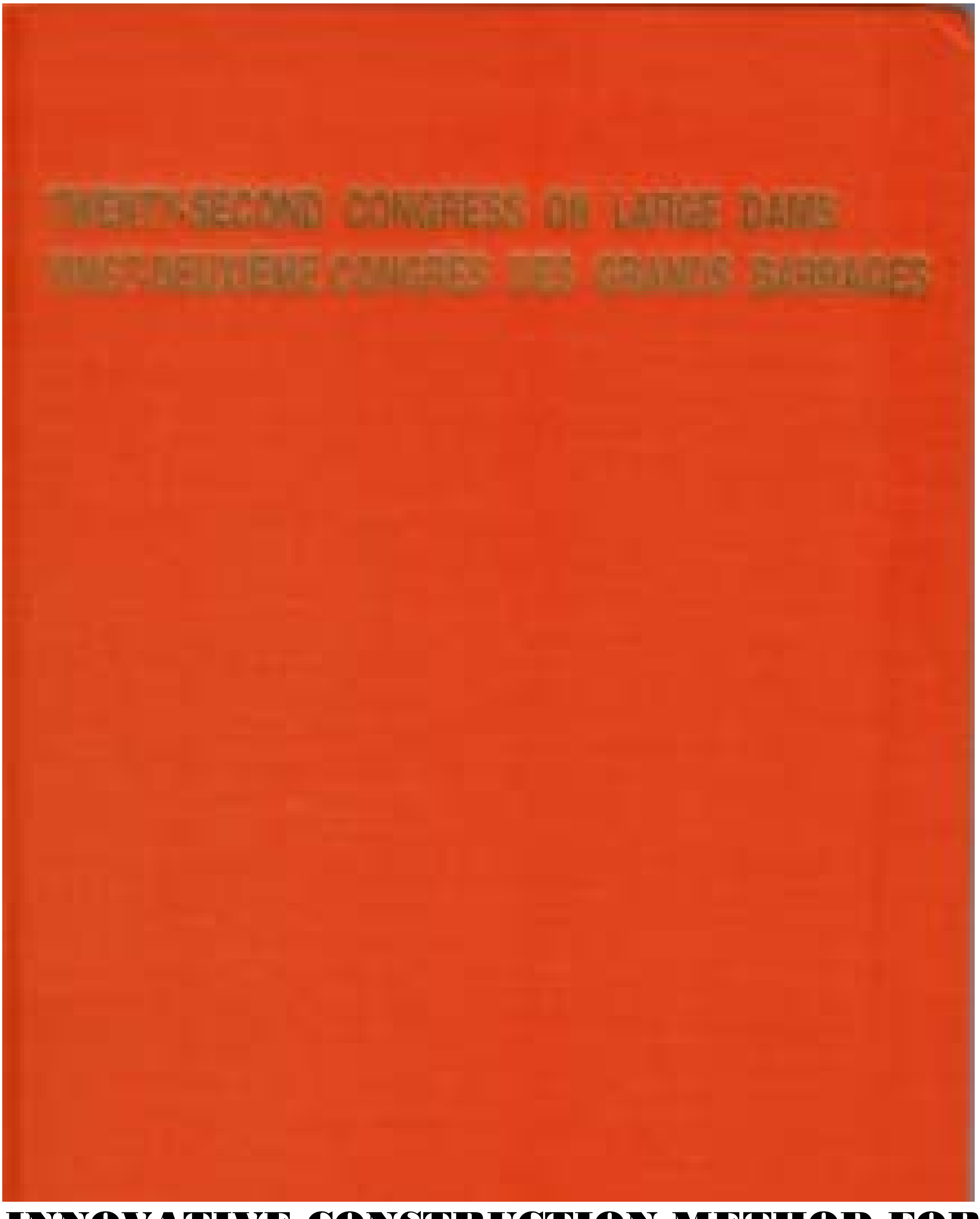

INNOVATIVE CONSTRUCTION METHOD FOR ARCH DAMS – THEORETICAL AND PRACTICAL APPROACHES OF THE STOD METHOD

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INNOVATIVE CONSTRUCTION METHOD FOR ARCH DAMS – THEORETICAL AND PRACTICAL APPROACHES OF THE STOD METHOD [(*)]

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[(*)] *Méthode de construction novatrice pour les barrages-voûtes – Approche théorique et pratique de la méthode STOD*

1. INTRODUCTION

Roller Compacted Concrete (RCC) has been used in the past 25 years for the construction of more than 250 gravity dams worldwide. The application of RCC to gravity dams turned out gradually to be a technical and economical success and nowadays no question or doubt arises about the quality of such dams. RCC has turned out as a universally accepted standard for the construction of gravity dams.

