DAM REPAIR SYSTEM

PASQUALE ZAFFARONI
Product Manager Building Line, Mapei S.p.A., Milan, Italy

SIMONE BARILE
Building Engineer, Mapei S.p.A., Milan, Italy

ABSTRACT

The dams safety and efficiency has a substantial social, economic and environmental interest.

For this reason, is of fundamental importance to identify the most suitable products and technologies to be used during the construction and repair of dams. Mapei, worldwide leader in the production of adhesives, sealants and chemicals products for building, offers several innovative solutions able to satisfy the requests coming from designers and general contractors. In the hydraulic works field, in particular in the dams one, the products have to be waterproofing, with high mechanical performances and high abrasion resistance ability to ensure the structure durability over the time.

Thanks to the important investments in the research field of more than 120 Million € (5% of the annual turnover), Mapei has been developing a wide range of products for repairing dams and in particular the following systems:

- *Shrinkage-compensated, fibre-reinforced, thixotropic mortars for the downstream and upstream faces of the dams.*
- *Wear-resistant mortars with high ductility for restoration and protection of the spillways.*
- *Specific injection products for sealing cracks.*
- *Reinforcement composite systems with organic and inorganic matrix.*
- *Solutions for waterproofing joints subjected to high pressure water.*

1. INTRODUCTION AND REGULATORY FRAMEWORK

The repair of a concrete structure is an extremely complex activity requiring the use of suitable products and the involvement of qualified and competent personnel.

However, this is not enough to ensure the durability of the intervention and the EN 1504 standard in force in Europe since January 2008, guides the designer in choosing the suitable systems based on encountered problems. The EN 1504 standard defines the procedures and the minimum requirements of the products to be used to repair, maintain and protect concrete structures. This standard is composed of 10 parts:

- EN 1504-1: Definition;
- EN 1504-2: Surface protection system for concrete;
- EN 1504-3: Structural and non-structural repair;
- EN 1504-4: Structural bonding;
- EN 1504-5: Concrete injection;
- EN 1504-6: Anchoring of reinforcing steel bar;
- EN 1504-7: Reinforcement corrosion protection;
- EN 1504-8: Definitions, requirements, quality control and evaluation of conformity;
- EN 1504-9: General principles for the use of products and systems;
- EN 1504-10: Definitions, requirements and quality control;

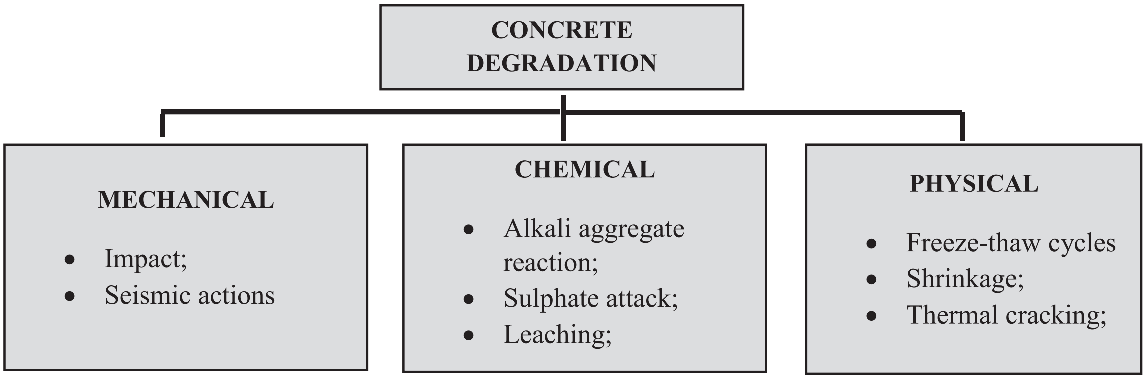
Principal aim of this standard is to supply valid tools to optimise the repair work. The EN 1504-9 part introduced the concept of products system, where each product contributes to the solution of a specific problem, by realizing in this way a durable and sustainable intervention. The phases complying with this standard are the following:

Structure management	Investigation process	Planning	Intervention design	Repair work	Work acceptance

