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Abstract: In the present paper different external surface treatments published in the literature as preventive solutions for improving the performance of existing concrete constructions are presented and discussed. They are categorized as repair materials for concrete conservation, protection surface methods against moisture and aggressive agent penetration, injection techniques for crack sealing and preventive repair solutions with smart functionalities. In a final section, the most extended testing methods for evaluating the effectiveness of the different repair solutions are summarized depending on the property to be enhanced: moisture control and resistance against penetration of aggressive agents. The review shows that although several possibilities exist for the repair of the existing constructions, there is a lack of comparative analysis between the different methodologies. SARCOS COST Action stablishes as scientific objectives to carry out comparative studies including the most advanced solutions for the external repair of concrete, giving criteria for effectiveness assessment and defining robust and reliable methods for charactering the performance of the repaired structures.

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Dear Editor of Construction and Building Materials:

Within COST Action 15202, SARCOS, “Self-healing as preventive repair of concrete”, we have prepared a complete state of the art document including the reported literature about external methods for the preventive repair of concrete structures. As you can see from the submission, the collaboration between well-known researchers in different aspects related to the repair of concrete has allowed to develop the manuscript entitled “External treatments for the preventive repair of existing constructions: COST Action CA15202 framework”, by M. Sánchez, P. Faria, L. Ferrara, E. Horszczaruk, H.M. Jonkers, A. Kwiecień, J. Mosa, A. Peled, A.S. Pereira, D. Snoeck, M. Stefanidou, T. Stryszewska, B. Zając·

We are sure that the publication of this review in a high rank journal can be highly interesting for giving visibility to the Action while researchers have access to a very useful reference document for advancing in the development of new advanced external repair methods. Thus, we would really appreciate if you consider the present review manuscript for publication at Construction and Building Materials journal.

Kind regards,

Córdoba, 25th April 2018

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External treatments for the preventive repair of existing constructions: COST Action CA15202 framework

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Abstract

In the present paper different external surface treatments published in the literature as preventive solutions for improving the performance of existing concrete constructions are presented and discussed. They are categorized as repair materials for concrete conservation, protection surface methods against moisture and aggressive agent penetration, injection techniques for crack sealing and preventive repair solutions with smart functionalities. In a final section, the most extended testing methods for evaluating the effectiveness of the different repair solutions are summarized depending on the property to be enhanced: moisture control and resistance against penetration of aggressive agents. The review shows that although several possibilities exist for the repair of the existing constructions, there is a lack of comparative analysis between the different methodologies. SARCOS COST Action stablishes as scientific objectives to carry out comparative studies including the most advanced solutions for the external repair of concrete, giving criteria for effectiveness assessment and defining robust and reliable methods for charactering the performance of the repaired structures.

1. Definition of the problem: preventive repair for non-structural damages

The proper maintenance of a concrete structure is essential to guarantee the designed lifetime [1]. In existing structures, the ageing of the concrete cover and its interaction with the environment may result in the appearance of an incipient damage affecting the structure functionality and compromising its future performance. In these cases, in which self-healing approaches were not considered from the design stage, preventive repair should be the strategy for avoiding further structural damages, being the development of innovative strategies, even incorporating healing properties and new functionalities, the real challenge for the sustainable repair of structures already in service.

The correct understanding and diagnosis of the causes of concrete deterioration is of high importance to avoid incorrect repair specifications, to choose the appropriate repair products and techniques, and to implement durable repair strategies [2]. The European standard EN 1504 classifies the causes of defects into two main groups, distinguishing between the cover concrete degradation induced by mechanical, chemical or physical interactions, and the degradation of the reinforcement associated to corrosion processes due to concrete carbonation, the presence of chlorides at the rebar level and/or stray currents. Suitable repair solutions have been elaborated over the past years, resulting in different guidelines and standards, e.g. EN 1504: 2004/2013, ACI 562-16 or ACI 546R-14.

In EN 1504: 2004/2013 the repair methods are categorized depending on the functionalities to be recovered [3]. Depending on the different mechanisms for protecting the concrete surface, three approaches are distinguished:

1. Impregnation: oils, waxes, innovative systems.
2. Sealing: resins.
3. Coatings: acrylic resins, renders

Repair mortars and concretes are used for concrete restoration and for structural strengthening. External surface methods are proposed for the protection against the ingress of aggressive agents, for moisture control and for increasing the mechanical, physical and chemical resistance of the concrete cover. Concrete injection is proposed for crack sealing in order to guarantee protection against the penetration of aggressive agents and moisture and/or for structural strengthening.

A preventive and protective strategy, based on the identification of non-structural damages and on the actuation of early repair and remediation is highly recommended as a preventive solution for avoiding the evolution of damage into increasingly serious stages, with structural implications. These preventive repair solutions should focus on improving the durability-related performance of the structure, including, e.g., protection against the ingress of aggressive agents, resistance against frost damage, waterproofing ability, by external treatments applied on the whole surface and/or by injection of compatible products for crack sealing.

The following sections will provide a compilation of the existing external surface treatment methods published in the literature as preventive solutions to improve the performance of existing concrete constructions, according to the following framework:

1. Conservation of the damaged concrete by repair materials;
2. Protection against moisture and aggressive agent penetration;
3. Crack sealing by injection techniques;
4. Preventive repair solutions with smart functionalities.

2. Restoration of damaged concrete by repair materials

The European standard EN 1504-3:2006 specifies the requirements related to the identification, performance (including the durability of the materials) and safety of the products and systems to be used for the repair of concrete structures, distinguishing between structural and non-structural repair. Repair grouts, mortars and concretes are recommended for extending the service life of a concrete structure exhibiting deterioration. They can be also used in conjunction with other products and systems to restore and/or replace defective or contaminated concrete and to protect reinforcement.

Repair products (mortars and concretes) must be adapted to the quality of the existing concrete and are classified for each type of application, as high strength or high E-modulus and low strength or low E-modulus. Appropriate repair materials must be chosen, since incompatibilities between the repair material and the host concrete can lead to a premature failure, e.g. because of differential thermal expansion or shrinkage. Sufficient bond strength must be guaranteed in order to withstand the interface stresses induced by environmental and/or mechanical actions. As a matter of fact, the interface is usually a weak zone in repair systems, due to the differences in physical, chemical and electrochemical properties between the two materials [4-5]. Morgan [6] has schematized the requirements that patch repair mortars must meet to ensure structural compatibility with the concrete substrate (Figure 1).

<Figure 1>

In general, various constituents can be incorporated into repair mortars and concretes to provide them with signature properties. As examples, admixtures, polymeric and mineral additives, including nanomaterials [7] and waste materials [8], have been used to improve the interface strength. Moreover, the incorporation of organic compounds into the mix is widely adopted to improve the cohesiveness of the matrix [9].

2.1. Cementitious repair materials

Repair renders include a wide range of cement-based materials used for protecting the concrete substrate, being their thickness and quality the regulating factors of the level of protection provided to the substrate. For cementitious repair materials, cement hydration and microstructure play an important role on the mechanical properties of interfaces. The water content of the concrete substrate affects the bond strength of interfaces, interacting with cement hydration and microstructure development in the repair system, due to the moisture exchange between the repair material and the concrete substrate itself. Understanding the cement hydration and the microstructure of the interfaces is critical to “engineer” the bond strength and implement durable concrete repairs [4]. Generally, the cementitious repair materials analysed in this section are recommended for existing concrete subgrades characterized by a pull-off strength higher than 1.5 MPa.

2.2 Polymer-modified repair materials

Polymer-Modified Cementitious (PMC) mixtures are defined as hydraulic cement combined at the time of mixing with organic polymers that are dispersed or re-dispersed in water, with or without aggregates [10]. Coalescence of the polymer occurs as the cement hydrates, resulting in a co-matrix of hydrated cement and polymer film throughout the concrete. The improvement in the mechanical performance, flexural strength, bond strength, tensile strength and abrasion resistance of the modified repair material has been established [11], together with a decrease in the permeability and elastic modulus.

Organic polymers come in three forms: a) latex, which disperses in water, b) re-dispersible powder and c) liquid, which disperse or dissolve in water [12]. Because of the lower water retention guaranteed by the polymer addition, the water content in the concrete can be kept low, resulting in a reduction of the corrosion and environmental causes of damage to the concrete and leading to a higher durability and longer service life of the structure.

