To overcome this difficulty, a modified 1-D strip model has been developed which allows to estimate temperatures and stresses in the core of a RCC dam at low CPU time cost. Temperatures predicted by this model fit the data obtained from a series of thermometers installed in Rialb RCC dam (Spain). Results of such simulations can be used as input parameters for 2-D or 3-D models or if decisions on the construction schedule or on the placing temperature have to be made during the construction phase.

10.3 Bonding between layers

The results of a penetration test performed at different times have shown an excellent correlation with the quality of the bond between layers, evaluated by means of the flexural strength of specimens compacted in two layers. This type of tests is intended to eliminate some of the problems posed by the direct tensile tests. Also with this aim, an special testing device has been developed to improve the alignment of the specimen with the theoretical axis of the load generated by the direct tensile test machine. Results can be deemed satisfactory, most of the specimens being broken around their central part.

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Table I - RCC dams completed in Spain

NAME	**RIVER**	**BASIN**	**OWNER**	**PURPOSE**	**GEOLOGY**	**COMPLETION YEAR**
ERIZANA	BAHIÑA	NORTE	COM. GALLEGA	S	GRANITE	1985
CASTILBLANCO	CALA	GUADALQUIVIR	COM. ANDALUZA	S	DIABASE & DIORITE	1985
LOS MORALES	MORALES	TAJO	COM. MADRID	S	GNEISS & GRANITE	1988
STA. EUGENIA	JALLAS	NORTE	CARBUROS METALICOS	H	GRANITE & SIENITE	1988
MAROÑO	IZORIA	NORTE	COM. PAIS VASCO	S	MESOZOIC LIMESTONES & LOAM	1990
HERVAS	HERVAS	TAJO	COM. EXTREMADURA	S	GRANITE	1990
LOS CANCHALES	LACARA	GUADIANA	ESTADO	C	MESOZOIC LIMESTONES	1991
BURGUILLOS	MONTES	GUADIANA	COM. EXTREMADURA	S	CORNSTONE & DIABASE	1991
BELEN GATO	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC DOLOMITES	1991
PUEBLA DE CAZALLA	CORBONES	GUADALQUIVIR	ESTADO	I	MESOZOIC LIMESTONES & LOAM	1992
BELEN CAGÜELA	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC CHALKOSCHISTE	1992
BELEN FLORES	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC CHALKOSCHISTE	1992
CABALLARS	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC DOLOMITES	1992
AMATISTEROS I	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC DOLOMITES	1992
AMATISTEROS III	R. BELEN	SUR	COM. ANDALUZA	C	MESOZOIC DOLOMITES	1992
URDALUR	ALZANIA	EBRO	ESTADO	S	LIMOLITE & MESOZOIC SANDSTONES	1993
ARRIARAN	ARRIARAN	NORTE	COM. PAIS VASCO	S	LOAMS	1993
CENZA	CENZA	NORTE	IBERDROLA	H	GRANITE	1993
SIERRA BRAVA	PIZARROSO	GUADIANA	ESTADO	I	PALEOZOIC SLATE & GRAUWAKE	1994
GUADALEMAR	GUADALEMAR	GUADIANA	ESTADO	S	PALEOZOIC SLATE & GRAUWAKE	1994
BOQUERÓN	R. BOQUERÓN	SEGURA	ESTADO	C	LIMESTONE & DOLOMITE	1997
VAL	VAL	EBRO	ESTADO	I	MIOCENE CONGLOMERATE	1998
ATANCE	R. SALADO	TAJO	ESTADO	I	GNEISS	1998
RIALB	R. SEGRE	EBRO	ESTADO	I	MESOZOIC LOAM & SANDSTONE	2000