The first necessary operation is collecting the data that are useful for the project realization. It is fundamentally important to analyse the conditions, to know the history and collect all documents related to the work, besides verifying if in the past other maintenance works were carried out. It is then necessary to define the conditions of the structures through the planning of several visual inspections, as well as taking samples and analyse them in situ or in a laboratory, to prepare an accurate diagnosis of the degradation causes. After this preliminary phase, it is possible to proceed with the intervention design, by defining the principles and methods of the structure repair and making a careful evaluation of the material to be used, based on the structure degradation level. For this reason, it is highly important the drawing up of the technical specifications where, besides the conformity of selected materials, several aspects including the preparation of the substrate to be treated that is related to the conditions and dimensions of the structure, must be considered. Once the repair operations are concluded, it will be necessary to validate its correct execution.

2. THE DEGRADATION CAUSES

All concrete structures are subject to different degradation phenomena that could be mechanical, chemical or physical and are strictly related to the surrounding environment where the structure is located. The principal causes of degradation of the dams are the following:



The mechanical defects can be caused by different phenomena such as impact or seismic actions. This document will not deal with the causes of mechanical degradation but only those of chemical and physical nature.

From the chemical point of view, three of the most frequent phenomena are the alkali-aggregates reaction, the sulphate attack and leaching.

2.1 Alkali-aggregates reaction

The alkali-aggregates reaction is due to the presence inside concrete of aggregates containing amorphous silica, that reacts with alkali of sodium and potassium. The reactive aggregates, that are exposed to contact with water, increase their volumes due to the formation of a gel based on hydrated silicates of sodium and potassium, causing an irregular macro-cracking phenomenon that strongly limits the structure durability or the detachment of small portions of concrete (pop-out).

Figure 1 : Colorimetric test with sodium hexanitrocobaltate

Figure.1 shows two samples taken from a concrete structure, that have been analysed through a colorimetric test with sodium hexanitrocobaltate that allows to verify the presence of reactive aggregates containing amorphous silica.

2.2 Sulphate Attack

The sulphate attack is due to the interaction of the sulphate ions (SO_4^-) with the substances composing the cementitious matrix. The sulphate ion that are possibly contained in soil and water penetrates in the porosities of the cementitious matrix and interacts with the calcium hydroxide $Ca(OH)^2$, forming gypsum which can react with calcium aluminate hydrates (C-A-H), by forming secondary ettringite that causes concrete swelling, detachments and cracks as a result of the volume increase. To limit this type of phenomenon, it is important to realize high quality concretes, that have to be compact with a low water/cement ratio or to use a resistant sulphate cement with a low content of C_3A.

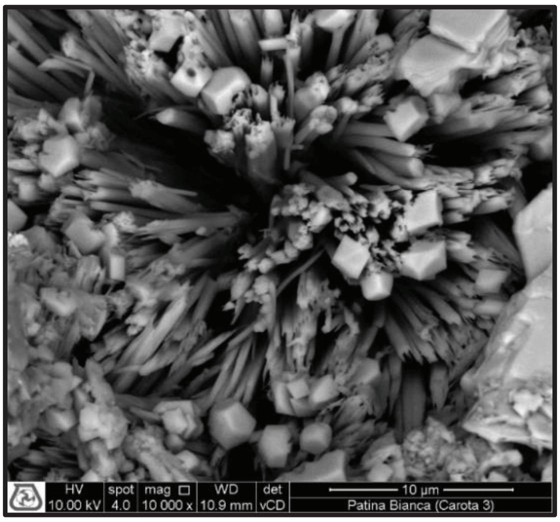


Figure 2 : Analysis by electron microscope of the formation of secondary ettringite

2.3 Leaching

A further phenomenon that can affect dams is the leaching generated by pure waters having a low saline content or waters having a high content of carbon dioxide. These waters solubilize and remove calcium hydroxide that is contained in the concrete and the leaching effect becomes more marked as a result of the water movement because the dissolving action is continuously renewed. The removal of calcium hydroxide from the cementitious paste determines the formation of voids causing an increase of the concrete permeability.

