EXPERIENCES IN THE REPAIR OF MORE THAN 300 DAMS WITH FULL RESERVOIR LEVEL

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ABSTRACT

The main inconveniences when dealing with the repair of a dam with huge leakage, is that the repair materials, usually cement or fluid resins, are washed away by the flow of water. Twenty-five years ago, the first steps were taken to repair dams with significant water leaks, even under high pressures. The injection of extremely viscous epoxy resins at high pressures has allowed sealing leaks of 300 l/s at pressures of 240 meters of water column. No divers were needed.

Resins that can be a million times more viscous than water, needed to be specially formulated for these jobs. Also, the injection pumps had to be designed, as well as the drilling machinery, very light and powerful. These technologies have made it possible to repair successfully, with the maximum water level, and without the need of expensive divers, more than 300 dams in the Middle East, Africa, Europe, America, and very soon Africa. Thus, the normal operation of the facility is not affected during repair works.

The same technique has proved to be an excellent solution for the injection, or reinjection, of vertical joints of arch dams. The results achieved confirmed the suitability of this innovative methodology for the treatment of this type of needs.

The cracking, or inadequate sealing, of the joints in the concrete galleries or reinforced pipes may cause water under pressure to leak into the ground. Over time, this will cause not only flow losses in the pipes themselves, but also result in erosion and decompression of the rock. In such a scenario, the damaged concrete must be restored, and the cracks repaired to reestablish mechanical continuity and to seal the joints. The waterproofing and bearing capacity of the rock, which may have been affected, must also be restored, by means of high-pressure injection of very viscous resins, combined with cement injections.

1. INTRODUCTION

The resolution of certain problems in dams, such as crack sealing, joint leak-tightness, upstream heel detachment in gravity dams, internal erosion of clay cores or large flows passing through deep, often call for the reservoir to be emptied before tackling the repair.

Traditional repairs based on cement injection, cannot be carried out if there is water flowing, otherwise the grout will be washed away. Reservoir emptying generally involves high costs to which is added loss of profit, the environmental cost and, often, a political cost to the authorizing authority. In general, emptying involves a high financial and social loss, and a decrease in the service guarantee, which is particularly serious for water supply dams.

If the reservoir is emptied, the repair is carried out blind, and the result thereof can only be checked when the reservoir has been refilled. Often in works of this kind, once the operating level has been reached, or the original problem has diminished but not been completely solved.

Over the last 25 years, the formulation of polymers specially designed for carrying out such kind of work, has enabled this type of problem to be solved with a full reservoir, without affecting its operation. Working with a maximum water level obviates all the problems of traditional solutions. In fact, work is no longer carried out blind and, therefore, the efficacy of the repair is immediately apparent. No expensive and slow-moving divers are needed.

From the economic point of view, although this type of material is notably more expensive, since no loss of profit occurs as the dam and its facilities are kept in service, the end cost of the operation is usually completely favourable to this new technology without taking into account the greater efficiency of these products and, therefore, their lower consumption for achieving the same objectives.

2. SOME WORDS ABOUT THE RESINS USED

Epoxy resins are thermo-stable polymers which harden when mixed with their pertinent hardener or catalyser. They were first marketed as adhesives in the first third of the 20th century. Apart from their facet as a powerful adhesive, they commenced being used in surface applications as corrosion protection layers or primers to improve adherence between a substrate and the final paintwork.

As early as in the fifties, they began to be used for making industrial pavements, electric material encapsulating, as printed circuits or for making laminates of which the maximum current exponent are the blades of wind turbines spread over our landscape. The epoxy resin industry annually moves more than $20,000 million the world over, and it is practically all used in the aforementioned applications.

Epoxies earmarked for other purposes have been used for our applications. A large part of commercial resins have a compressive strength close to 100 MPa and more than 40 MPa tensile strength. It is obvious that injecting concrete with a material with these characteristics is a really senseless financial waste. The strength of the fully hardened resins used is higher than 55 MPa (compressive) and 15 MPa (tensile).