Since the mid-80's the application of RCC to the construction of arch dams has been tried repeatedly, particularly in South Africa and in China. Whereas the Chinese experience included arch dams, the South African experience was limited to arch-gravity type of dams. Ten dams or so (among which the highest is Shapai RCC arch dam, 132 m high) have been constructed so far in those two countries. Due to the inherent nature of arch dams, RCC does not seem at first sight to apply straightforwardly : amongst others the issues of

- transversal joints (linked with the problems of grouting to transmit horizontal thrust forces, and cracking caused by cement hydration heat)
- the high concrete compressive strength required, and
- the double curvature forming

have caused problem and should be addressed in great detail.

STUCKY as a renowned consultant in arch dam design, and ODEBRECHT as a leading company in RCC dam construction, have been interested for several years in this pioneer experience. Since the beginning of the year 2002 they have teamed up to develop the STOD method – a new construction method for RCC arch dam based on their own know-how and on the lessons learned through the South African and Chinese experiences. Both partners are supported and advised by F. Andriolo, international expert in RCC. Based on a novel approach of the problem, they are being running since 2004 a series of full-scale tests on a RCC dam in Brazil. Besides proving the relevance and validity of the innovative construction method for arch dams, this latter also turns out to be economic. It is assessed to bring around 20% reduction of investment cost vs the traditional arch dam construction method, and very significant time saving on the construction schedule.

2. ECONOMIC AND TECHNICAL ENVIRONMENT

It is a general trend observed in the recent years that the arch dam industry has been slumping on a worldwide scale. This is mainly due to the advent of the RCC material which, applied to the gravity dam construction, provides significant time and cost savings. Thanks to that, gravity dams tend to compete with arch dams more and more, even in relatively narrow valley sites where arch dams used to be the most technically appropriate and economically competitive. It must be emphasized that the arch dam industry is a conservative market and has only slightly and marginally been developed for the last 50 years or so.

Yet from an environmental standpoint, which tends to become a more and more decisive parameter when selecting the dam type for a given dam site, arch dams remain amongst the most favoured solutions. Indeed this type of dam involves the smallest volumes of rock excavation, cement and concrete used, and is also usually the least demanding in terms of transportation (rock, soil, aggregates, cement, etc.). Therefore building an arch dam triggers the smallest damages to the environment and is probably the most accountable decision a dam owner can make.

There is little doubt that the streamlining of arch dam construction lies in linking the well-tested and established arch dam design processes to the RCC material and construction technology. RCC has been used widely during the past 25 years in the gravity dam construction. The RCC material and the related construction method have progressed significantly since the early experiences until becoming credible and acknowledged by the engineering community, and today most of the gravity dams are built with RCC.

The first experiences of RCC application to arch dam construction started at the end of the 80's in South Africa, soon followed by other experiences in China. To cope with the intrinsic properties and qualities of the RCC technology, which are :

- the speed and simplicity of placing
- the low cement quantity per cubic metre of concrete
- the basic equipment used, and therefore
- the low cost,

is at first sight not easily compatible with the accepted standards and practice of arch dam design and construction, and thus the design of these pioneer RCC arch dams had to be adapted. In particular, crucial design elements like upstream-downstream transversal joints formation and grouting, concrete cooling, and double curvature dam shaping had to be adjusted to allow the implementation of the RCC technology.

Namely according to common practice, arch dams are usually best designed and optimised as double curvature structures which are built as a series of independent, adjacent blocks. The concrete is successively brought in place on the top of each formed block by means of a cable crane installed through the valley above the future dam crest level. The concrete used is of conventional mass type, which has to be vibrated internally in order to be compacted dense, strong and watertight. After completion of the dam, the joints in between blocks have to be grouted so as to ensure watertightness and continuity of the structure, and arch effect. The key characteristics of Conventional Vibrated Concrete (CVC) arch dams are recalled on the schematic Figure 1 below.