Several polymer-modified repair cementitious materials are widely available on the market. In EN 1504-4 it is recommended that failure should occur in the repaired concrete substrate, thus repair mortars must be stronger than the substrate. Polymer Repair Mortars are recommended for concrete substrates characterized by pull-off strength higher than 1.5 MPa (R3 class according to EN 1504-4). For repair of higher class concrete substrates, more robust repair materials are proposed [13]: Polymer-Cement Concrete (PCC) for subgrades characterized by pull-off strength higher than 2 MPa (R4 class according to EN 1504-4) or Polymer Concrete (PC), i.e. a concrete in which an organic compound serves as binder, for subgrades characterized by pull-off strength higher than 4 MPa. Anyway, this approach should be applied carefully, taking into consideration also thermal compatibility aspects. Improper choosing of the repair material may result in failure of the retrofitted structure and even significant consequences, e.g. application of too strong and stiff repair material on airfield pavement, thermally incompatible with the weak concrete of an old runway, as observed in Figure 2.

<Figure 2>

2.3 Geopolymers as repair materials

Geopolymers (GPC) can be considered as relatively new sustainable construction materials incorporating industrial wastes into their composition [14-16]. They are cement-free alternative materials produced by the chemical action between alumino-silicate materials such as fly ash, metakaolin and/or granulated blast furnace slag and an alkali activator, often a mixture of sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3) [16].

GPC are good repair materials for Portland cement concrete, because both materials feature comparable modulus of elasticity, Poisson's ratio and tensile strength [14, 17]. They can be implemented using the same equipment and practices as used for OPC concrete to repair deteriorated infrastructures [18]. Geopolymers currently employed for repair work in concrete structures have shown good bond strength [19] and other mechanical and durability properties, including high early strength, low porosity, elevated temperatures resistance and high performance in acid and sulphate environment [14]. Zhang et al. [20] have confirmed the potential of GPC as coating for marine concrete structures on the basis of their low permeability and excellent anticorrosion properties. The same authors have also reported the effective bonding with cement paste and mortar substrates [21, 22] due to the coexistence of C-S-H gels on cement and geopolymer surface [21]. Furthermore, GPC are permeable to vapour pressure and thus do not delaminate from the parent surface [23].

Although the cost for geopolymer preparation is slightly higher than that of OPC [24], Torgal et al. [25] has concluded that geopolymer mortars are as much as 7 times cheaper than the current commercial repair mortars.

2.4 High-Performance Fibre-Reinforced Cement-based Composites (HPFRCCs) for concrete repair

Since the sixties, fibre reinforced concrete has been intensively studied [26, 27] and several review papers on fibre reinforced cement-based composites can be found in literature [28-32]. Several materials can be used as fibre reinforcement ranging from natural fibres such as flax to steel fibres and polymeric ones such as polypropylene or polyvinyl alcohol. The homogeneous distribution of fibres into the mixture and the reduced plasticity of the fresh mixture when fibres are introduced need special care and design.

In the last decade or so, a peculiar category of fibre reinforced cementitious materials, known as high-performance fibre-reinforced cementitious composites (HPFRCC), has been developed. Their composition is characterized by the absence of coarse aggregates, a relatively large (around 2%) volume fraction of fibres (steel or synthetic amongst others), low water-binder ratio and high binder and fines (usually microsilica) content. This composition, developed on the basis of micromechanics concepts, results into superior fresh state performance, very high compressive strength, high modulus of elasticity and extremely low permeability that prevents the ingress of detrimental substances. Moreover, these materials feature a signature tensile behaviour characterized by tensile strain hardening response and multiple cracking with strain capacity as high as several %. This is due to the “bridging effect” of the dispersed fibre reinforcement, which, once a crack is formed, promotes a stress redistribution which makes the energy to continue the opening of the same crack higher than the one to form a new crack at another location, thus allowing to spread a single localized damage into multiple tiny hairline cracks. This contributes to increase the resistance of the material against environmental degradation and high mechanical loading even in the cracked state, thus making it a promising solution able to significantly improve structural resistance and durability of deteriorated concrete structures [33]. Two typical forms of HPFRCC are Engineered Cementitious Composite (ECC) [34] and Ultra-High-Performance Concrete (UHPC) [35], mainly differing in the matrix tensile and compressive strength. These are in the range of 150-200 MPa and 7-11 MPa for the latter, whereas values of 50 to 80 MPa and 3-5 MPa respectively have been reported for the former.

HPFRCCs have been effectively employed to retrofit existing concrete beams, columns, beam-column joints, panels, frames and walls, carrying higher or sustained loads (also cyclic) even in the presence of cracks [36-43]. Rheology and fresh state performance can be adapted for different placement and application techniques. Because of the inherent crack width limitation characteristics, a fibre reinforced mortar or concrete, mainly in the case of HPFRCCs with their signature mix composition, has improved autogenous self-healing properties [44-57] which provides additional benefits when using it as a self-healing repair system to be applied on an existing concrete subgrade.

Because of HPFRCC composition, their bond and compatibility with the concrete host is optimal. The material is also able to suppress the widening of an existing crack, which needs to be repaired. A further load increase may cause the crack to grow, but a clear kink-trap mechanism can be activated in the repair material, in case avoiding both spalling and delamination [58]. This was also modelled numerically and the modelling approach can be used to tailor the properties of the repair system for specific applications [59]. A comprehensive durability design framework can further aid in this approach [35, 60].

Fibre-reinforced cementitious composites have been also used as patch overlay in road works. The freeze/thaw resistance, traffic abrasion resistance [61] and fatigue life are considerably improved [62]. Applications have been reported as an overlay suitable for energy absorption in structural shear walls for seismic retrofit of R/C buildings [63] as well as in masonry buildings, increasing their earthquake resistance [64]. Furthermore, patch repair with HPFRCC can effectively suppress chloride penetration and prevent reinforcement corrosion [65-67].

The applications of strain-hardening cementitious composites are not limited to the repair of existing structures. In new structures with requirements of high energy absorption, large deformation capacity, crack width control and high impact resistance, this category of materials can be applied from the beginning. For example, the use of this category of materials in beam-column joints in frame structures, where plastic hinge development is expected because of deformation concentration, can contribute to enhance to joint response and the seismic performance of the structure as a whole [68].

2.5 Textile Reinforced Concrete (TRC) for concrete repair

A further category of HPFRCCs is known as Textile Reinforced Concrete (TRC). TRCs are distinguished by the continuity of their textile reinforcement which is usually a grid of multi-strand, arranged in two or more directions [69,70], instead of randomly dispersed discrete fibres. TRC can be used for repairing of concrete components by applying layers of impregnated textile (in a cementitious matrix) at the bottom or sides of the component, as well as confinement which can be obtained in wrapping of a whole component such as a column or other. A similar method can be used by impregnating the textile in a polymer-based matrix (FRP) rather than cement-based and then applied it on the concrete substrate, but TRC includes inherent benefits such as greater compatibility with the concrete substrate. Generally, applying the TRC layers to a damaged/cracked concrete component improved its performance in two ways, (1) protection against environmental effects which have led to corrosion processes, and (2) mechanical strengthening. The strengthening mechanisms can relate to shear, tension/flexural behaviour and compression. The bonding of the TRC reinforcement to the concrete surface is of prime importance in controlling its reinforcing efficiency. Several bonding methods between the TRC repaired/strengthened layer and the concrete component are reported: interfacial bonding, using bonding agent such as epoxy resin or polymer modified cement, applying sand blasting on the concrete component surface or the textile itself before employing the TRC, as well as by mechanical anchoring [71-75].

An important parameter that highly affects the TRC repairing and strengthening efficiency is the number of the textile layers, the reinforcement effect is significant increases with monotonously increases of the number of layers of the textile reinforcement, which provide significant increase in the mechanical performance of the repaired/strengthen concrete component [74-76]. Furthermore, for confinement arrangement, the geometry of the concrete substrate is highly influences the reinforcing efficiency of the TRC layer, in column (for example) as the shape is becoming more circular, the reinforcing efficiency of the TRC increases significantly [76, 77].

Different types of textiles can be used having high performance such as carbon, glass and aramid as well as low performance which can be of polypropylene (PP) or polyethylene (PE). When mechanical strengthening of pre-damaged column concrete is considered, all yarn materials can restore the compressive strength of the original concrete component (before damaged) and even provide additional benefits if confinement is the case. However, the additional benefit is dependent on yarn strength, the greatest is its strength the higher is the benefit to the original concrete strength, i.e., its repairing efficiency [78]. Also, for beams when subjected to bending condition either under static or dynamic loadings greatest strength and modulus of elasticity fabrics provide higher reinforcing efficiency [79, 80].

