Cracks Repair in Reinforced Concrete Structures
Case Study – Reinforced Concrete Tunnel Repair

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ABSTRACT:

The use of epoxy resins by injection or just by sealing constitutes the most common solution for cracks repair. However, epoxy resins products are not able to fix properly all cracking problems, such as active cracking or in the presence of moisture. For this purpose, the existence of polyurethane and acrylic resins is a good solution to solve these problems. This paper describes, briefly, the reinforced concrete structures behaviour towards the most common anomaly, cracking, detailing cracks causes and characteristics. Then, a review of standard EN 1504 is presented, concerning products performance requirements, conformity assessment and test methods. Further, injection materials, equipment, methods and procedures are also described. Lastly, a case study is presented: a project that involved the repair of cracks in a reinforced concrete tunnel, using different techniques and materials.

1 Introduction

Although most concrete structures present a satisfactory performance, there are deterioration problems in many structures, commonly manifested by cracking, due to the most different causes. These causes can affect the appearance of concrete and can also indicate significant structural and durability problems [1]. A favourable conservation status improves the functionality and performance of a concrete structure, ensuring resistance and rigidity, good surface appearance, impermeability to water and sealing the entrance of moisture, aggressive agents for concrete and steel, thereby increasing the durability standards [2].

1.1 Concrete cracking

In concrete, cracks are the most frequent anomalies, due to several causes. In addition, the cracks are inherent occurrences to concrete, since the sections are usually designed for cracked section states, therefore, it does not always represent a pathological manifestation. In this regard, the differentiation between pathological manifestation or not must be made taking into account the characteristics and causes of the cracks.

1.1.1 Cracking causes

Concrete cracking may be caused by (i) concrete internal/chemical processes, (ii) external factors, (iii) design and/or execution mistakes and (iv) external agents, such as improper structure use, atmospheric factors that can cause or accelerate deterioration processes, and others.

With regard to concrete internal processes, special reference is made to:

- Plastic shrinkage – cracks occur in young age concrete, when water loss speed through evaporation exceeds the speed that the water reaches the surface by exsudation.
- Plastic settlement – cracks arise due to water migration to concrete exterior surface, causing decreases in volume and, consequently, settlement of the fresh concrete.
- Expansive reactions (steel reinforcement corrosion, alkalis or sulphate attack) – cracking caused by stress concentrations inside concrete.
- Thermal variations – cement hydration heat - exothermic reaction which results in internal stresses and causes cracking.

Regarding to external factors, the following causes stand out:

- Support settlements – supports relative displacement can cause cracking or elements deformation, corresponding to structure imposed changes [4].
- Temperature effect – in a structure differential temperatures distribution cause differential volume variations in the elements, and, against structure rigidity, tensions arise and can origin cracking [4].
- Long term shrinkage – occurs due to concrete decrease in volume by water loss and it is uninfluenced by the structural load.
- Creep – being submitted to constant loads over time, concrete tends to increase deformation by creep and often cracking [5].

1.1.2 Cracks characteristics

Before cracks repair, their **activity** is analysed, defining cracks as [6]:

- Active cracks – cracks that present width variation over time. Can be classified as stable (e.g. daily or seasonal temperature changes, causing materials expansion and contraction) or unstable (e.g. ongoing settlement).
- Passive or dead cracks – stabilized cracks, which do not move. Causes that originated these cracks have disappeared (e.g. shrinkage cracks after process stabilization).
- Dormant cracks – passive cracks that can become active after repair intervention (e.g. elimination of expansion joints)

Cracks width (**w**) is one of the most relevant characteristics. Currently, cracks are recognized by the maximum width, as [6]: (i) micro-cracks, $w < 0.05$ mm; (ii) medium-cracks, $0.05 \text{ mm} \leq w \leq 0.4$ mm, and (iii) macro-cracks $w > 0.4$ mm. But cracks that must have intervention is a choice made by the owner and/or the designer. It is usual to define that crack width is "normal" or acceptable if the width is smaller than 0.3/0.4 mm and in this situation usually the cracks are not repaired. On the other hand cracks bigger than 0.5 mm are not acceptable, for which repairing is recommended. This is a somewhat simplistic approach only to frame measures for the cracks because there are several factors that will affect the decision to repair them.

Regarding the cracks **location and orientation**, the following aspects must be considered: to analyse if cracks are horizontal, vertical or diagonal; to understand if cracks are extending along a single material or if developing is at the boundary between different materials; to evaluate if the cracks are affecting concrete elements or just surface finishing [3].