The other disadvantage of commercial epoxy resins is their low viscosity, which makes them unsuited for injecting into fast flowing water as they are easily washed away. Analysing the technical features as given by the main manufacturers of these materials, we can see viscosity figures generally between 400 cP and 10,000 cP (water's is 1cP). However, figures above 100,000 cP and up to 1 million Cp, are required for sealing leakages in a dam. (Fig.1)

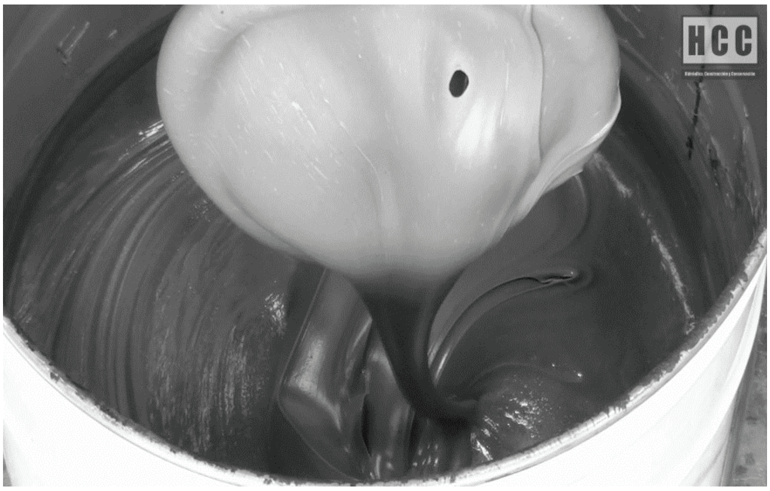

Figure 1 : High viscous-thixotropic putty flowing. Viscosity can be one million times more than water.

In fact, leakage of several hundred liters per second require the material injected not to be miscible or allow water to wash it away, and this is only achieved with very high viscosity putties and these polymers are not to be found in manufacturers catalogues.

Apart from high viscosity, we have seen that the polymer has to have high thixotropy. Thixotropy is a feature of non-Newtonian fluids that lose viscosity when subjected to a shear stress, for example, when shaking them or when passing through a fissure having been injected into it. Due to thixotropy, the material advances through the fissures whilst being injected and behaves like a fluid, but turns into highly viscous putty as soon as the pump stops. This property is essential for controlling the material's advance since it cannot be washed away by water and only spreads through the fissure when pushed by the pump's pressure.

To make the mastic flow, inside the fissures with thicknesses of 0.1 mm, needs a large input of energy or, in other words, the pump must be able to give high pressures. The machines we use at this time are capable of reaching 100 MPa, at the pump's outlet. This type of injection can therefore be considered as active since the resin displaces the water and its flow through the fissures is quite accurately controlled. Given the high pressures used, it is necessary to take a control of movements of the structure near the injected zones. Dial indicators or topography of precision, according to the cases, are used to make the control of these movements that usually remain under tenths of millimetres.

Obviously, to the aforementioned properties is to be added the fact that the polymer hardens and adheres under water and does not pollute. Not only can large water leaks, of up to hundreds of litters per second, be sealed with these materials, but on adhering and having high mechanical characteristics, they return lost monolithism to the structure being treated.

3. PIEDRA DEL AGUILA DAM. ARGENTINA.CRACK INJECTION

Piedra del Aguila is a concrete gravity dam. Its main dimensions are 170 m high above foundations and 820 m crest length, with a concrete volume of 2,780,000 m3. (Fig. 2)