A real example of TRC application for strengthening repair of a damaged steel reinforced concrete hypershell can be found in Mechtcherine [31] and a summary of other existing cases in [32, 69, 70].

3. Protection against moisture and aggressive agent penetration

As the interaction of concrete with the environment occurs through the concrete cover, improving the performance and the quality of the concrete surface layer appears as an interesting and cost-viable solution to protect concrete constructions. Recently Pan et al. have published a comprehensive review about the surface treatments for concrete protection [81, 82]. Different solutions have been proposed depending on the functionality to be improved: hydrophobic treatments when moisture control is required; surface coatings forming a physical barrier to prevent penetration of aggressive agents; pore-blocking surface treatments to increase the impermeability of the concrete surface.

The most common application techniques of the external surface treatments are by immersion, brushing and spraying. Immersion is often the laboratory technique of choice, since it is easily controlled and effective, but in situ quite often it cannot or can only partially be applied. Brushing is a slow technique which usually needs multiple applications even if the first one is considered the most important [82]. Spraying is easily performed in situ, allowing the treatment of large surfaces in affordable times.

Both the composition and nature of the surface treatment agents and the condition of the substrate are of paramount importance for the effectiveness and durability of the external surface treatments. Concerning the chemical composition of the treatment agents, both organic and inorganic compounds have been commonly used. Organic agents are highly protective but they feature limited service life and are susceptible to easy detachment [83]. Different silicates have been proposed as inorganic agents for concrete surface treatments with sodium silicate solution being the most common [84]. Concerning the conditions of the substrate, the roughness, the existing porosity and the moisture content are the most relevant parameters that should be taken into account. Dust and water droplets may prevent the penetration of the treatment agents while surface roughness can influence the adhesion of coatings.

Several properties are tested in order to evaluate the effectiveness of the surface treatment on the concrete: physical properties (porosity and pore size distribution, absorption, capillarity, water permeability), chemical properties (resistance against carbonation and chloride penetration) and mechanical properties from the nano- to the macro-scale (abrasion resistance, flexure, compression, hardness).

3.1. Waterproofing treatments

Impregnating the concrete surface with hydrophobic materials able to penetrate through concrete pores is an effective solution for improving the performance of concrete against ingress of water. This type of treatment is based on the application of silanes and/or siloxanes on the concrete surface. The composition and the structure of the molecule define the penetration depth and durability of the treatment and hence the obtainable degree of hydrophobicity of the treated water-repellent surface [81].

It has been established that hydrophobic impregnation treatments decrease the internal humidity in concrete and suppress the capillary water absorption [85] but allows vapour exchange enabling the concrete to “breathe” freely [86]. The effectiveness of water-repellent agents against chloride penetration has also been reported [85-87], even in the case of cracked reinforced concrete [87]. Recently, Muhammad et al. [88] have published a critical review on the waterproof performance of concrete including a quite complete scheme with the different tests used for the evaluation of waterproof efficiency of several waterproof approaches and considering different variables. Ferrara and Pattarini [89] have also tried to add a siloxane compound directly in the mix, obtaining as high water repellent characteristics as with the use of a conventional surface treatment, most likely because the siloxane molecules in the pores act on the capillary surface tension.

Currently, a new trend for water-repellent treatments based on applying waterborne silane-based hydrophobic agents (micro-emulsions) on the concrete surface appears as a promising alternative for improving the durable performance of concrete [90]. Silane/siloxane emulsions have been also applied for increasing the thermal efficiency of the building envelope without compromising the aesthetics or functionality [91]. Furthermore, the addition of nano-sized titanium and zinc oxides to the water-repellent surface treatment agents has also been reported to improve the performance of silane/siloxane oil/water emulsions. As a matter of fact, the employed nanoxides do not only act as effective emulsion stabilizers but also incorporate added-functionalities, such as photocatalytic activity [92] or biofouling resistance [93].

3.2.Treatments for sealing the concrete surface

Pore blocking surface treatments increase the hardness and impermeability of the concrete surface layer while blocking the capillary pores [94, 95]. The most common sealant agent is sodium silicate [96] although no agreement can be found in the literature concerning its effectiveness. Pan et al. [97] have confirmed the effectiveness of both sodium silicate and fluorosilicate in reducing the air permeability of concrete, measuring penetration depths up to 5 mm. However, Ibrahim et al. [98] have compared the performance of different of surface treatment materials for improving the resistance of concrete against sulphate attack, carbonation and chloride diffusion, obtaining the worst protection for the sodium silicate treatment. Dai et al. [88] have also reported that sodium silicate-based pore blockers do not prevent water absorption and chloride penetration. Moon et al. [99] have proposed the application of a more complex surface-treatment system consisting of an inorganic coating based on calcium silicate compound after the prime coating with sodium silicate.

4. Crack sealing by injection techniques

The European standard EN 1504-5 specifies requirements and conformity criteria of injection products for repair and protection of concrete structures. Injection is applied for filling cracks, voids and interstices in concrete for deformability, load transfer capacity and tightness. A concrete injection can be carried out both with non-structural (to achieve water-tightness and to avoid penetration of aggressive agents) and with structural (to strengthen the surface) objectives.

The injection of cracks can be carried out by gravity, injecting the material into a crack with a width of approximately 0.3 mm under its own weight or by a capillary suction process. This method is used in the repair of shallow surface defects and corrosion protection of reinforcing bars located near the surface of the element. The sealant can be also injected by applying pressure using packers or injectors, from low pressure (less than 0.15 MPa), in the case of inability to drill holes in the material under the injection tips, to high pressure (above 0.80 MPa) for thicker parts with fine scratches less than 0.2 mm wide. As an alternative, vacuum injection has been employed that uses the vacuum created by the vacuum generator [100]. Detail information about application methods are provided by industrial companies.

4.1.Cementitious grouts

Cement slurries have been long used as injection materials because of their good compressive strength and their high compatibility with the concrete. Their modern modifications are slurries of microcement with particle size between 2 to 16 microns, and more than 95% of the particles with a size less than 12 microns [101]. Due to the small grain size, these slurries have good penetration characteristics, which allow filling of very small voids, and significantly higher reactivity. A common method for improving the strength of cracked brittle materials is also injecting preparations containing colloidal nanoparticles of calcium hydroxide with size from 50 to 300 nm [101, 102]. The reaction of water and carbon dioxide with calcium hydroxide is followed by the crystallization of calcium carbonate, transforming to a stable calcite after 28 days and creating new intergranular connections [103]. Nano-SiO_2 can be also used for injection, both as an additive to cement slurries and in a suspension form, by a low-pressure injection procedure [104].

4.2.Polymers

Injection materials with organic origin, such as epoxies [105, 106], polyurethanes [107] acrylics and acrylamides have been also proposed as crack sealants [108]. The low flexibility and the high strength of epoxies make them as the most effective materials (filling scratches) for load-bearing constructions because they recover the initial surface strength that previously reduced by e.g. shrinkage. One- and two-component polyurethanes have lower stiffness and are able to bond in the presence of water. They can be placed on damp or even wet materials and then form a strong foam, which facilitates the obstruction of water. Polyurethane injections feature a better compatibility with concrete substrates if applied under high temperatures [107] as they do not generate high stress under temperature increase (as epoxies) when filling cracks because of their low stiffness. The group of acrylic resins based on methyl methacrylate presents a very good adhesion with concrete and may control the rate of hardening reaction. Due to their low viscosity, they have the ability to penetrate microcracks. The combination of organic/mineral materials favours the compatibility of the filling material with the mineral substrate.

4.3.Electrodeposition

Another technique for filling cracks is the electrodeposition method [109] which has been mainly applied to off shore structures. Electrodeposition methods aim not only at filling the cracks but also at coating the concrete surface providing a physical protection layer to the concrete and preventing the entrance of aggressive agents. Under the action of an electric current between the rebar acting as cathode and an external anode located under seawater the formation of electrodeposits that fill the crack is activated [110, 111]. In Figure 3 the set-up for the treatment application is schemed.

<Figure 3>

Applying electrodeposition methods for rehabilitation of cracked concrete structures on shore requires the selection of appropriate external solutions to promote the formation of electrodeposits. The investigations are based on stable solutions, i.e. not strongly acidic electrolytic solutions. The effectiveness of the treatment depends on the external electrolytic solution, as the deposits can just cover the crack or they can penetrate and fill the crack, as in the case of $MgCl_2$ and $ZnSO_4$. Also the nature of the applied current, direct or alternate, has been reported to be a significant factor influencing the effectiveness of the electrodeposition treatments [112].