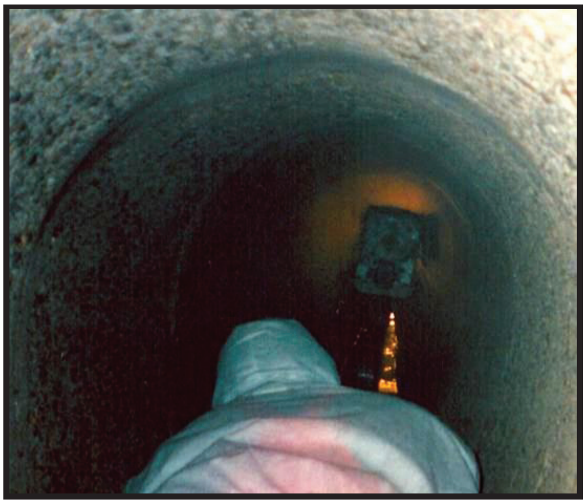


Figure 3 : Example of degradation due to leaching phenomenon

As regards the physical defects, they could be caused by different phenomena related to thaw/freeze cycles, thermal factors, shrinkage.

2.4 Thaw/freeze cycles

The principal phenomenon is represented by thaw/freeze cycles; in particular when the temperature is below 0°C, the water that is contained in the concrete pores can freeze causing a volume increase of about 9%. This phenomenon occurs when the humidity rate inside the pores exceeds the so called "critical saturation" value which is equal to about 92%. The volume increase consequent to the transition of water from the liquid to the solid state, determines the trigging of tensions causing widespread cracking phenomena (scaling).

Figure 4 : Typical example of degradation caused by thaw/freeze cycles

2.5 Thermal cracking

Dams could be interested by cracking phenomena that are thermal in nature, because during seasonal thermal cycles, the difference of temperature between the most internal and the most externally exposed structure areas is extremely high and is influenced by both external environmental conditions and the water level of the artificial basin. This different temperature distribution between the most internal layer and the most external layer makes the first one subject to a thermal dilatation phenomenon, while the second one is subject to a thermal contraction phenomenon. This causes the formation of tensile stresses in the most external layer with the following formation of cracks. This phenomenon strictly depends on the local mechanical and deformation characteristics of the material.

3. TYPICAL INTERVENTIONS

After defining the degradation causes and carrying out the damage diagnosis, it is possible to proceed with the definition of the most suitable repair intervention cycle.

3.1 Repair of vertical and horizontal surfaces with mortars in compliance with EN 1504-3

The choice of the suitable repair mortar is necessary to ensure the success of the repair intervention. The principal characteristics of the repair mortar are the perfect compatibility from the chemical-physical point of view with the substrate, low shrinkage values and the absence of cracks, besides low permeability to water and the possibility of being easily pumped. From the performances point of view, the EN 1504-3 envisages different types of mortars. As shown in the table below, this standard divides the mortar in 4 classes in relation to their mechanical characteristics, such as compressive strength, elastic modulus, adhesive bond, shrinkage. There are also other parameters that are taken into account such as the thermal compatibility measured as bonding to freeze/thaw cycles, storm cycles and dry thermal cycles and it is also evaluated the resistance to accelerated carbonatation.

Performance characteristics	Test method	Requirement (Table 3 in EN 1504, part 3)			
		Structural		Non-Structural	
		Class R4	Class R3	Class R2	Class R1
Compressive strength	EN 12190	≥ 45 MPa	≥ 25 MPa	≥ 15 MPa	≥ 10 MPa
Chloride ion content	EN 1015-17	≤ 0.05%		≤ 0.05 %	
Adhesive bond	EN 1542	≥ 2 MPa	≥ 1.5 MPa	≥ 0.8 MPa	
Restrained shrinkage / expansion	EN 12617-4	Bond strength after test			No requirement
		≥ 2 MPa	≥ 1.5 MPa	≥ 0.8 MPa	
Durability - carbonation resistance	EN 13295	d_k ≤ control concrete		No requirement	
Durability - thermal compatibility freeze / thaw	EN 12617-4	Bond strength after 50 cycles			Visual inspection
		≥ 2 MPa	≥ 1.5 MPa	≥ 0.8 MPa	
Durability - thermal compatibility thunder / shower	EN 12617-4	Bond strength after 30 cycles			Visual inspection
		≥ 2 MPa	≥ 1.5 MPa	≥ 0.8 MPa	
Durability - thermal compatibility dry cycling	EN 12617-4	Bond strength after 30 cycles			Visual inspection
		≥ 2 MPa	≥ 1.5 MPa	≥ 0.8 MPa	
Elastic modulus	EN 13412	≥ 20 GPa	≥ 15 GPa	No requirement	
Skid resistance	EN 13036-4	Class I: > 40 units wet tested Class II: > 40 units dry tested Class III: > 55 units wet tested		Class I: > 40 units wet tested Class II: > 40 units dry tested Class III: > 55 units wet tested	
Capillary absorption	EN 13057	≤ 0.5 $kg/m^2 \cdot h^{0.5}$		≤ 0.5 $kg/m^2 \cdot h^{0.5}$	No requirement