Concerning the **depth**, it is necessary to distinguish between surface and deep cracks. Naturally, the cracks that develop in depth are more harmful to the elements, causing further negative effects on durability, concrete mechanical strength and structure waterproofing [7].

Cracks spatial distribution is understood as the repeatability of the cracks, i.e., cracks frequency and arrangement in the element. It should be analysed if there is a pattern of cracks, as parallel cracks, cracks with an inclination towards the supports, helically oriented cracks, *craquelet* cracks or irregular generalized cracks, which may indicate the forces or stresses to which the element is subjected to.

It is also of great significance to evaluate the cracks **water presence**, i.e., the cracks moisture state. This state can be summarized defining the cracks as dried cracks, moist cracks, cracks with water infiltration (with or without pressure) [7].

2 Normative framework

The European Standard **EN 1504 –** ***Products and Systems for the Protection and Repair of Concrete Structures*** covers all the aspects related with concrete repair, including repairing principles, products performance requirements and test methods, factory production control and conformity assessments, including CE marking and application methods and quality control [8]. This standard is subdivided into ten parts, but in what concerns concrete cracking just six of them are relevant: **EN 1504-1** – Definitions [9]; **EN 1504-3** – Structural and non-structural repair [10]; **EN 1504-5** – Concrete injection [11]; **EN 1504-8** – Quality control and evaluation of conformity [12]; **EN 1504-9** – General principles for the use of products and systems [13]; **EN 1504-10** – Site application of products and systems, and quality control of the works [14].

2.1 Performance requirements

EN1504-9 lists 37 repair methods related to 11 acting principles, based on physical and chemical laws which permits prevention or stabilizing concrete deterioration processes. Table 1 shows the principles and methods related to concrete cracking.

Table 1 – Principles and methods of repairing related to concrete cracking (adapted from [8])

Principle	Definition	Method	
P1	Protection against ingress	**M1.4**	Protection against ingress and waterproofing by filling cracks
P4	Structural strengthening	**M4.5**	Structural strengthening by injecting cracks
		M4.6	Filling cracks, voids or interstices

2.2 Injection products performance characteristics

Repairing systems and products should have satisfied the requirements defined at three levels: (i) it should be indicated a certain number of materials properties through the characteristic or certificated values; (ii) it is necessary that these characteristics and properties satisfy the normative requirements and (iii) it is necessary that some repairing materials characteristics fil the conformity criteria.

The products are classified according to three categories: **F – Injection products for filling cracks, voids and interstices in concrete with transmission of forces; D – Injection products for ductile filling of cracks, voids and interstices in concrete** and **S** – **Injection products for expansive filling of cracks, voids and interstices in concrete.** EN1504-5 also distinguishes injection products as to the chemical type and main constituents, according to two categories: **P – Injection products with polymer binders** and **H – Injection products with hydraulic binders.**

The producer must perform products initial performance tests according to normative methods indicated in EN1504 tables, for each type of cracks filling mentioned.

3 Cracks repair by injection technology

3.1 Injection materials

The selection of the appropriate injection material is the first key factor for a successful cracking repair. The main materials requirements are the strong adhesion to the concrete, low viscosity, flexibility and mechanical resistance suitable to structural or non-structural repairing, capacity of deformation after hardening, volumetric shrinkage control and chemical stability of the components mix that compose the product of injection [15].

Crack width is a crucial characteristic for injection material choice. Generally, lower width cracks require an injection material with lower viscosity so they can enter in the void easily and with lower injection pressure.

Cracks activity also has a huge influence in the material choice. In the case of passive/dead cracks with small dimension, the best solution is the injection of rigid materials. In active cracks it is necessary to apply a flexible material, with capacity of deformation after hardening [16].

The **water presence** will also affect the use of materials due to the chemical reactions (expansive) of certain materials with the water molecules and to the materials adhesion (or the lack of it) with the concrete in case of moist cracks.

3.1.1 Resins

Resins are the most used materials in injection systems. **Epoxy resins** have high compressive and tensile strength comparing with concrete and, as a rigid material, they are used in structural repairs ensuring the efficient transfer of strengths and recovering the structure rigidity conditions [17], due to the strong adhesion between epoxy resins and concrete. The main injection epoxy products properties are the hardening without shrinkage, the low viscosity, the applicability at low temperature and the fact that they guarantee a barrier against water infiltration and corrosive elements entering [18]. On the negative side, regular epoxy resins are too sensitive to water/moisture presence and water affects also the adhesion between epoxy and concrete, can reduce their strength, and also the bad performance of these products at high temperature.