Permeability tests on electrodeposited specimens using these electrolytes [110] have shown that electrodeposits promote the closure of the mortar crack and the refinement of the mortar surface, decrease the permeability of the treated specimens and improve the concrete water-tightness [113]. The electrodeposition treatment has been reported to be effective for the rehabilitation of reinforced concrete specimens cracked by chloride attack, reducing the chloride concentration in concrete and promoting the reinforcement re-passivation [114].

Recently, Hongquang et al. [112] have proposed four indexes for evaluating the healing effect of electrochemical methods applied for repair of concrete cracks: the rate of weight gain, the rate of surface coating, the rate of crack closure and the crack filling depth.

5. Preventive repair solutions with smart functionalities

The development of new cementitious-based composites, incorporating advanced properties and functionalities, also provides new challenges in the field of repair and retrofitting of existing concrete constructions. Nowadays, the search of multifunctional solutions, able to seal concrete pores with waterproof abilities, even combining smart functions such as healing abilities, self-cleaning properties, bactericidal action… open a highly promising new field of the research for improving not only the durability but also the functionality of constructions already in service.

5.1.Surface treatments with healing properties

Recently, surface treatments employing nano-composite coatings have attracted the interest of many researchers, because of the ability of this kind of materials to penetrate through the concrete cracks and pores, down to very small sizes, and potentially refine the pore structure and heal the cracks due to their high reactivity. Polymer nano-composites with improved properties (high strength, abrasion resistance, super-hydrophobicity, thermal stability and reduced degradation) have been tested [81, 82]. Addition of nano-CaO in cement renders provided satisfactory results in relation to the pore healing according to Stefanidou and Tsardaka [115], as can be observed in Figure 4.

<Figure 4>

Nano-SiO_2 surface treatments are totally compatible with the cementitious substrate and capable to incorporate in the cementitious matrix [116]. Nanosilane-clay composites as surface treatment agents appears as a new class of surface treatment materials able to change the microstructure of the concrete surface, improving its resistance against chloride entrance, while showing waterproof properties [117].

Surface treatments with colloidal nanosilica have been also reported to improve the performance of the treated concrete against the chloride penetration by blocking capillary pores of about 0.1 µm [118]. Moreover, they have also proved being effective in guaranteeing a compact microstructure due to their filler effect and pozzolanic reactivity [119]. The application of an electrical field, similar to the case of electrochemical repair methods [120, 121], has been proposed by different authors as an alternative for accelerating and improving the penetration of the nanoparticles by migration under the action of the electric current [117, 123, 124].

Surface treatments based on the penetration of TEOS, the colloidal penetration precursor through the concrete pores are also proposed for effectively improving the quality of concrete surfaces [124-126]. TEOS penetrates though the concrete pores, and hydrolyses forming silanol and ethanol, thus favouring the precipitation of silica gel inside the pores [126]. TEOS also reacts with calcium hydroxide due to its pozzolanic nature [127], promoting a more refined pore distribution and then, improving the imperviousness of the treated concrete.

5.2.Surface treatments with self-healing ability: biomineralization

5.2.1 Microbially-induced calcium-carbonate precipitation

Innovative solutions based on biomineralization with self-healing functionalities have been used in the production and protection of cement-based materials employed as preventive repair of concrete. Both bioformulation (biocementation) or biotreatment (biodeposition) of concrete have been studied: respectively when a bioproduct is used as a component to produce concrete or when a bioproduct is applied as surface treatment of old concrete. The use of Microbially-Induced Calcium-Carbonate Precipitation (MICCP) has been the focus of several studies on concrete [127, 128]. It can be considered as a surface-controlled coating system with limited penetration of bacteria in the cementitious matrix. This application is also used as protection of ornamental or masonry stone by a microbially deposited carbonate layer to prevent degradation and as consolidant [129,130]. The biodeposition treatment on a cementitious material led to a higher freeze/thawing resistance, improved surface strength and lower permeability [129, 131-135].

Figure 5 presents the biodeposition of calcium carbonate crystals in presence of calcium acetate as calcium source for the bacteria activation.

<Figure 5>

5.2.2 Iron-based bioproducts

Achal et al. [136] have reported the use of surface treatments alternative to MICCP, employing industrial by products, which resulted in comparable performance but at more affordable prices. Moreover, these treatments, unlike the MICCP, do not produce urease [136]. The importance of formulating and employing cost-effective and sustainable bioproducts and applying techniques for large-scale *in situ* applications on concrete structures is remarkable [137] because of the large use of concrete.

In this framework, innovative less expensive solutions have been studied with reference to other construction materials and soils. A technology employing iron-based bioproducts - iron mineralization through iron-oxide precipitation has been investigated by Ivanov et al. [138, 139] for soil improvement. Two different bioproducts have been used: an iron-based bioproduct and a calcium-carbonate precipitating bioproduct as control. The control bioproduct consisted on calcium-chloride, urea and urease-producing bacteria, while the iron-based bioproduct consisted on iron-reducing bacteria with iron ore and organic waste [138]. The compressive strength and water permeability of biotreated soil samples have been measured. Despite the iron-based biotreated samples could not achieve compressive strengths as high as the calcium-based biotreated samples, water permeability was significantly reduced. It has been also observed that the precipitate from the iron-based biotreatment has a gel-like form, whereas the calcium-based biotreatment precipitate has a crystal-like form, which could result into an easier clogging of the soil.

Several iron-based bioproducts have been applied as surface treatment of an earth plaster [140] providing improved resistance to water ingress. It is worth remarking that when an iron-based bioproduct was used as kneading water to bioformulate the earth plastering mortar it strongly affected the mortar workability, similarly to an air entraining agent.

As for calcium-carbonate, good results may be achieved with an iron-based bioproduct applied on cementitious material subgrades. As a matter of fact, this technique has two features that must be taken into account: the colour of iron-oxide bioproducts, which may jeopardize its acceptability with reference to the resulting appearance and aesthetics of the concrete, and the interaction with the steel reinforcement in steel-reinforced concrete structural elements. Ivanov et al. [141] highlighted that typical pH values that can be created by these processes range from 8.3 to 9.5. Therefore, the possible negative effects of the application of iron-based bioformulation on reinforced concrete also need to be carefully studied and, in case, the through-thickness reach of the biotreatment, with reference to the position of the steel reinforcement, needs to be carefully controlled.

It is also worth remarking that an eventual slight colour change on the surface of biotreated concrete, as produced by an iron-based biotreatment, may even be positive for colour reintegration of a recently cleaned old concrete surface.

The use of iron-reducing bacterial cells is one of the most inexpensive ways to produce iron-based bioproducts. Ivanov et al. [138] used EDTA, even if many other ferric chelators may be chosen from the group of aminopolycarboxylates [142], or from the group of phosphonates [143]. The worldwide production of aminopolycarboxylates and phosphonates sums up to several hundred thousand tons [138]. Therefore, these chemicals are readily available for the production of iron-based bioproducts. Another way to diminish the cost of iron chelates for bioproducts could be the production of the solution of dissolved ferrous chelates at neutral pH using cheap iron ore, organic waste materials, and iron-reducing bacteria [141]. Therefore, iron-based bioproducts can be a competitive low cost solution for biotreatments.

5.2.3 Polymers-based bioproducts

Within a Short Term Scientific Mission performed in the framework of Cost Action 15202 - SARCOS, in parallel with different iron-based bioproducts, also different bioproducts based on polymers from biomass grown with biodiesel waste have been produced and applied for surface biotreatment of different construction materials. These include earth plaster, adobe brick, compressed earth blocks (CEB), fired brick, calcareous stone, air lime mortar and cement mortar [144]. It can be observed that iron-based biotreatment slightly changes the colour of cement mortars (Figure 6-Left) while no colour change occurred with the polymer-based biotreatment. Nevertheless, this can depend on the bioproduct polymer concentration and the porous structure of the material: higher concentration on low porous materials may induce colour change. Moreover, the time for absorption of a water drop (Figure 6-Right) increases of up to 10-12 times for cement mortars, air lime mortars and calcareous stone with one biotreatment; a time increase of up to 14-17 times has been recorded for CEB, brick and adobe. For instance, the biotreated cement mortar takes 37 seconds to absorb the water drop in comparison to 3 seconds of the untreated cement mortar.