Figure 5 : Performance characteristics of the mortar in compliance with EN 1504-3

In addition to the characteristics indicated in the previous table, two significant tests are used to determine the resistance to cracking: the "O Ring Test" and the impermeability to water test. As regards the cracking test, the mortar is placed in a confined contraction condition by pouring it around a steel toroid able to contrast the free shrinkage. This causes an increase of the tensile stress inside the mortar that allows to simulate the effect of the confined shrinkage, without considering the friction components. After 180 days of curing under constant temperature and humidity, no cracks should appear. Instead, as regards the impermeability to water, the test is carried out in compliance with the EN 12390/8 and allows to determine the water penetration depth under pressure into the hardened mortar. Water is applied at a pressure of (500 ± 50) kPa for approx. 72 hours.

Figure 6 : "O Ring" Test

Figure 7 : Water impermeability test

3.2 Substrate preparation

In order to correctly prepare the repair intervention it is necessary to ensure a suitable preparation of the substrate that, based on the type of degradation, can be carried out by mechanical demolition or hydrodemolition to remove all loose and detaching concrete, to obtain a rough, solid and resistant surface having unevennesses higher than 5 mm, able to promote the adhesion between the new mortar layer and the original substrate. Before proceeding with the mortar application, it is necessary to wet the substrate with water to obtain a S.S.D. condition (Saturated Surface Dry) and then wait the evaporation of the exceeding water.

Figure 8 : Examples of substrate preparation

3.3 Application of the repair mortar

As previously described, the choice of the correct mortar is necessary in order to ensure a correct restoration intervention. Repair mortars are essentially of two types: flowable mortars and thixotropic ones. Obviously in relation to the type of mortar the application will be different. For what concerns the flowable mortars, the application must be carried out by pouring the product into the previously prepared formworks. To facilitate the expulsion of air, it is necessary to pour mortars continuously into the formworks by one side only. Furthermore, it is fundamental to guarantee that the water of mortars must not be absorbed by the formworks so for this reason it is important to pre-treat them with a form-release oil. For what regards thixotropic mortars, the application is usually carried out by spraying using a piston or worm screw rendering machine.

Figure 9 : Typical examples of repair with a screw pump

3.4 Final protection with mortars in compliance with EN 1504-2

The horizontal and vertical surfaces subject to a restoration intervention can be protected by using different coatings which must comply with the minimum performance requirements of the EN 1504-2 standard. For example, for the protection of the upstream face of the dam it is possible to use specific mortars with high resistance to wear, containing selected aggregates, special additives and synthetic polymers in water dispersion. These types of mortars, once hardened, become impermeable to water and chemical atmospheric agent and for this reason they are suitable to protect all the concrete structures subject to high abrasion.

Among all the coatings that can be employed for the final protection, it is of fundamental importance to consider elastic cementitious coatings that can be used for example, to protect the downstream face of the dam. Here below, it will be considered a two-component elastic cementitious mortar suitable for this kind of application, complying to the EN 1504-2. The mortar is applied in a mean thickness of 2 mm and remains elastic up to a minimum temperature of -25°C under all environmental conditions and is completely impermeable to the penetration of calcium chloride, sulphates and carbon dioxide.

Thanks to its high crack-bridging ability this mortar can protect the repaired structure from possible cracks caused by dynamic loads, shrinkage and thermal variations, also in presence of harsh climates. This characteristic is extremely important especially if we consider that this cementitious coating maintains its crack-bridging performances constant in presence of a wider temperature range.

Figure 10 shows that the mortar crack bridging ability remains almost unaltered in a range of temperature between -25° e +30° C.