Polyurethane resins are flexible and guarantee a strong adhesion with the concrete in wet or dry cracks. Within each polyurethane resins products, one can distinguish (i) polyurethane **foams** and (ii) **polyurethane gel**. These two types of products have different characteristics and, consequently, different functions, but, in general, these solutions are used in conjunction, complement each other and make the best use possible of the properties of each one [15]. Polyurethane foams expand in contact with water, being used in areas with water flow to staunch temporary the water entering. Its expansive speedily reaction in contact with water form a flexible and elastic foam [15]. For a permanent waterproofing, the cracks with polyurethane foam could be reinjected with not expansive resins [15] like (i) **polyurethane gel resins**, that are flexible, with a high chemical resistance, recommendable to fill cracks permanently with variable opening over time, adapting to movements, with minimum width of approximately 0.2 mm or (ii) **acrylic gel resins**, a very elastic material with an extremely reduced viscosity (similar to water), having ideal properties to penetrate structures voids, they can be injected in cracks thinner than 0.05 mm. Acrylic resins application is common in the use of injection curtains technics as a repair solution to other waterproofing systems or as preventive waterproofing in retaining walls in underground structures.

3.1.2 Microcement grouts

Microcement grouts are not flexible and, consequently, they do not adjust to structures movements. These materials can be used in injection works to repair structural cracks (wider than 0.5 mm), but are usually used in structural joints treatment. Therefore, microcements are not products with a high demand for common cracks injections, because their penetrability and mechanical characteristics are lower than those of epoxy resin products.

3.2 Injection equipment

The appropriate selection of injection equipment is the second key factor for the injection systems success [15]. The **pumps** and **packers** depend on the injections materials, the injection pressure and the concrete quality in the cracks surround.

3.2.1 Injection pumps

There are two injection pumps technologies: (i) Single-component and (ii) bi-component. **Single-components pumps** can be manual, pneumatic (compressed air) or electrical. In this type of pumps, the product composed by two components (resin + hardener) is mixed beforehand, being deposited into a container. The product work time begins after components are mixed, and that it is necessary to implement the complete volume mix inside the indicated pot life in the *Product Technical Data Sheet.* **Bi-component pumps** are usually pneumatic (delivery of compressed air) and have two storage containers, each one being filled with a part of product (usually part "A", mix of pre-dosed liquid resin and hardener and part "B" with a mix of an accelerator and water). The two components product mix is only made in the injection moment, in the pump head, when components are pumped, and products pot life begins counting when two parts are mixed.

3.2.2 Injection packers

Two types of injection packers can also be distinguished: (i) surface packers and (ii) mechanical packers. **Surface packers** (Fig. 1) are plastic or metal filling valves that are installed above the cracks, at structures surface. These packers are commonly used epoxy resins injections when a structural reinforcement is necessary [7] and in cases where it is not recommended to drill the concrete [15]. There are also simple cylindrical packers, similar to surface packers but without the circular injector basis and that are placed manually inside the crack.

Fig. 1 - Surface packer [7]

Mechanical packers are cylindrical shaped, are installed after drilling the concrete and then the rubber swelling is tight forced to hold packers to support high injection pressures [15].

Fig. 2 - Mechanical packers to inject different materials

3.3 Injection methods

Injection method is the third key factor. Injection under pressure is the most common method and it may consist of direct crack injection surface packers or injection with mechanical packers through holes made beforehand.

Cracks direct injection under pressure, with surface packers, should be used when it cannot be possible to drill the concrete, there is no infiltration and the injection pressure is low (below 20 bar).

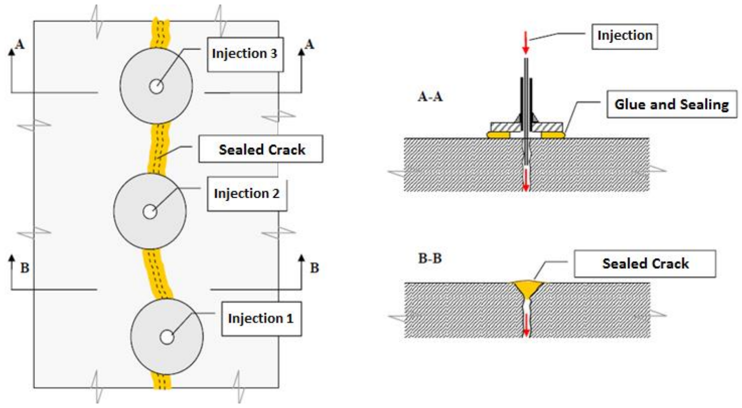

Fig. 3 - Injection with surface packers (adapted from [18])

Cracks injection under pressure by mechanical packers placed by mechanically drilling, is the most common and effective method. However, such packers' application is only possible when concrete is healthy and there is no risk of reinforcement steel damage [15]. By this method it is possible to inject with low or high pressures. As Fig. 4 shows, concrete must be drilled and packers must be placed across cracks thickness.