<Figure 6>

As for iron-based bioproducts, polymers-based bioproducts formulated from by-products and wastes also allow the production of low expensive and eco-friendly self-healing surface-protection products for construction materials, particularly for cement based ones.

For the time being it can be stated that not only the bioproduct but also the biotreatment techniques and the bioformulation procedures play a fundamental role. In fact, the biologic nature of the bioproducts can impact on their storage, distribution and life cycle since their microbial and macromolecular activities depend on several factors, including temperature, pH, availability of nutrients (concentration and diffusion rates).

5.3.Surface treatments with self-cleaning and bacteriological properties

The use waste glass cullet in repair mortars for high mechanical properties and bacteriological resistance is a highly interesting possibility to be exploited, e.g., for clean rooms in hospitals and in various branches of industrial production. Cement mortars treated with a non-recyclable glass cullet as a replacement of fine quartz aggregates in the range of 25 to 100% have been proposed to this purpose. In addition, nanosilica and titanium dioxide, which are widely commercially available, have been also used in combination with glass cullets to optimize the mix composition to the target performance requirements [145].

Nanosilica, due to its high pozzolanic activity and nanofiller effect, improves the bond between the waste glass and the cement paste resulting in improved properties of cement mortars. It has been observed that sand can be successfully replaced up to 100% with brown-soda waste glass (to obtain similar mechanical properties) while optimum amount of nanosilica is incorporated [146-148].

Nano-TiO_2 is a low-cost material exhibiting photocatalytic, self-cleaning and antifogging properties [149-151] which has been already employed in coatings, paints, rendering and plastering mortars or concretes in façades exposed to highly polluted environment [149, 150]. In addition, there is a great amount of research confirming its potential application in self-cleaning cement mortars and concretes [152, 153] and promising results were obtained for cement mortar with glass cullet in the form of aggregate. Incorporation of waste glass as an aggregate in cement mortars containing cement modified with nano-crystalline titanium dioxide can improve the bactericidal properties of cement mortars against Gram-negative coliforms. Moreover, the presence of nanosilica contributes to the pore structure refinement that increases the specific pore surface area, which is favourable for bacteria removal [146], as can be observed from Figure 7.

<Figure 7>

Experimental investigation [154] also has showed that the presence of waste glass fine aggregate significantly decreased the thermal conductivity of the cement mortars and that, furthermore, the sorptivity coefficient decreased. Additionally, the incorporation of nanosilica (especially in higher contents – 3 %wt) leads to a further decrement in thermal conductivity and sorptivity and improves compressive strength [154].

5.4.Mechanical closing of micro-cracks in concrete

Non-structural and structural repair of concrete can be also accomplished through pre- or post-tensioning of high strength steel wires or fibre reinforced composites. Compressive stress introduced in concrete by tensioning causes mechanical closing of micro-cracks, being as advantageous as injection.

Structural repair of concrete can be realized not only by repair mortars and concretes characterized by high and medium stiffness (E-modulus > 1 GPa) and low deformability (ultimate strain < 1%), but also by Polymer Flexible Joints (PFJ) characterized by very low stiffness (E-modulus < 1 GPa, even reaching the value of 1 MPa) and high deformability (ultimate strain > 1%, even up to 500%). This bonding element is able to recover the initial load capacity in cracked concrete structure by reduction of stress concentration and stress redistribution, despite the weakened area around the crack. Micro-cracks around the main crack are closed by the PFJ, when the flexible polymer repair is applied [155, 156]. Closing of micro-cracks in cracked concrete has been presented by Zdanowicz et al. [157, 158], using Digital Image Correlation (DIC) method [159] applied to a tensioned and damaged concrete element repaired by PFJ. Obtained maps of strain distribution highlighted strain concentrations appearing in concrete just before damage. For the same ultimate load level, lower strains were observed (closing of micro-cracks) in the same element repaired by PFJ, caused by strain redistribution (see Figure 8).

<Figure 8>

Also the use of superelastic shape memory alloys (SMAs) for closing cracks has been proposed [160]. Malagasi et al. [161] have developed an overall nonlinear model for the analysis of reinforced concrete beams with SMA acturators for cracks repair, validating the numerical results with experimental tests concerning smart concrete beams subjected to three-point bending tests.

6. Experimental evaluation of the external repair performance

The effectiveness of the preventive repair operations will depend both on the interaction between the surface treatment and the treated surface and on the interaction of the external treatment with the environment. Thus, in order to guarantee the required service life improvement for a repaired construction it is important to characterize not only the enhancement on the properties of the treated existing concrete but also the ageing and durability of the treatment itself [82].

The extended catalogue of the surface treatments presented in the sections above makes highly difficult to propose common criteria for assessing the effectiveness of the external preventive repair in a comparative way. The interaction between the treated substrate and the surface treatment will depend on several parameters, including the state of the concrete surface before the treatment application, the method for applying the treatment, the thickness of the protective coating/layer.

Considering the concept of external preventive repair, non-structural damage is expected. Thus, the improvement of the structure functionalities is mostly based on durability aspects such as moisture control, resistance against aggressive agent penetration and freezing-thawing resistance. In the following section the main testing methods proposed in the literature for assessing the effectiveness of surface treatments in improving concrete performance concerning such properties is summarized.

6.1 Moisture control

The parameter most commonly employed for characterizing the water penetration resistance is the capillary water absorption coefficients. In the literature, different methods are described for assessing the effectiveness of external surface methods, often based on standards (EN ISO 15148, EN 1062-3, EN 15801, UNI 10859, DIN 52617/87, ASTM C1585-13). A comparative quantification between the different studies is quite difficult as many significant experimental parameters will affect the results. Almusallam et al. [162] have comparatively evaluated the performance of five different surface coatings by measuring the % weight gain of concrete specimens. Only the treated face was in contact with water. The specimens were weighted at periodic intervals up to 56 hours testing, and the rate of water absorption and the sorptivity were evaluated. These variables have been also employed by Medeiros et al. [85, 86] to evaluate effectiveness of different types of coatings by using the standard DIN 52617/87, considering different testing times: 96 hours for the assessment of hydrophobic surface treatments and 16 days for the comparative evaluation of several types of coatings. Only the circular treated base surface of the cylinder specimens was exposed to water contact.

Other authors base the evaluation of the water capillary resistance on the water uptake giving it as a weight gain percentage. Franzoni et al. [163] have made reference to the Italian standard UNI 7699:2005 for assessing the effectiveness of impregnation and electrochemical methods as protective surface treatments, and the performance of ethyl silicate for surface protection of concrete [124]. The same authors have also evaluated the water capillary uptake of concrete specimens after treating the concrete surface with ethyl silicate [126] by immersing the treated concrete face, originally in surface-dry conditions, into a 3-5 mm layer of deionized water, and weighting at different times between 4 minutes and 24 hours. Diamanti et al. [164] have used the percentage of weight increase for evaluating the effectiveness of polymer-modified cementitious coatings.

Jia et al. [165] have evaluated the water absorption resistance in concrete specimens after inorganic surface treatments estimating the water absorption from the difference of weight between the saturated and the oven-dried (105°C until constant weight) specimen. These authors also proposed a relation between the permeability index, estimated under pressure conditions using the Autoclam Permeability measurements [166], and the water capillary absorption.

Hou et al. [167] have proposed using the “wet-cup” method to evaluate the breathability of surface treatments based on nano-SiO_2 penetration. Medeiros et al. [168] have used the standard ASTM C642/97 for investigating if surface hydrophobic agents based on silanes and siloxanes prevent water from leaving the concrete. In this case the treated sample was exposed to controlled environmental conditions (70 ± 3% RH, 21±2 ºC) and the drying loss of water was registered for 60 hours. Diamanti et al. [165] have measured the water vapour permeability of polymer-modified cementitious coatings applying according to the standard ASTM E96.

6.2 Resistance against aggressive agent penetration

In general, the penetration of aggressive agents through the concrete pores is a slow process that requires development of accelerated test methods for assessing the performance in acceptable periods of time [169]. This situation is even more accentuated in the case of concrete protected by surface treatments, as reflected by the studies found in the literature for evaluating the effectiveness of different surface treatments against penetration of chlorides, sulphate attack and carbonation of concrete cover carbonation, which are mainly based on accelerated exposure conditions.