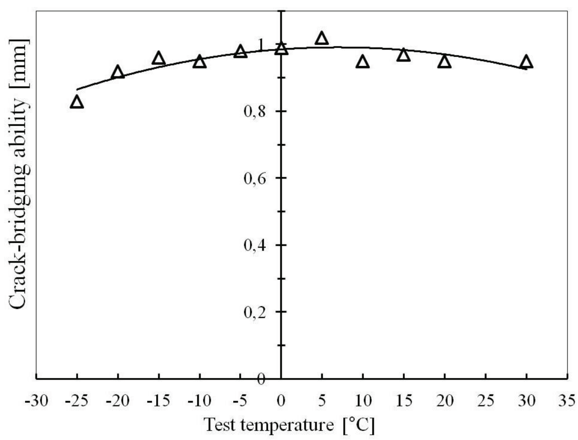


Figure 10 : Crack-bridging test carried out on the elastic cementitious coating

Additional tests were carried out on this elastic protective cementitious coating, in particular the evaluation of the CO2 penetration through an accelerated carbonatation tests. The specimen was placed for 90 days in a climatic chamber in an environment rich in CO_2 (30% in volume). The CO_2 penetration was calculated in different times through a colorimetric test made with phenolphthalein. The figure below shows the elevated penetration of CO_2 in a concrete having a high water/cement ratio (0,8), that reduces in a higher quality concrete (W/C = 0,4) and further decreases in a R4 Class mortar. The penetration of carbon dioxide is negligible when the elastic cementitious coating is applied on a concrete having a W/C ratio of 0,8.

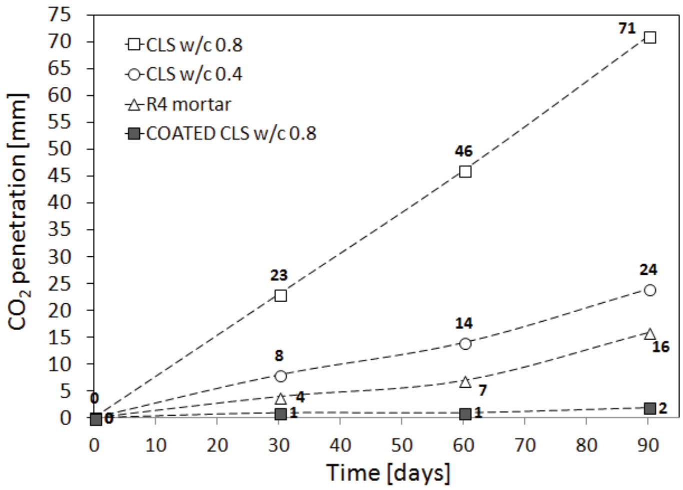


Figure 11 : Test of CO_2 penetration

Instead, the waterproofing level was determined according to the EN 14891, that requires the application of a jet of water under pressure (1.5 bar) for 7 days and a following visual inspection to determine the possible penetration of water through the coating in subject. In particular, the level of water penetration in a concrete having a W/C ratio equal to 1 was determined. The result showed that the concrete was completely penetrated with a consequent weight increase of about 470 g. On the contrary, the elastic cementitious coating was almost not penetrated, showing a weight increase of 8 g only.

4. CRACK INJECTION AND VOIDS IN COMPLIANCE WITH EN 1504-5

One of the principal problems related to hydraulic works is the formation of cracks, that convey the ingress of water in the structure, thus affecting its waterproofing level. EN 1504-5 requires injecting the cracks by using 5 types of products as indicated in the following scheme.

Injection products for force transmitting filling of cracks, voids and interstices in concrete (F) : Product able to bond to the concrete surface and transmit forces across them. Product for injection for force transmitting filling of cracks, voids and interstices can also be used for saturation without receiving a force transmitting bond.

Injection products for ductile filling of cracks, voids and interstices in concrete (D): Flexible products which are able to accommodate subsequent movement.

Injection products for swelling fitted filling of cracks, voids and interstices in concrete (S) : Products which are able, in the reacted state, to swell repeatedly by water adsorption, where the water molecules are bonded to the molecules of the injection product.