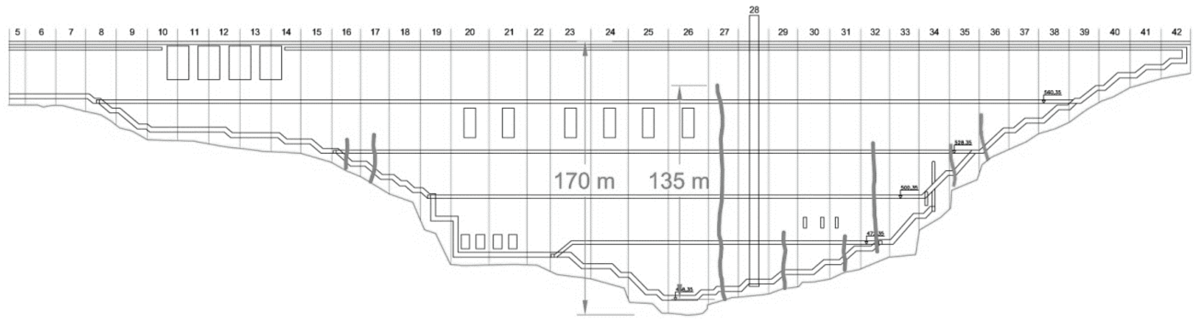

Fig. 2 : Elevation plan of the estimated crack dimensions. Solid lines are cracks of thermal origin and green lines are structural cracks.

The dam's construction concluded in 1991 and it was first filled in 1992. Thermal gradients between the dam body and the upstream face in this first filling, increased because the face quickly cooled down as a consequence of low water temperatures. This high temperature gradient caused significant vertical cracks up to 5 mm wide and up to 135 m long, and leakage flows close to 300 l/s in some of them (Fig. 3).

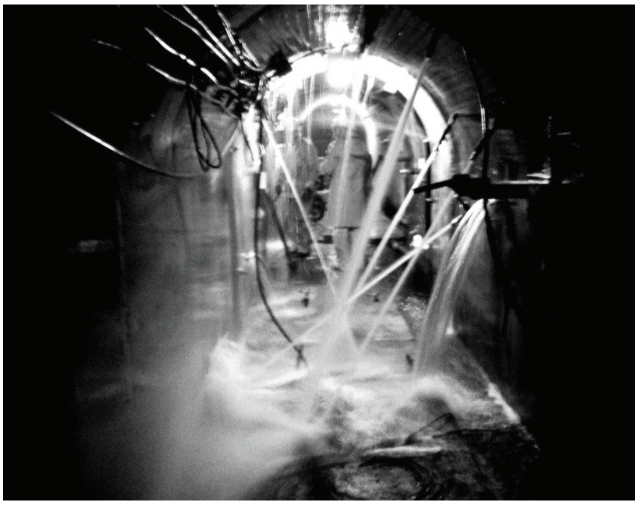

Fig. 3 : Leakage up to 300 l/s

The dam's thermal balance first had to be achieved in order to execute this sealing operation. Fitted in the body of the structure, numerous sensors indicated that the initial setting heat was regularly but slowly dissipated. The change in average temperatures is shown (Fig. 4). In 2010, 18 years after the dam was first filled, full stabilisation of temperatures was still not achieved. However, under these conditions there was no longer any risk of cracks extending since, even under the worst hypotheses, the traction stresses such a thermal gradient might produce would be only 0,2 to 0,3 MPa, values below the concrete's tensile strength.

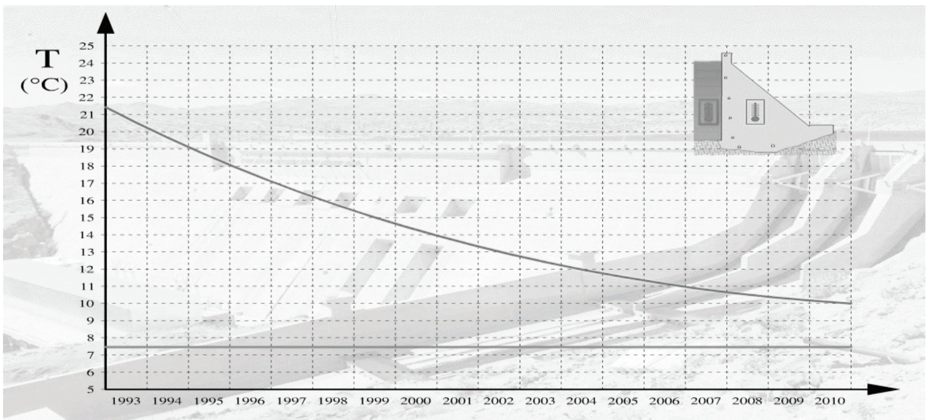

Fig. 4 : Change in temperatures detected over time.