6.2.1 Chloride permeability

The rapid chloride penetration test (RCPT), based on the standard ASTM C1202-97, has been extensively used for evaluating the related effectiveness of surface treatments. The method is based on applying a voltage between the two faces of a sample located in a diffusion cell. The non-treated face is in contact with a chloride-free alkaline solution, connected as anode, and the treated face is in contact with a sodium chloride solution, connected as cathode to force the transport of the chloride ions. The current passed through the system during a known period of time is registered; this charge is used as the criteria for evaluating the performance of the treated concrete surface against the chloride penetration.

Several authors have applied the RCPT method to assess the effectiveness of silane-based water repellents, applying a voltage of 60 V_{DC} maintained between the two sides during 6 hours [170-172]. Medeiros et al. [168] have used the RCPT methods for evaluating the effectiveness of silicate-based treatments by applying 12 V_{DC} between both sides of the concrete and analysing periodically the chloride content of the electrolyte connected as anode until a steady-state situation is reached, and the chloride diffusion coefficient can be estimated from the Nernst-Planck equation. The experimental set-up proposed has been included in Figure 9.

<Figure 9>

Also natural methods for evaluating the permeability of surface-treated concrete have been proposed, considering the diffusion of chlorides through thin slices of concrete in order to reach a steady-state situation along an acceptable periods of time (some weeks). The effective chloride diffusion coefficient was estimated from the 1st Fick's Law as the quantitative parameter for evaluating the performance of the surface treatments against the chloride penetration. Franzoni et al. [124] have assessed the effectiveness of several inorganic surface coatings against the chloride penetration through the immersion of the specimens in a 10% NaCl aqueous solution for 7 and 40 days. As can be observed from Figure 10, they measure the chloride penetration depth splitting the sample and spraying an $AgNO_3$ solution of the fresh faces.

<Figure 10>

Diamanti et al. [164] have evaluated the effectiveness of polymer-modified cementitious coatings testing the treated concrete in a diffusion cell with a free-chloride solution in one side and a 0.5 M NaCl solution in the other. Analysing the increase of chloride with time in the free-chloride solution until reaching the steady-state, the nominal chloride diffusion coefficient can be estimated. The schemed set-up for the testing of chloride diffusion proposed by [164] is represented in Figure 11.

<Figure 11>

6.2.3 Carbonation

Methods for assessing performance of treated surfaces against carbonation also often propose accelerated testing conditions, favouring the kinetics for the carbonation reaction occurs. Aguiar et al. [173] have evaluated the carbonation resistance of different protection systems using the Portuguese specification LNEC E391, based on creating an accelerated carbonation environment (65% RH, 20ºC and 5% CO2) for 7, 14 and 28 days. Zhu et al. [170] used RILEM recommendations CPC-18 to assess the carbonation resistance of concrete treated with silane-based water repellent exposed to an environment with 4% CO_2 for 112 days.

The part common to the different studies was the method for evaluating the carbonation depth by slicing the sample in two halves, spraying phenolphthalein on the fresh surface and measuring the thickness of the non-coloured part.

Park et al. [174] have created a high-concentrated environment with 20% CO_2 for the exposure of concrete treated with different types of coatings. They performed the carbonation experiment all along 48 weeks, and determined the permeation and diffusion coefficients using a high-vacuum differential pressure method with a mass spectrometer as a detector. A scheme of the experimental arrangement is represented in Figure 12.

<Figure 12>

6.2.3 Sulphates

Surface treatment systems have been proposed for improving the resistance of concrete against the sulphate attack that often appears in wastewater collection and treatment systems [82].

Aguiar et al. [175] have used the ASTM Standard C88-99a for assessing the performance against of sulphate attack of different surface protections. The method is based in 8 cycles each one consisting in 16-18 hours of immersion in a sodium sulphate solution, 15 minutes draining and finally a drying period in oven until constant weight. The resistance to sulphates attack was evaluated by calculation the weight variation along the cycles.

Vipulanandan and Liu [176] have evaluated the chemical resistance against sulphate attack of an epoxy coating reinforced with glass-fiber mats using the holiday test (ASTM G20-88). The specimens are immersed in a 3% sulphuric acid solution to half the specimen height, exposing the specimen both to the liquid and vapour phase. The sulphate attack is evaluated by monitoring the changes in weight and appearance at regular intervals. Suleiman et al. [177] have evaluated the protective ability against sulphate attack of 4 types of surface treatment materials. Coated samples were partially immersed in a 5% sodium sulphate solution and placed inside a walk-in environmental chamber with cycling temperature and relative humidity.

De Muynck et al. [178] have proposed an antimicrobial concrete based on polymer fibers and metal zeolites for controlling the biogenic sulphuric acid (BSA) corrosion of concrete. They propose a chemical exposure test for assessing the effectiveness of the antimicrobial concrete. The method uses a testing apparatus for Accelerated Degradation Testing (TAD) based on cycles consisting of immersion in a 0.5% H_2SO_4 solution, followed by drying by air and brushing the surface at the end, as can be observed from Figure 13.

<Figure 13>

6.2.4 Resistance against freeze and thaw cycles.

The effectiveness of surface treatments in improving the concrete performance against the freeze and thaw action has been often assessed under accelerated conditions. Several cycling protocols have been proposed in the literature, with different temperatures for amplitude and duration of the cycles. This makes it difficult to establish a quantitative comparison between different studies. The damage monitoring and rating has been generally carried out through changes in the sample mass along the cycles and by visual inspection.

Basheer and Cleland [179] have evaluated the effectiveness of pore liners in improving the concrete response against freeze and thaw by applying two different accelerated tests, based on the protocols proposed in ASTM C666 Procedure A test and in RILEM recommendations [180]. The progress of deterioration was monitored by visual inspection and rating on a scale of 0–5, 0 being no damage and 5 being total breakdown, as have been represented in Figure 14.

<Figure 14>

Liu and Hansen [181] have also used the RILEM recommendation [182] for evaluating the effect of silanes on the freeze-thaw durability of concrete. Dang et al. [183] have proposed a test protocol that simulates salt-scaling of the field concrete under accelerated conditions for assessing the performance of several surface treatments in protecting against freeze and thaw cycles. They exposed the treated samples to a 3% wt NaCl solution making 15 cycles of freeze/thaw in wet/dry conditions, and periodically evaluated the mass change for evaluating the effectiveness of the different treatments.

Summary

A comprehensive overview of the different technologies employed to repair non-structural flaws in concrete structures and the main methods used to characterize their efficiency in improving the performance of the damaged concrete has been provided in the present paper through an extensive analysis of bibliographic references.

A careful selection of a repair product is important to guarantee the compatibility with the substrate as well as the bond strength. Several materials, such as cementitious mortars, polymer-modified compounds, geopolymers or HPFRCCs have been reported for repairing the damaged concrete. Looking for advanced materials, more durable and even incorporating signature properties is the challenge for the most recent research in this area.

Concerning the surface treatments for the concrete protection against moisture and aggressive penetration, the current trend is the development of multifunctional solutions, able to seal the cracks incorporating waterproofing properties at the same time, and even including smart functionalities such as healing ability, self-cleaning properties or bacteriological nature. For example, mutating Microbial Induced Calcium Carbonate Precipitation from concrete self-healing technologies, innovative solutions have been proposed also for preventive repair using bioproducts based on wastes or by-products, in order to find more eco(economic)-eco(ecological)-efficient alternatives.

Innovation in the field of injection of cracks appear both in the development of new materials with enhanced performance, but also in the implementation of more effective application methods, such as injections under vacuum, application of electric fields for promoting electrodeposition of precipitates inside the crack, or methods for promoting the mechanical closing of micro-cracks.

The effectiveness of the different external surface methods applied for the preventive repair of damaged concrete has been evaluated through several characterization techniques, depending of the parameter to be improved. The assessment of different durability aspects has been addressed in the literature, such as the moisture control, the resistance against aggressive agent penetration and the freezing-thawing resistance. However, it is difficult to make a comparative analysis from the different results as many times different testing methods are used. And, even when the same testing methods is applied, the experimental conditions can be different. In this sense, the development of more standardized studies, with common criteria for the testing development, appears as a need.

In this context, SARCOS COST stablishes as scientific objectives to carry out comparative studies including the most advanced solutions for the external repair of concrete, giving criteria for effectiveness assessment and defining robust and reliable methods for characterizing the performance of the repaired structures.