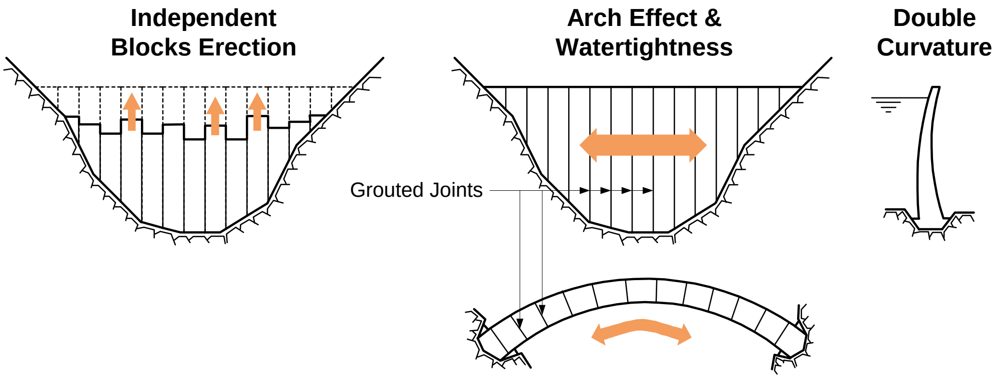


Fig. 1
CVC arch dam, key characteristics
Barrage-voûte en béton vibré, caractéristiques essentielles

3. THEORETICAL APPROACH – METHOD DEVELOPMENT

While working out its own RCC arch dam solution [1], STUCKY and ODEBRECHT have reversed the problematic. Instead of compromising the well established common practice of arch dam construction by giving up some crucial design concepts of arch dams like mentioned above, they have decided to adapt the RCC technology to the key features of arch dams. Therefore the proposed technology turns out to be a construction alternative, which uses RCC as a mere material impacting on the construction process only. The key characteristics of arch dams, which are :

- the formation of an optimised double curvature geometry
- the treatment of the horizontal joints to guarantee the proper bounding between the successive concrete lifts (joint shear strength and watertightness). This is appropriate to all types of concrete dams, but even more relevant in the case of arch dams
- the formation of upstream-downstream transversal joints to be grouted before reservoir impounding, in order to give the arch effect to the structure
- the concrete technology, amongst others the high compressive strength required and the thermal issues to be addressed (concrete post-cooling),

are preserved. The design of the dam body structure remains largely unchanged, with limited impact on the structural behaviour and serviceability of the dam during operation. Figure 2 below shows the chief principles of the STOD RCC Arch Dam technology.

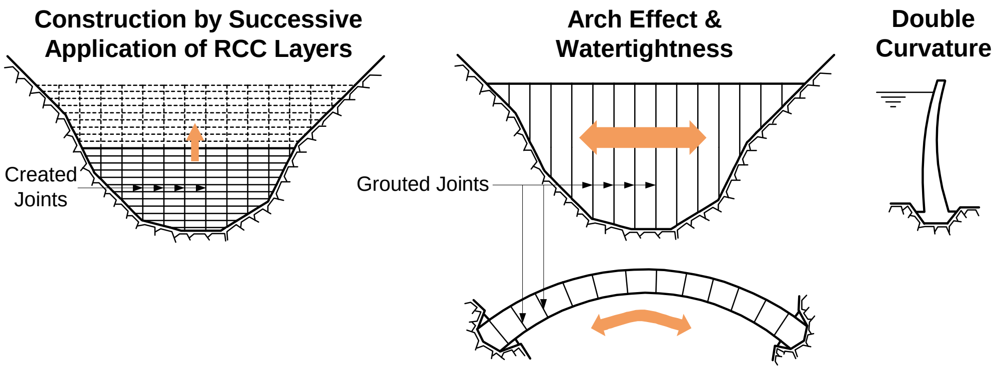


Fig. 2
STOD RCC arch dam, key characteristics
Barrage-voûte en béton BCR STOD, caractéristiques essentielles

In greater detail, the RCC arch dam construction method proposed by both partners is defined by the following characteristics :