Injection products formulated with reactive polymer binder (P) : Product where the hardening is related to the curing of a reactive polymer binder. The reactive part of a polymer binder involved in the hardening of the binder is the functional group.

Injection product formulated with hydraulic binder (H) : Product where the hardening is related to the hydration reaction of an hydraulic binder.

The cracks repair depends on different factors such as their width, depth, but also if they are wet or dry or if they are static or subject to small movements and can be carried out by use of epoxy resins if a monolithic adhesion is required, with expansive and flexible polyurethane resin in case of water leakages or with micro cement if voids have to be filled in. The size of particles present in micro-cements ranges from 10 µm to 25 µm so as to be able to fill even the smallest voids.

Figure 12 : Coring of a cracked concrete portion

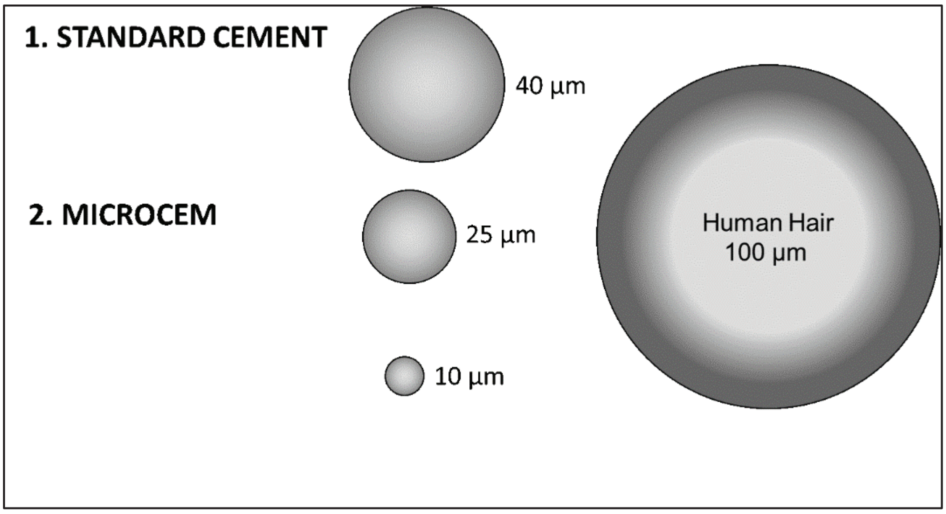


Figure 13 : Comparison between the particle size of a standard cement and a micro cement

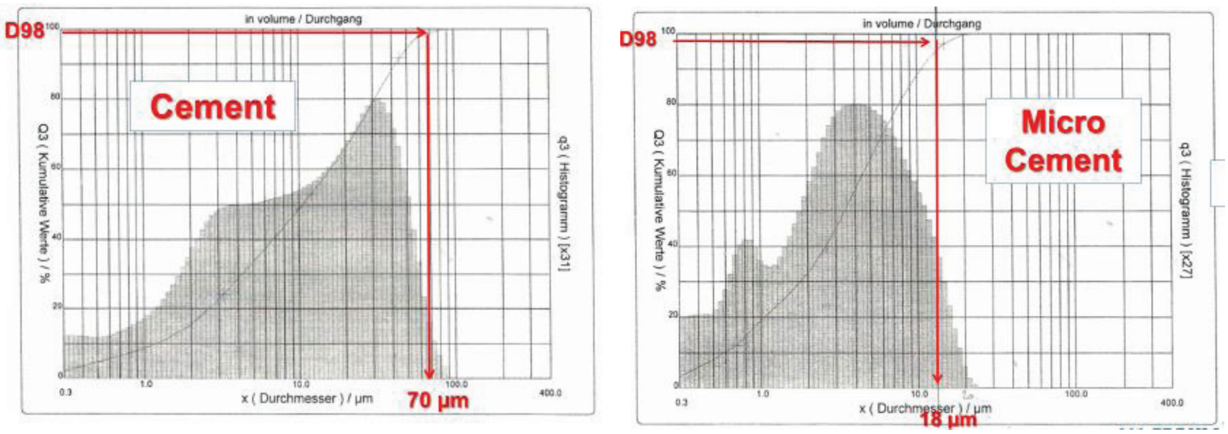


Figure 14 : maximum dimensions of the particle size of a cement and of a micro cement

All the products can be applied by pouring or injection. In this last case it is necessary to place a series of packers, in suitable quantities and dimensions, that must be vertically distributed and equidistant from each other. In case products with a long pot life are used, before starting with injection it is necessary to externally seal the crack with two-component thixotropic epoxy adhesives that have to be injected from the bottom to the top until the cracks is completely sealed.