As a result of the foregoing, after confirming that the temperature in excess of the final thermal balance expected was less than 1.5 ºC, in the year 2010, the dam's owner, HPDA, considered that the time had come to finally seal the cracks. Prof. G. Lombardi was on hand to advise in defining the technical solution.

The essential conditions when designing the repair work were:

- The need to keep the facility in service, forcing work to be carried out with a full reservoir thus, a water level of 170 metres above the foundations.
- Sealing cracks and recovering the structural integrity of the dam, with leaks close to 300 l/s.

The chosen solution was an injection of epoxy resin with high-performance mechanical characteristics into the entire crack area, whilst keeping the dam in service and the reservoir close to maximum load.

Starting from Dr. Ing. Giovanni Lombardi's recommendations drawn up in September 2009 and the Owner's operating conditions, HCC drafted an execution project, based on its own experiences in similar projects, which it submitted for approval to the owner, its advisers and the Argentine Dam Safety Regulating Body, ORSEP. The essential points of the initial design with which the preliminary work was executed in 2010 were as described below.

Once the size of each crack had been determined by exploratory drilling, a network of boreholes was drilled from the galleries, allowing the injection to be carried out uniformly, starting with the lowest level downstream, and moving on in stages, as shown (Fig. 5), until the downstream face was reached.

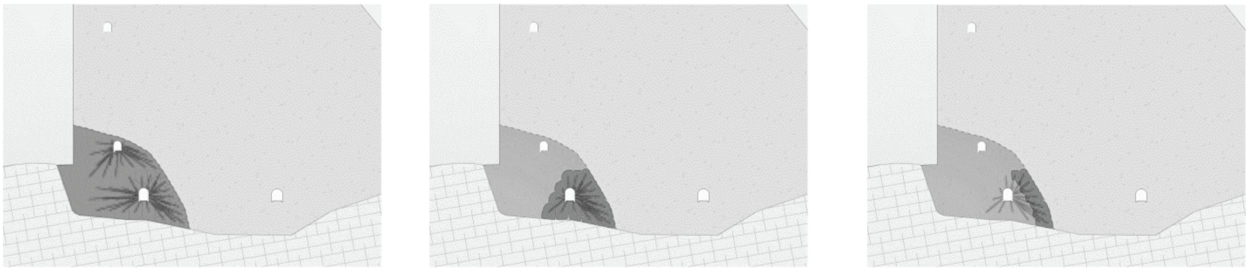

Fig. 5 : Stages of injection of a crack

The areas treated achieved the double objective of completely sealing the leaks and restoring the structural integrity of the dam, an extremely important factor, considering this is an area with a high level of seismicity. The results obtained were completely satisfactory for the owner, the Regulatory Body and the panel of national and international experts who participated.

4. KARUN 4 DAM. IRAN. CRACK INJECTION

The Karun-4 Dam is an arch dam on the Karun River, located in the province of Chaharmahal and Bakhtiari, Iran. It is a concrete double curvature arch-type and is 230 metres high from the foundation. The commission started in 2011. The dam soon began to show some pathologies, such as cracks in the dam's body, possible cracks in the foundation and significant opening in some of the vertical joints. In 2013, an international expert panel considered that HCC's technology, based on the injection of high viscosity epoxy resins and high pressure, was suitable for the repair.

The work began in 2014, and so far, nine cracks (in seven blocks) have been found. Rotation boreholes have been drilled with small, lightweight equipment from different galleries. Around 9,800 m have been drilled, to investigate and inject the cracks. Some boreholes had water flows with more than 20 bars of pressure (Fig. 6). Thanks to our TV inspection equipment, we can find the depth of the intersections with the crack in the boreholes and lay out a 3D drawing of the cracks. With these drawings we can calculate the area of the cracks. At the moment, we have found around 4,500 m² of cracks.

The total resin amount injected has been more than 40 tons. The injection of high viscosity resin has already resulted in the recovery of the structural integrity of the injected blocks. Resin was injected with very high-pressure pumps without emptying the reservoir, with 220 metres of water pressure.

Control boreholes drilled in the injected areas show that not only has the leakage been stopped, but the resin has bonded to the cracked concrete, restoring structural integrity. (Fig. 6).