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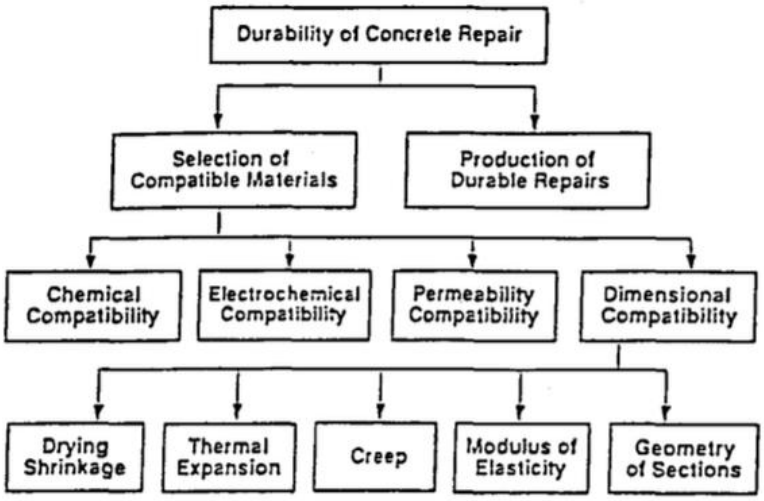

Figure 1. Factors affecting durability of concrete repairs according Morgan [6].

Figure 2. Improper choosing of repair material (too strong and too stiff) in retrofitting of an airfield pavement. Left: View of a spalling PC cover from an old runway made of weak concrete. Right: Detail of failure in the repaired concrete substrate, caused by thermal incompatibility. Credits: B. Zając.

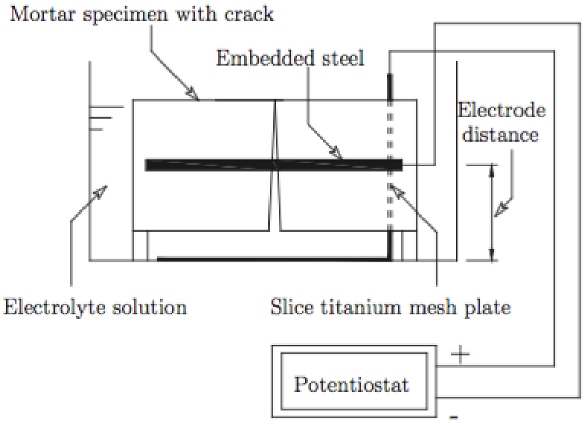

Figure 3. Sketch of the experimental device proposed by Hongqiang et al. [113].

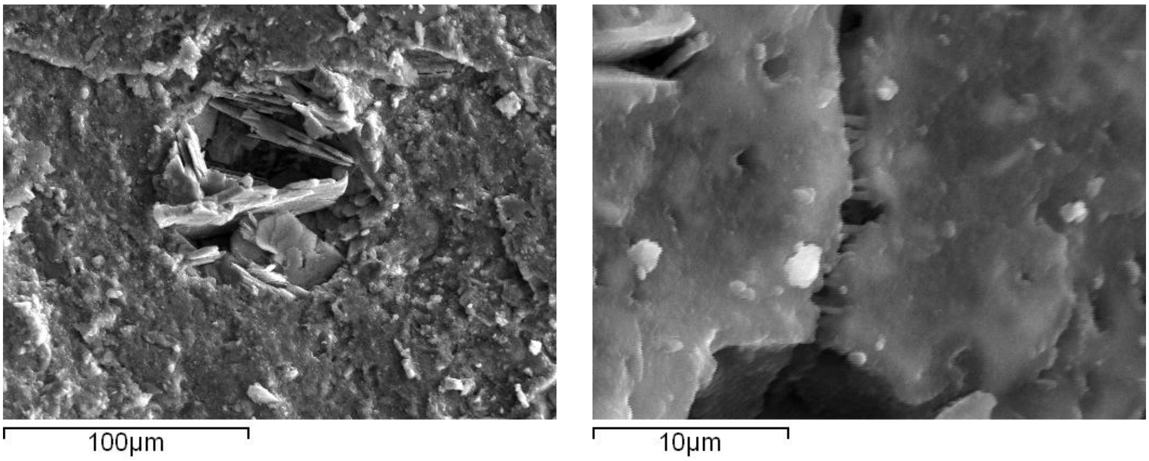

Figure 4. Left: Secondary crystals formed into a pore of cement paste modified with nanoCaO. Right: Bridging the crack in cement paste using crystallites. Credits: M. Stefanidou.

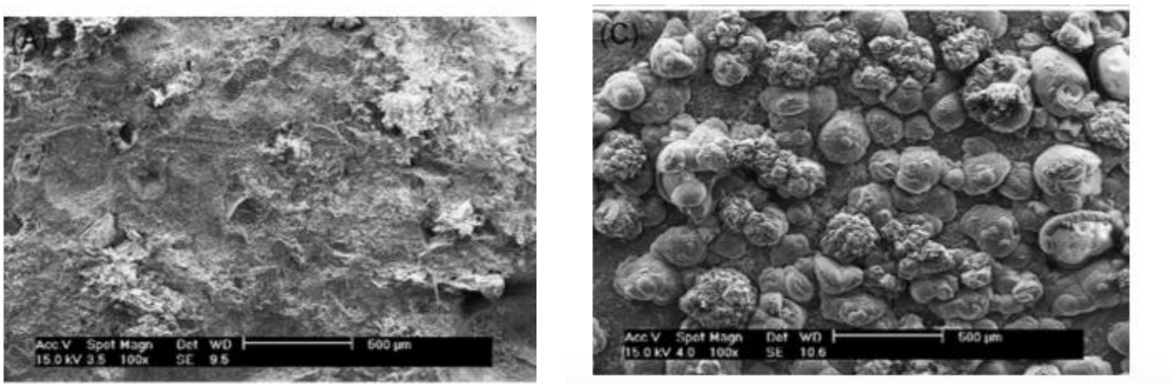

Figure 5. Scanning electron micrographs of: untreated CEM I mortar specimens (left) and biodeposition treated CEM I mortar with calcium acetate (right) [130].

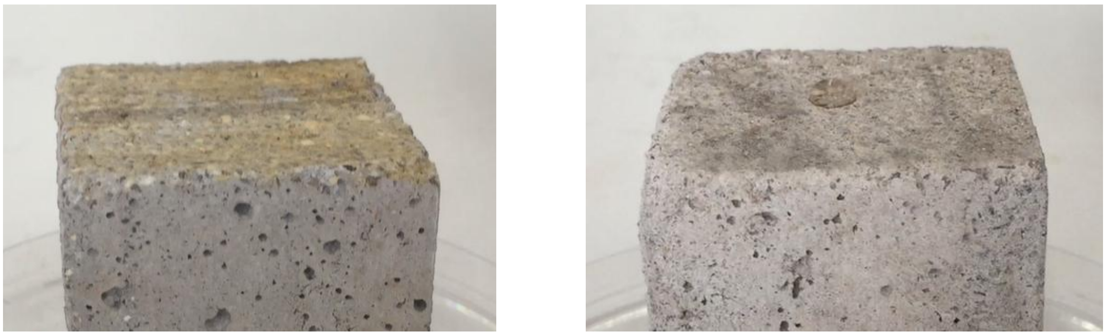

Figure 6. Left: Cement mortar: colour change with iron-based biotreatment. Right: Resistance to water absorption after a polymer-based biotreatment. Credits: Julia Garcia-Gonzalez.

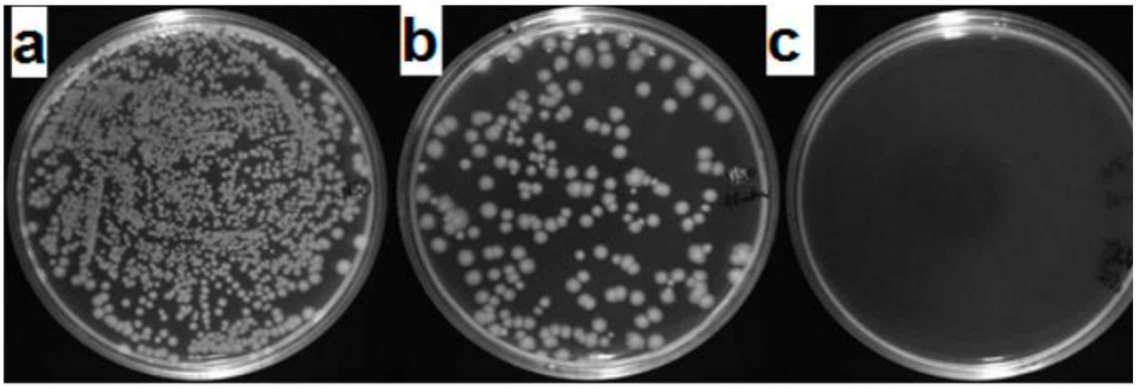

Figure 7. Reduction in quantity of viable bacteria in time on Tryptone Soy Agar (TSA) medium after contact with mortar incorporating nano-TiO2 and nano-SiO2 after [147]: (a mins, (b) 15 mins, (c) 30 mins.