Table II - Main features of RCC dams completed in Spain

NAME	HEIGHT (m)	CREST LENGTH (m)	RESERVOIR CAPACITY (10^6 m³)	SLOPES H:V		CONCRETE VOLUME (10^3 m³)		VOL. RATIO RCC / CC+RCC	SPILLWAY
				UPSTREAM	DOWNSTREAM	CC	RCC	%	
ERIZANA	12	115	0.48	0.1	0.60	2	9.7	71	NO
CASTILBLANCO	25	124	0.87	VERTICAL	0.75	6	14	86	SLOPING-CC
LOS MORALES	28	200	2.84	VERTICAL	0.75	3.5	22	89	SLOPING-CC
STA. EUGENIA	83	280	16.60	0.05	0.75	29	225	88	SLOPING-CC
MAROÑO	53	182	2.23	0.05	0.75	11	80	56	SLOPING-CC
HERVAS	33	210	0.22	0.15	0.70	19	24	46	SLOPING-CC
LOS CANCHALES	32	240	15.00	VERTICAL	0.50 - 0.80	29	25	76	SLOPING-CC
BURGUILLOS	24	167	2.50	VERTICAL	0.60	8	25	88	SLOPING-CC (Curbs)
BELEN GATO	34	158	0.25	0.25	0.75	5	38	93	STEPPED-RCC
PUEBLA DE CAZALLA	71	220	7.40	VERTICAL - 0.20	0.80	15	205	83	STEPPED-RCC
BELEN CAGÜELA	31	160	0.20	0.05	0.75	5	24	83	STEPPED-RCC
BELEN FLORES	27	87	0.30	0.05	0.75	2	10	83	SLOPING-CC
CABALLARS	16	98	0.03	0.05	0.75	1	6	86	STEPPED-RCC
AMATISTEROS I	11	91	0.03	0.05	0.75	0.5	3	86	STEPPED-RCC
AMATISTEROS III	15	78	0.01	0.05	0.75	1.0	5	83	STEPPED-RCC
URDALUR	58	396	5.40	VERTICAL	0.75	48	160	77	STEPPED-CC
ARRIARAN	58	206	3.20	0.05	0.70	13	110	89	SLOPING-CC
CENZA	49	640	4.30	VERTICAL	0.75	8.5	215	96	STEPPED-RCC
SIERRA BRAVA	53	800	232.00	0.05	0.75	63	277	89	STEPPED-RCC (Curbs)
GUADALEMAR	13	400	4.00	1	1.00	5	50	91	SLOPING-RCC
BOQUERÓN	58	290	15.00	0.05	0.73	8	150	94	STEPPED-RCC
VAL	94	379	25.30	VERTICAL - 0.02	0.80	130	630	83	STEPPED-CC
ATANCE	45	185	35.30	VERTICAL	0.80	6.5	60	90	STEPPED-RCC
RIALB	101	604	402.00	0.15 - 0.35	0.65 – 0.40	150	1,050	87	SLOPING-C.C.

Table III - Structural characteristics of RCC dams in Spain

NAME OF DAM	NUMBER AND WIDTHS OF BLOCKS	VERTICAL JOINTS - TYPE	LIFT THICKNESS (m)	FACING CONCRETE	
				UPSTEAM	DOWNSTREAM
ERIZANA	Two: 45 + 70 m	FORMED	0.35	RCC	RCC
CASTILBLANCO DE LOS ARROYOS	Two: 62 + 62 m	FORMED IN BLOCKS & (Start Joint in U/S facing)	0.45	CC	CC
LOS MORALES	Two: 84 + 104 m	FORMED	0.40	RCC	RCC
SANTA EUGENIA	Four: 80 + 60 + 65 + 90 m	FORMED	0.30	RCC	RCC
MAROÑO	Three: 2 x 60 + 61 m	SAW CUT	0.30	RCC	RCC
HERVAS	Four: 57 + 32 + 74 + 47 m	FORMED IN BLOCKS & (Joints in U/S facing: 15 m)	0.30	CC	CC
LOS CANCHALES	Two: 65 + 116 m	FORMED	0.25	RCC	RCC
BURGUILLOS DEL CERRO	Four: 40 + 65 + 45 + 17 m	DRIVEN METAL PLATES	0.30	CC (Curbs)	CC (Curbs)
BELEN GATO	Three: 3 x 53 m	METAL PLATES	0.30	RCC	RCC
PUEBLA DE CAZALLA	Five: 20 + 3 x 60 + 20 m	SAW CUT (PARTIAL) AND FORMED	0.30	RCC	RCC
BELEN CAGÜELA	Three: 3 x 54 m	METAL PLATES	0.30	RCC	RCC
AMATISTEROS I	Two: 2 x 46 m	METAL PLATES	0.30	RCC	RCC
CABALLAR I	Two: 2 x 49 m	METAL PLATES	0.30	RCC	RCC
BLEN FLORES	Two: 2 x 43 m	METAL PLATES	0.30	RCC	RCC
AMATISTEROS III	Two: 2 x 39 m	METAL PLATES	0.30	RCC	RCC
URDALUR	Five: 77 + 96 + 81 + 65 + 70 m	FORMED IN BLOCKS & (Joints in U/S facing: 21 m)	0.30	CC	RCC
ARRIARAN	Five: 12 + 65 + 61 + 42 + 18 m	FORMED	0.30	RCC	RCC
CENZA	Two: only in the upper 20 m	FORMED (upper 20 m) DRIVEN METAL PLATES: 20 m	0.30	RCC	RCC
SIERRA BRAVA	Five: 225 + 135 + 90 + 90 + 245 m	FORMED (DRIVEN METAL PLATES)	0.30	CC (Curbs)	CC (Curbs)
GUADALEMAR	Continous: 400 m	NO JOINTS	0.30	RCC	RCC
RAMBLA DEL BOQUERÓN	Seven: 73 + 35 + 37 + 16 + 37 + 35 + 57 m	DRIVEN METAL PLATES	0.30	RCC	RCC
VAL	Eight 3 x 60 + 5 x 40 m	FORMED	0.30	CC	CC+RCC
ATANCE	Six: 6 x 30 m	DRIVEN PLASTIC PLATES	0.30	RCC	RCC
RIALB	Sixteen: 7 x 40 + 3 x 28 + 6 x 40 m	FORMED	0.30	RCC	RCC