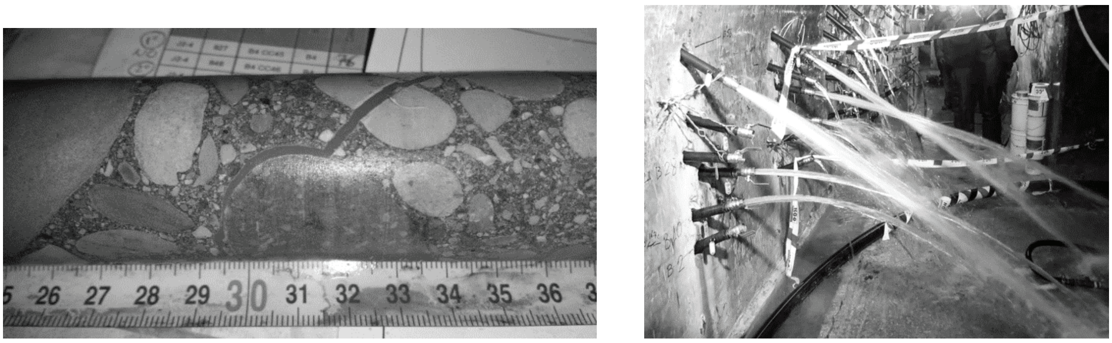

Fig. 6 : Gallery during injection and bonded core.

5. SUSQUEDA ARCH DAM. SPAIN. VERTICAL JOINTS INJECTION.

Susqueda Dam, is located in the province of Girona, Spain, in a tight consisting of gneiss, diorite and granite porphyry. It was completed in 1968. (Fig. 7)

It is a double-curvature symmetrical vault dam, with a maximum height of 135 meters over foundation and 510 meters in crown length, located at 357 meters above sea level. It is divided into 33 blocks 15 meters wide each, forming grouting enclosures between galleries with corresponding sealing. The thickness of the structure varies between 25 meters of the base in its most central zone to 5 meters of the crest. The dam's headline is ENEL GREEN POWER SPAIN.

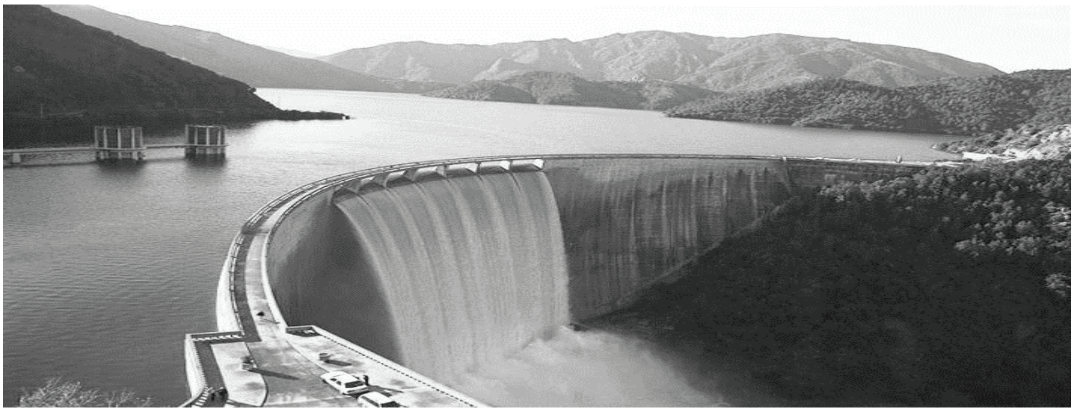

Figure 7 : Susqueda Dam overview.

Auscultation of the Dam revealed that the transmission of compressive stresses of contiguous blocks did not have the desirable continuity for a structure of this kind. Therefore, the opening of joints between blocks showed some drift, which made advisable to proceed with the re-grouting of the vertical joints, to improve the structural response of the dam to the solicitations it received, mainly thermal and hydrostatic load, and to regain their ability to transmit stresses between blocks, up to the stirrups.

The analysis of the dam's prior behavior, recommended carrying on the re-grouting of the contraction joints of the structure. According to these studies, we decided to perform a grouting project that would define in detail, the most appropriate method and times to execute the grouting.