- Upstream-downstream vertical joints are created while placing and compacting RCC across the entire dam section. To be effective, these joints have to be continuous and well delimited, capable of following a helical shape and groutable on completion of the dam. In addition, they must be as unobtrusive as possible to the RCC placing activities and rapid to form. The spacing between two transversal joints shall be in the range of 20 m to 30 m.
- The numerous horizontal joints (every 30 cm – one RCC layer thickness) are treated in a special form that provides the required shear strength between layers and does not create high permeability paths within the dam body.
- RCC mixes with high strength characteristics are produced and used, which are able to reach up to 35 - 40 MPa compressive strength. In addition, these RCC mixes must be watertight, similar to CVC mixes. Whenever demanded by some specific local conditions, the issue of concrete cooling is solved by implementing post-cooling, just the same way it has been applied for decades with CVC arch dam construction.
- To form the arch dam according to the optimal double curvature shape, a special formwork panel adapted to the particular requirements and specific features of RCC applied to arch dam construction has been developed by the partners. Thanks to the double curvature shape, the thickness and consequently the concrete volume of the dam are reduced.

These advantages, along with the savings both in time and cost, which are intrinsic features of RCC, lead to an estimated, approximate 20% reduction in the unit cost of RCC versus CVC (direct cost). Therefore the arch dam market may become more competitive in the coming years, especially in the light of the increasingly stringent environmental requirements imposed by the international financing agencies. The saving in terms of time is directly dependent on the arch dam height. It is estimated that for a dam around 150 m high, the time saved during construction amounts to one year. This means that a scheme can be commissioned one year earlier, thus reflecting again in substantial savings (indirect cost saving).

4. PRACTICAL APPROACH – FULL-SCALE TESTS

At that theoretical stage of development, the STOD technology relied on several proposals and assumptions which needed to be checked. The execution of a full-scale test block was therefore considered as the fundamental step to collect data and demonstrate beyond any doubt the feasibility, practicability and economy of the new construction method. Such test would also serve to collect important cost component elements.

The opportunity to carry out an extensive test program on the STOD RCC arch dam construction process occurred in 2004 in the framework of the RCC gravity dam of Picada in Brazil, a hydroelectric scheme generating 50 MW and owned by VOTORANTIM, a Brazilian privately owned company. The whole scheme is built by ODEBRECHT and the project is due to be completed by mid-2005. The dam owner allowed the dam design to be slightly modified to incorporate the tests. The dam is 27 m high, the crest length 97 m, and the volumes of RCC around 13’000 m^3 and CVC around 4’000 m^3. Figure 3 below shows a general picture of the dam under construction.

Fig. 3
Picada RCC dam, general overview from downstream
Barrage BCR de Picada, vue générale de l’aval

The test section is 30 m long across the valley and 9 m high (30 RCC layers, each 30 cm high), incorporated into the lowest half of the dam body, as illustrated in Figure 4. Of particular interest is the small curved protrusion on the upstream face, which was introduced into the project to test the double curvature. The total RCC volume concerned by the test is 4'300 m^3.

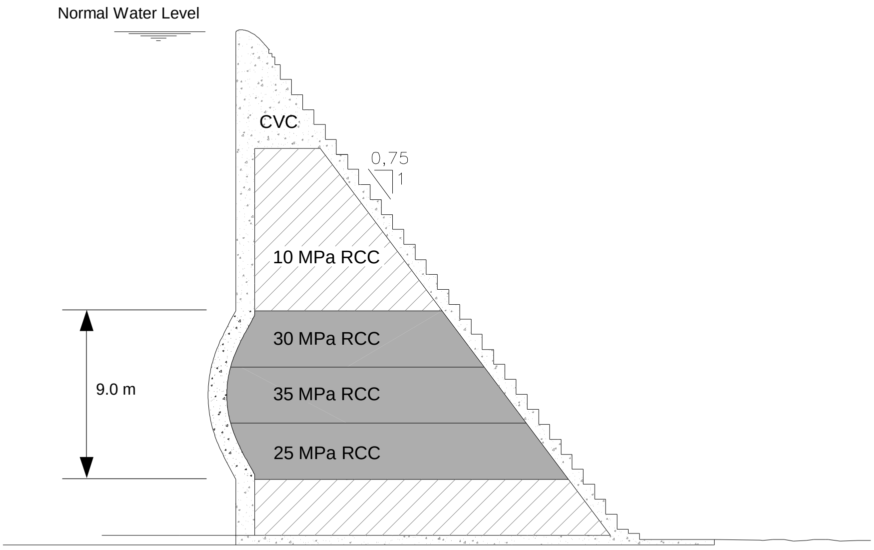


Fig. 4
Picada RCC dam, cross-section with test section incorporated
Barrage BCR de Picada, coupe-type avec section du test

The main characteristics plus some technical details of the STOD technology tested in Picada [2] are developed further below.