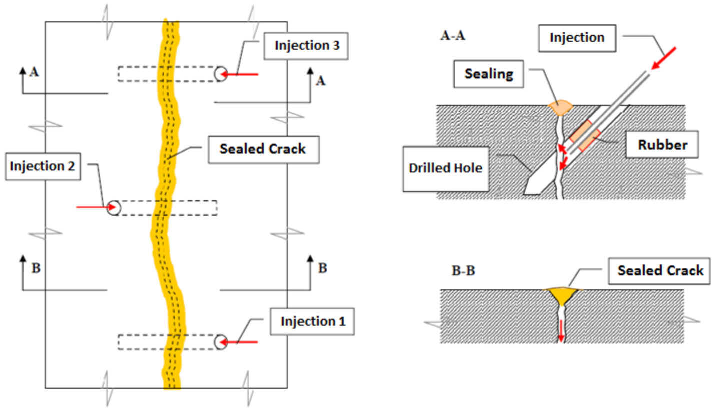

Fig. 4 – Injection with mechanical packers (adapted from [18])

The injection can be made by low or high pressure, however, this method is recommended for high pressure injections to ensure all voids filling.

In both methods, when injection material flows out of the second nozzle the packer valve should be closed as soon as possible, stopping the injection in the first nozzle and continuing it in the second one, repeating the procedure until the last injection. Injections in vertical cracks must be made upwards, and horizontal cracks injection should start a central hole and be toggled in contiguous holes, or split into two sections (one for each side of the centre hole).

4 Case study – Cracks repair in reinforced concrete tunnel

Firstly a survey of all structural anomalies was made and a mapping was produced with all of these anomalies characterization. The most significant anomalies found during inspection were: (i) widespread cracking in some parts of the structure over the tunnel sections and (ii) structures surfaces with damaged concrete with reinforcement steel exposed or hollow areas with signs of imminent delamination.

Regarding to the **cracks**, the existence of a few cracks due to structure movements and vibrations was diagnosed and generalized cracking origin by concrete shrinkage. Some cracking consequences were identified along the tunnel, which were under pressure water infiltration in through cracks and expansion joints, deposition of salts in areas with some water infiltration and moisture signals in some cracks.

The intervention started by concrete characterization (mechanical and physical characteristics), and water characterization (chemical characteristics). For each cracks type to be treated depending on cracks dimensions, water presence and structural requirements, the following procedures was defined: (i) dry cracks repaired by epoxy resin injections; (ii) cracks with water repaired by water-reactive polyurethane foam resin to stanch water flow; and (iii) acrylic flexible gel resin injection in wet cracks or joints, submitted to movements (variable thickness) and previous water passages, and in cracks with risk of occurrence of new water entering, previously injected with polyurethane foam resin.

By the fact of being a tunnel it was really hard to implement the works because one could only access the inside of the structure. For this reason, it was difficult to evaluate anomalies and their repair. In terms of quality of the intervention, part of the crack repair material could get lost to the ground in structure surrounding, not filling the expectable voids (tunnel cracks). The material quantity to inject in each cracking areas had to be estimated considering cracks with the same size throughout its length and with concrete element's depth. In fact, when only one side of the structure is accessible, it becomes impossible to be precise in cracks characterization, and it turns harder to repair them.

5 Concluding remarks

Since European standard EN1504 was published, all issues related to concrete repair and protection, including cracks and voids repair, have evolved quite significantly ensuring quality works with appropriate products for each type of interventions. It has been noted that a document that gathers all the information to promote proper repair and maintenance of concrete structures is really important. Now there is a single integrated document that covers all key issues related to concrete repair.

Injection systems with resins are the most common technology for cracks repair, because the injection process is simple and expeditious and resin materials characteristics provide solutions with quality assurance. Among the injection resin products, the most used over the past years are the epoxy ones. If it is necessary to restore structural rigidity, the use of epoxy resins is generally the most suitable. However, epoxies cannot effectively repair all cracking problems, depending on cracks characteristics and structure conditions. That is why the injection products development like polyurethane and acrylic resins was very important, providing solutions with materials with different properties and characteristics, to solve many problems which epoxy resin cannot solve.

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