Figure 15 : Example of a cracked concrete of a spillway

In addition to the causes of degradation previously analysed, another problem that could affect the hydraulic works is the loss of waterproofing of the dilatation joints due to ageing, with a consequent degradation of the internal waterstops. These elements are subject to high variations of temperature and humidity, thaw and freeze and mechanical actions that could cause their deterioration. This could determine the cracking of the joint cover and a loosening or even a breaking of the waterstop, with consequent water leakages to the inside of the joint.

A further waterstop protection can be done by using an additional external joint made of different materials that are mechanically fixed by using an epoxy putty having a very high viscosity, which is generally used for underwater applications. After mixing, this epoxy putty has a pasty consistency with a high thixotropy that allows its application on vertical surfaces and is also able to polymerize on wet substrates. After hardening, the product is waterproofing and is characterized by high mechanical strengths, besides having an excellent adhesion to the concrete support. This product is suitable for the protection and repair of concrete structure being marked according to EN 1504-2 and EN 1504-3.

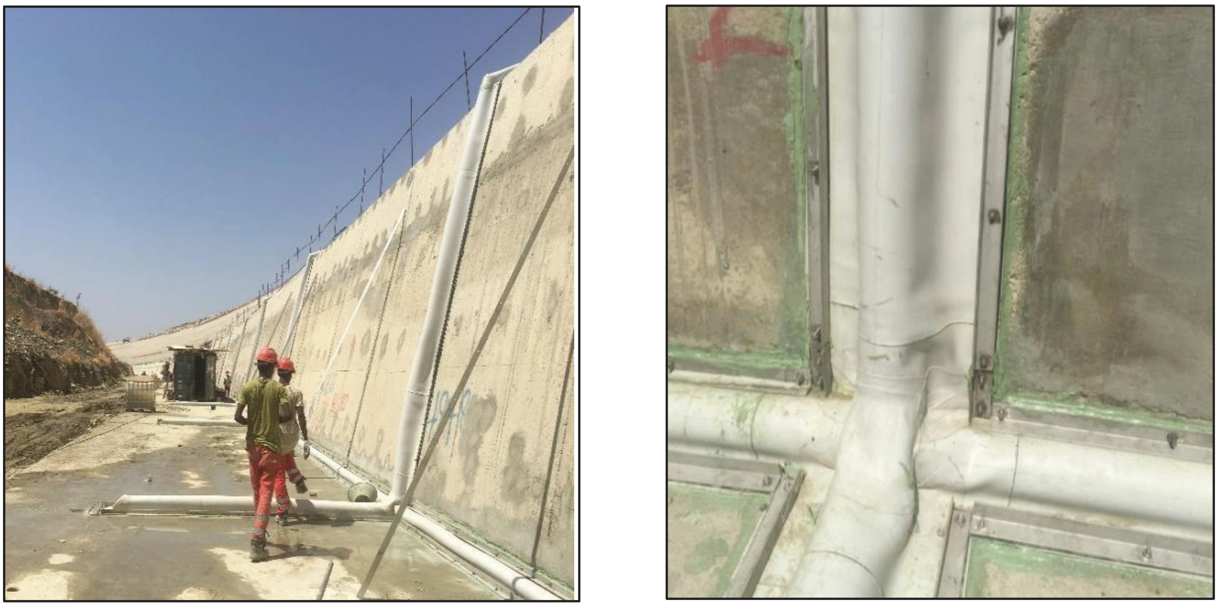


Figure 16 : Joint sealing intervention on a saddle dam

Figure 16 shows a system composed by the following materials: circular profile, hybrid carbon/glass bidirectional non-woven tissues, a PVC membrane having a 2,5 mm thickness, rubber gaskets, metal profiles, the above-mentioned epoxy putty and a high weight non-woven tissue for the final protection. To ensure the complete waterproofing of the system, after the putty hardening, it was tensioned by means of a dynamometric key.