4.1 DOUBLE CURVATURE FORMWORK PANEL

In order to check the relevance of the formwork panel specially developed to apply RCC to arch dam construction, a small protrusion is incorporated into the upstream dam face (see Figure 4 above). The geometrical definition of this protrusion allows to test the double curvature both with concave and convex radii and with the smallest radii commonly found in arch dams, in the range of 30 m.

A special formwork panel has been developed in the framework of the STOD technology. The panel is at the same time light but robust enough to allow fast handling and positioning, as well as adjustable and flexible enough to form properly the tricky double curvature shape that usually is specific to any arch dam. All panels are designed to be raised into new position simultaneously throughout the entire dam length.

Figures 5 and 6 show different views of the formwork panels and the double curvature obtained by application of the STOD technology. The method proposed to form the double curvature shape gave positive results, especially in terms of face concrete aspect (finishing) and handling flexibility. The test also served to spot minor shortcomings, and most of them could already be fixed in the course of the test.

Fig. 5
Picada RCC dam, upstream view of the formwork panels and double curvature
Barrage BCR de Picada, vue amont des coffrages et de la double courbure

Fig. 6
Picada RCC dam, lateral view of the formwork panels and double curvature
Barrage BCR de Picada, vue latérale des panneaux de coffrage et de la double courbure

4.2 TREATMENT OF HORIZONTAL JOINTS

If not handled thoroughly, horizontal joints may create weaknesses in the dam body; particularly the issues of shear strength between successive layers and joint permeability are to be addressed. The remedy to these weaknesses is the systematic placement of a mortar mix a few minutes before the RCC placement on all of the horizontal RCC layers, irrespective of the joint being a so-called hot or cold joint.

On completion of the dam concreting, rotating boreholes with core recovery were drilled, allowing visual inspection of the cores and performance of joint shear strength tests. The outcome of such tests was satisfactory, with joint shear parameters in a magnitude comparable with values obtained for the horizontal joints in CVC dams. Figure 7 shows a core sample before shear testing. Interestingly the horizontal joint is hardly noticeable (joint shown with arrows).

Fig. 7
Picada RCC dam, core sample showing the horizontal joint between two RCC layers
Barrage BCR de Picada, carotte montrant le joint horizontal entre deux couches BCR

Although positive, the test allowed to point out the sensitivity to time of such joint treatment; to be really efficient, such mortar mix must be applied on the dam surface only a few minutes prior to RCC placement, thus the importance to organize the job site in a very industrial form. The quality sensitivity of the joints to the segregation of the RCC mixes has also been evidenced.

4.3 UPSTREAM-DOWNSTREAM TRANSVERSAL JOINTS

Two upstream-downstream transversal joints are designed in the test section of Picada dam, to allow two different alternatives of transversal joint formation to be tested. Mainly the two solutions result in two approaches :

- The insertion of a blade in the joint, which is raised gradually at the same time as the RCC placement progresses. This method creates an open joint (thickness of the blade) that can later be grouted, on completion of RCC shrinkage and temperature cooling which still will open further the formed joint.
- The use of a geotextile fabric to form the continuous joint. The fabric is left inside the RCC and thanks to the conjugated effect of RCC shrinkage and temperature cooling the joint is expected to open at this weak spot and is subsequently grouted.

Figure 8 shows both transversal joints within the test section. It can be noted in the picture that shear keys, which are indispensable devices for arch dams built in highly seismic regions, were implemented as well, to be tested.

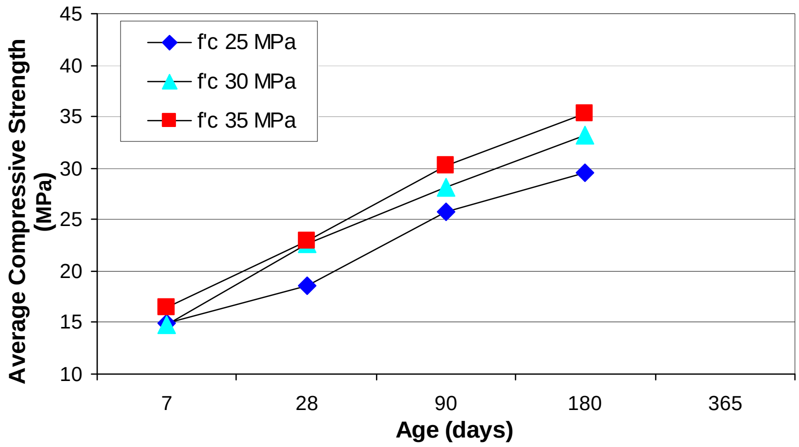
Fig. 8
Picada RCC dam, two upstream-downstream transversal joints
Barrage BCR de Picada, deux joints transversaux amont-aval