Table IV – RCC Mixes

NAME OF DAM		MAX SIZE OF AGGREGATES (mm)	AGGREGATE QUANTITY (kg/m³ of concrete)	SAND QUANTITY (kg/m³ of concrete)	WATER QUANTITY (l/m³ of concrete)	CEMENTITIOUS MATERIAL (kg/m³ of concrete)			F / C ? F %	RATIO W / C ? F
						C	F	C+F		
ERIZANA		100	1668	532	115	90	90	180	50	0.60
CASTILBLANCO DE LOS ARROYOS		40	1452	628	102	102	86	188	46	0.54
LOS MORALES	RCC1	40	1426	618	108	81	140	221	63	0.46
	RCC2	80	1548	562	98	74	128	202	63	0.48
STA. EUGENIA	RCC1	70	1635	552	100	88	152	240	63	0.42
	RCC2	100	1830	430	90	72	143	215	67	0.40
MAROÑO	RCC1	70	1575	670	100	80	160	240	67	0.42
	RCC2	70	1575	670	98	65	170	235	72	0.42
HERVAS		80	1540	540	95	80	155	235	66	0.40
BURGUILLOS DEL CERRO		60	1662	593	85	75	135	210	64	0.40
LOS CANCHALES	RCC1	40	1490	620	105	84	156	240	65	0.44
	RCC2	80	1650	585	100	70	145	215	67	0.46
PUEBLA DE CAZALLA	RCC1	40	1409	720	127	85	137	222	62	0.57
	RCC2	80	1512	688	113	80	130	210	62	0.51
AMATISTEROS I AMATISTEROS III CABALLAR I BELEN GATO BELEN CAGÜELA BELEN FLORES		40	1364	800	105	73	109	182	60	0.60
URDALUR		80	1524	691	90	72	108	180	60	0.50
ARRIARAN		80	1730	550	100	85	135	220	61	0.45
SIERRA BRAVA		80	1590	610	95	80	140	220	64	0.43
CENZA		60	1519	733	95	70	130	200	65	0.47
GUADALEMAR		80	1364	836	100	60	125	185	68	0.54
RAMBLA DEL BOQUERÓN		80	1568	615	94	55	130	185	70	0.51
VAL		80	1552	660	100	80	100	180	55	0.51
ATANCE		40	1332	811	109	57	133	190	70	0.56
RIALB		100	1695	570	95	70	130	200	65	0,47

Table V – Main features ff spanish RCC dams under construction

NAME	BASIN	HEIGHT (m)	CREST LENGTH (m)	RESERVOIR CAPACITY (10^6 m^3)	CONCRETE VOLUME (10^3 m^3)	COMPLETION YEAR
ESPARRAGAL	GUADALQUIVIR	21	391	4	60 (RCC)	2003
ENCISO	EBRO	105	378	47	750 (CC + RCC)	---