In order to define the re-grouting, we analyzed historical records of joints movements, setting them according to the time of year and reservoir levels suitable to undertake the work in each area of the dam (Fig. 8).

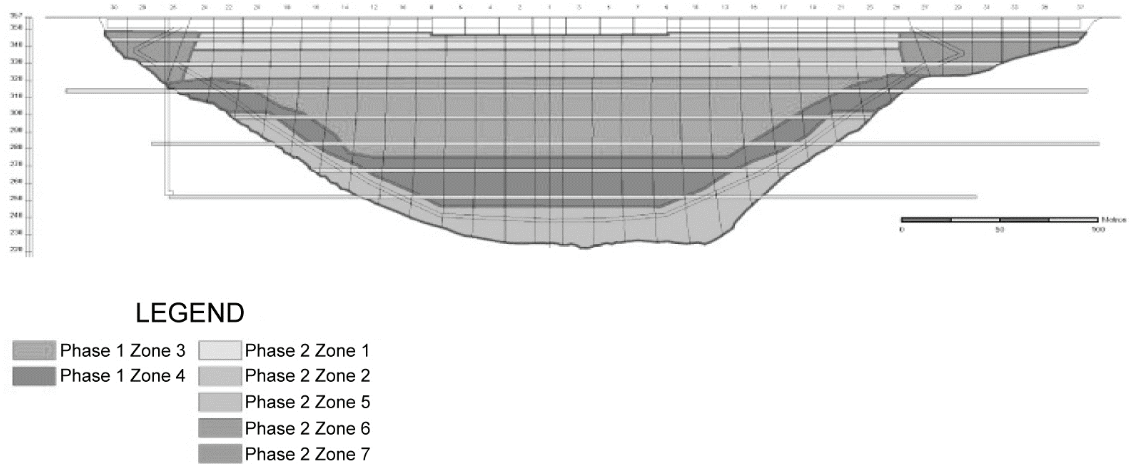

Figure 8 : Elevation view of the Dam with zones and campaigns of vertical joints re-grouting.

It was decided to perform the grouting by secant drills to the joints, executed from the galleries, with uniform distribution in each joint, to cover the entire area to be grouted (Fig. 9). As specified in the Project, rotation boreholes were drilled, with samples extraction using diamond core and commercial diameter of 46 mm, with different lengths and inclinations. The fact that the work was carried from within the galleries and the holes had depths of up to 20 mts in some cases, required the use of a small-sized machinery, albeit with sufficient power.

The condition of the observed joints was variable, with some joints detached, others filled with apparently insufficient grout, and even some bonded joints. Over 1,500 boreholes were made along the dam, with a total length drilled over 6,000 mts.

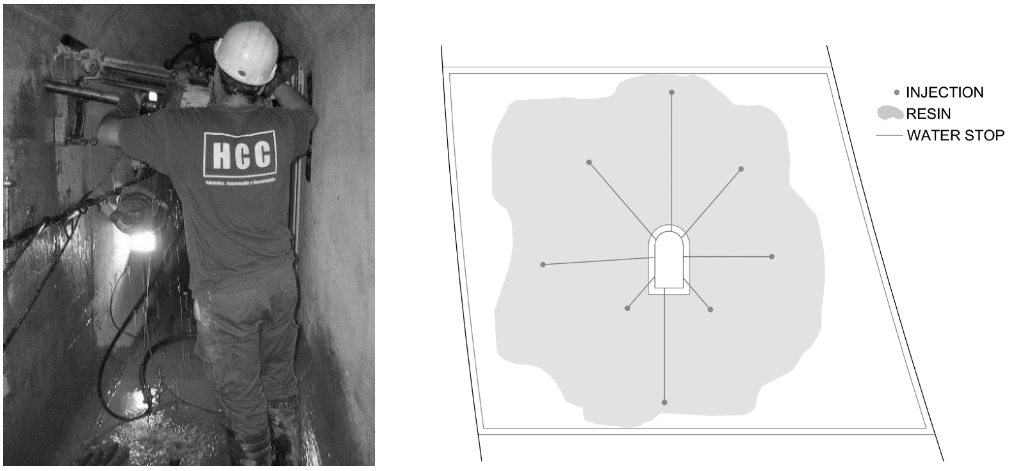

Figure 9 : Sketch of the proposed drilling in one of the joints, and drilling works

The joints re-grouting Project, established that the micro-cement was had to be the grouting material. Taking into account the variability of the condition of the joints, it was decided to develop a viscous epoxy resin specially formulated for the work to be done, equipped with physical and chemical characteristics consistent with the stresses to which would be subjected.