To guarantee the adequate grouting of the joints, waterstop PVC sheets are installed in the upstream and downstream dam face concrete (see Figures 4 and 8), as well as horizontally within the lowest and highest RCC layers belonging to the test. That way, the grouting panels are delimited just like in CVC arch dams. A net of grouting pipes is incorporated into the dam body between RCC layers. The grouting operation was carried out on dam construction completion. No grout leakage was observed and the joints could be grouted from the downstream face with no major obstacle.

The implementation of two different approaches to joint formation turned out to be very positive for the STOD technology. Firstly, merely as a comparison means of one alternative versus the other. Secondly, it allowed to learn a lot about organizational aspects of the job site, and improve significantly some constructional and technical details of the technology. Once again the necessity of a perfectly planned job site organization is pinpointed. Technical quality and economic performance of the STOD technology are bound with industrial job site organization.

4.4 RCC TECHNOLOGY AND RELATED THERMAL ISSUES

An extensive laboratory test programme is developed to check the key characteristics of RCC. Several RCC mixes are designed, with different compressive strength targets. The use of silica fume is tested as well. Eventually three RCC mixes are implemented in the test, with compressive strength target values of 25 MPa, 30 MPa and 35 MPa at on year age (see Figure 4). The resistances obtained are shown in Figure 9. It is observed that the target value 35 MPa is reached after 180 days.



RCC Class	Coefficient of Variation			
	7 days	28 days	90 days	180 days
25 MPa	23%	19%	18%	17%
30 MPa	22%	19%	11%	16%
35 MPa	26%	18%	11%	8%

Fig. 9
Compressive strength of RCC mixes used at Picada dam
Résistance à la compression du BCR utilisé pour le barrage de Picada

As well, it can be noted in Figure 9 that the variations obtained in the test (expressed in terms of coefficient of variation) are in the same range of values obtained for CVC used for arch dam construction and RCC applied to gravity dam construction [3].

In addition to the usual compressive strength tests, tensile strength (Brazilian test), elasticity modulus and permeability tests are performed on RCC core samples. Figure 10 shows the tensile strengths obtained after 28 days, which appear to be in line with the common values found in CVC arch dams.

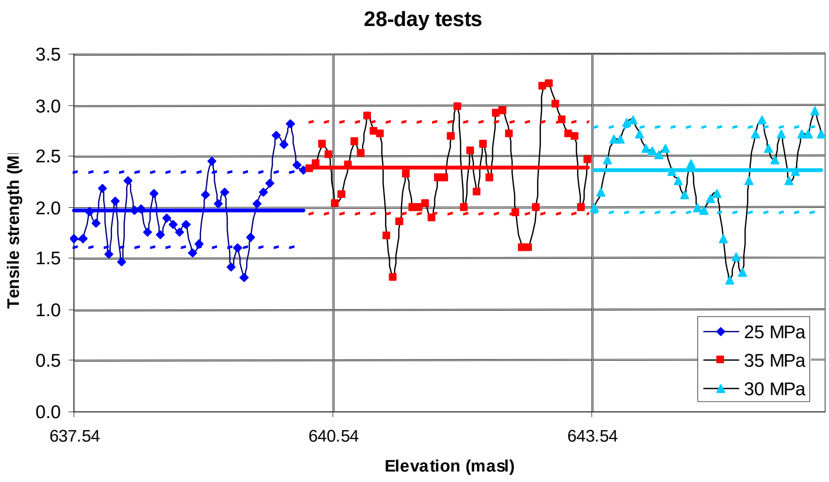


Fig. 10
Tensile strength of RCC mix used at Picada dam
Résistance à la traction du BCR utilisé pour le barrage de Picada

VeBe tests, density and moisture measurements are also carried out on fresh concrete on a daily basis.