A priori we sought a material whose main characteristics were:

- Compressive strength comparable at least to that of concrete.
- Ability to polymerize dry or even in the presence of a stream of water.
- Not to be dragged by water.
- Low adherence to dry and wet concrete.
- Modulus of elasticity in low compression and tension, to allow some deformation of the product.

Table 1 summarizes the main mechanical properties obtained from the tests conducted there. Deformation curves were also obtained.

Table 1 : Mechanical properties of the resin developed specifically for the re-grouting of the vertical joints

Variable	Average value
Direct tensile resistance	7.5 N/mm²
Flexural strength	9.9 N/mm²
Compressive strength	42.2 N/mm²
Compression modulus of elasticity	323.6 N/mm²

In summary, it could be concluded that:

- The compressive strength, 42,2 N/mm^2, is in the range of a very good concrete, and notably higher than the grout and/or micro-cement.
- The modulus of elasticity is about 100 times lower than the concrete.
- Once exceeded the tensile strength, the material, albeit showing some degree of cracking, plasticizes.

The main units of work (1500 drills executed, 6000 meters of boreholes, and 45,000 kg of resin) attests to the magnitude of the action performed. To our knowledge, it has been the first re-grouting of vertical joints in an arch dam in the world using this technology.

The re-grouting of the joints was performed with the facility in service, maintaining the reservoir elevation at optimum levels for re-grouting each season, without being forced to lower it more than strictly necessary.

The applied methodology and the materials used, all uniquely developed for this work, have had highly satisfactory results, as demonstrated by the fact that the current data for the overall behavior of the structure with regards to the records indicate that the monolithic nature of the dam has improved substantially.

Based on the results of Susqueda, Lombardi Engineers drew up a project for a similar work in El Cajon dam, Honduras. It is a double arch vault dam with a maximum height on foundations of 226 m, which makes it the highest of its kind in the entire western hemisphere and the fifth in the world, and a length coronation of 286 m. More than 30 tons of resins were injected in a very satisfactory way.

6. CONCLUSIONS

The injection technique presented in this paper, is unique of its kind in the world. Different materials and types of machinery, developed over the last 25 years, have made it possible to design a specific solution for each problem. More than 40 different types of resin have been formulated to date, allowing the best choice in each case, e.g., cracks, joints, joints of the rocks, etc.

It was first observed that with the use of suitable technology, the reservoir did not have to be drained to satisfactorily execute the work. In fact, injecting with a full reservoir level, the effectiveness of the work could be confirmed as it was performed. Injecting in the worst possible scenario of pressure and leakage flows, guaranteed that sealing would not fail if conditions changed but could only improve.

Applied to RCC dams, this technology enables water-proofing to be fine-tuned during filling. The solution is more reliable, more stable and resistant against ageing, and above all, several times less costly than generalised water-proofing with impervious membranes.

Commercial materials are not valid for satisfactorily injecting given that very high viscosity (up to 1,000,000 cP) and high thixotropy resins are required. These resins must be injected at very high pressures and specific equipment adapted to such material is needed. Pumps must have enough power to reach 100 MPa.

Variants of the technique and materials, has been applied successfully in galleries and pipes with excessive leakage and loss of the rock's mechanical capacity.

The conclusions would seem fairly obvious: there exists a technology, developed and extensively proven, able to seal leaks with full reservoir level, and recovering the structural integrity. No divers are needed, to carry out the work.

Our experience, during the last 25 years, of more than 300 dams repaired, and more than 2000 tons of high viscosity resins satisfactory injected in Middle East, Europe, America, and soon Africa, have made HCC world leader in this field.