As it is often the rule in CVC arch dams, an adequate pipe network installation and post-cooling programme are implemented within the test. The objective of such trial is double :

- Checking if installing a pipe network on the dam surface is compatible with the stringent time constraint imposed by the concreting pace, which is intrinsic to RCC technology
- Observing the post-cooled concrete behaviour.

For that, the dam test section is instrumented with thermo-sensors to assess the thermal properties of the concrete whilst releasing heat caused by cement hydration, and jointmeters to monitor simultaneously the upstream-downstream transversal joint opening due to concrete cooling and shrinkage. All these data are being followed up and processed; they allow to better understand the RCC properties and cross-check the dam behaviour.

Performing such extensive concrete test programme with several RCC and CVC mixes enabling qualitative and quantitative comparisons, allows to remove the last doubts and question marks over the relevance of RCC material applied to arch dam construction. Most of the tests gave positive outcomes, and where the results were not fully satisfactory, explanations could be found and the technology was improved, so as to reach the target values.

5. CONCLUSIVE REMARKS

The series of tests performed on Picada dam to check the relevance and validity of the STOD RCC arch dam construction method allowed to gain confidence in the technology. Most of the theoretical, technical solutions developed by the partners proved to be adapted, and when this was not the case, other solutions could be proposed that fulfill the stringent design and construction requirements inherent to the arch dam industry.

The main conclusions reached after the test on the STOD technology can be summarized as follows :

- The STOD method is an economic construction method applying RCC to arch dam construction. The chief strength of the method is to adapt the features of the existing RCC technology to the specific design and construction requirements of arch dams, and not the opposite, i.e. compromise the key characteristics of arch dams with the own characteristics of the RCC material.
- Consequence of the above, the design of STOD arch dams is essentially similar to conventional arch dams. This is an additional guarantee that can be credited to the STOD technology.
- The STOD method turns out to be competitive in the arch dam market, allowing significant construction cost savings in the range of 20% versus CVC arch dams, and also time savings of several months up to one year.
- The success of the STOD technology is greatly dependent on a efficient job site organization. The logistics must be properly designed and tested in advance, as the construction process must be fast to be successful. This implies a strong preoperational effort and upfront investment from the constructor, that will later on pay off during construction.

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SUMMARY

The STOD RCC arch dam construction method has been developed since 2002. After solid theoretical developments, it was possible to propose a new concept to apply the RCC material to arch dam construction. The central argument of the novel technology is straightforward : The STOD arch dam is not a new kind of arch dam borrowing from both worlds of arch dam design and RCC construction technology. It is a mere construction method only, that applies the RCC principles to the construction of a true arch dam.

Following the theoretical developments, both partners felt the necessity to validate the assertions of the STOD method as soon as possible. In the framework of Picada dam construction, which started in 2004, a full-scale test section could be carried out. The crucial issues of double curvature forming, upstream-downstream transversal joints creation, the bonding of the successive RCC layers, and the specific concrete properties that are required to apply RCC to arch dam construction could be tested to satisfaction. The outcomes confirm the relevance of the STOD method and allow its consolidation, before the implementation of the promising technology to a real arch dam.

RÉSUMÉ

La méthode de construction STOD des barrages-voûtes en BCR a été développée dès 2002. A la suite d'études approfondies, il a été possible de donner naissance à un concept innovateur d'application du matériau BCR à la construction de barrages-voûtes. L'argument de base de cette nouvelle technologie s'énonce simplement : le barrage-voûte STOD n'est pas un nouveau type de barrage qui emprunterait à la fois aux deux mondes des barrages-voûtes et de la technologie existante du BCR. Il ne s'agit que d'une méthode de

construction, qui applique les principes du BCR à la construction d'un authentique barrage-voûte.

Pour donner suite à ces développements théoriques, les deux partenaires ont jugé nécessaire de vérifier et valider les bases de la méthode STOD. Dans le cadre de la construction du barrage BCR de Picada, qui a débuté en 2004, un bloc de test en grandeur nature a pu être réalisé. Les sujets principaux tels que la formation de la double courbure, la création des joints transversaux amont-aval, la liaison des couches de BCR mises en place successivement, et les propriétés spécifiques du béton qui sont nécessaires pour appliquer le BCR à la construction de barrages-voûtes ont pu être testés d'une façon convaincante. Les résultats obtenus confirment et renforcent l'intérêt de la méthode STOD, avant sa mise en oeuvre sur un premier barrage-voûte.