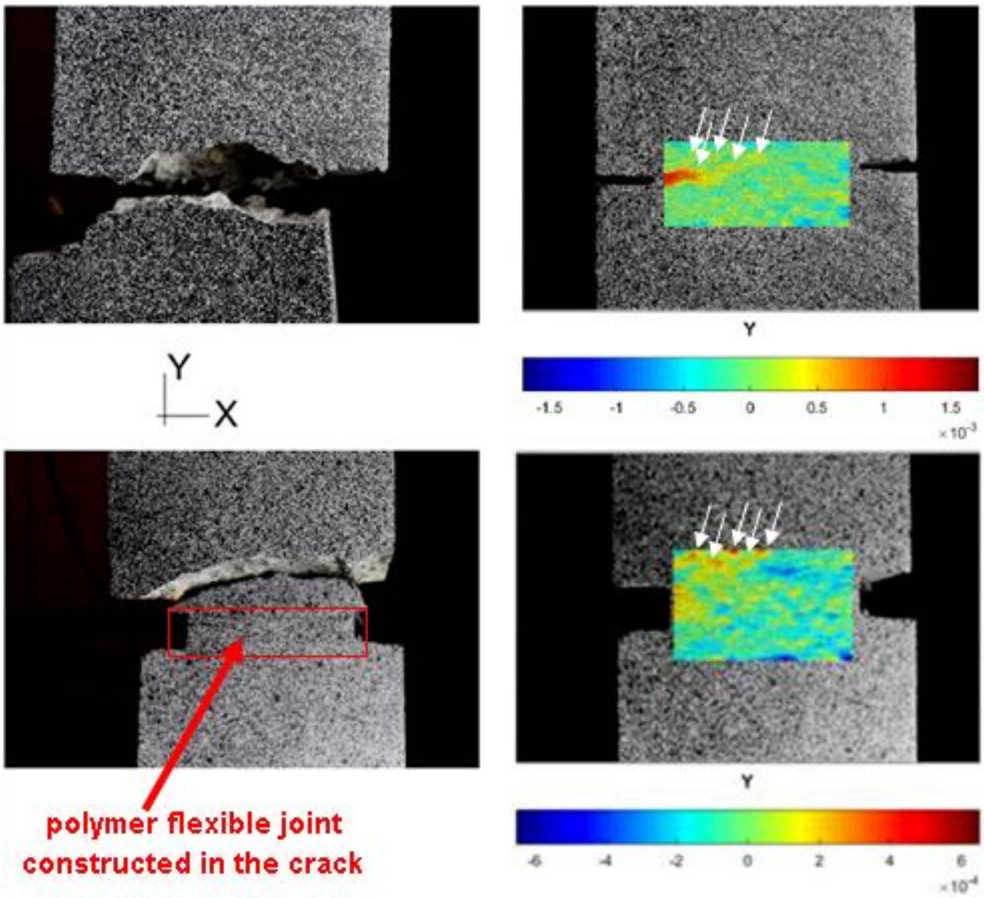

Figure 8. Maps of strains presented by DIC in tensioned concrete elements: strain concentration in the crack location (top) and strain redistribution in concrete with the lower strain level (closing of micro-cracks) close to the polymer flexible joint repairing cracked concrete (bottom) [158].

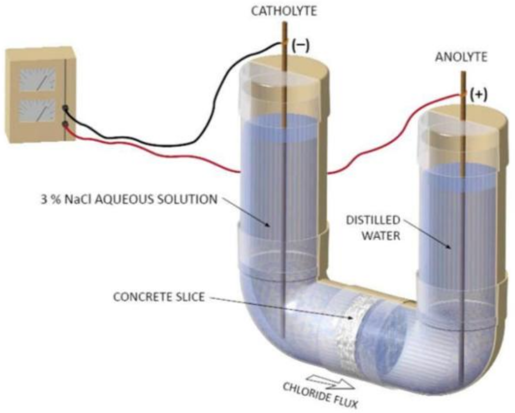

Figure 9. Experimental arrangement of steady-state migration test [169].

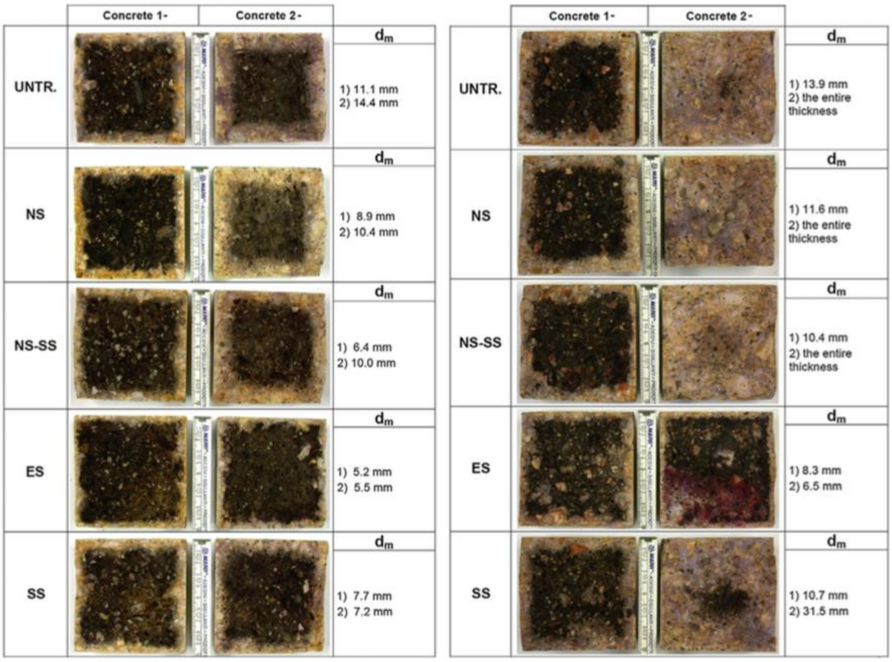

Figure 10. Results from the chloride resistance test on two different concretes with different surface treatments after 7 days (left) and 40 days (right) of immersion in a 10% NaCl solution (d represents the mean chloride penetration depth) [125].

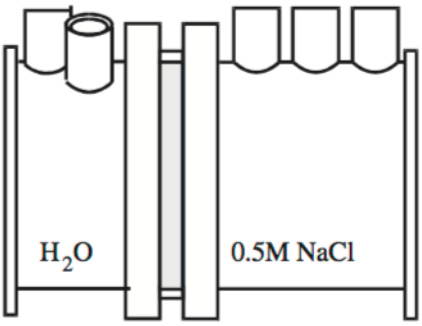

Figure 11. Stationary chloride diffusion test proposed by Diamanti et al. [165].

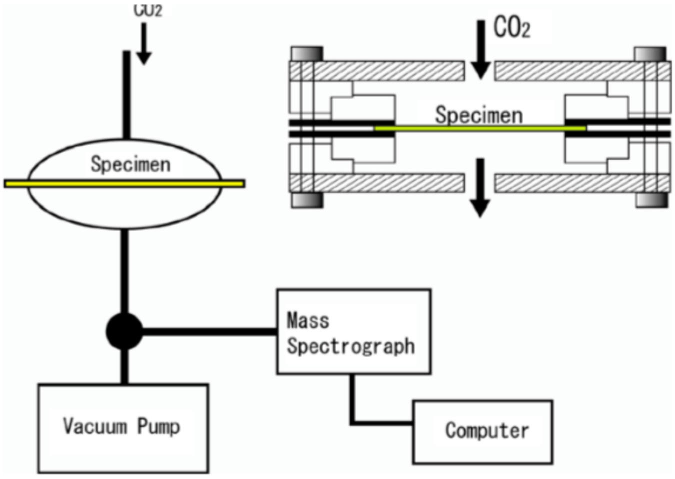

Figure 12. Overview of permeation – measuring (differential pressure method) experiment for carbon dioxide [162].

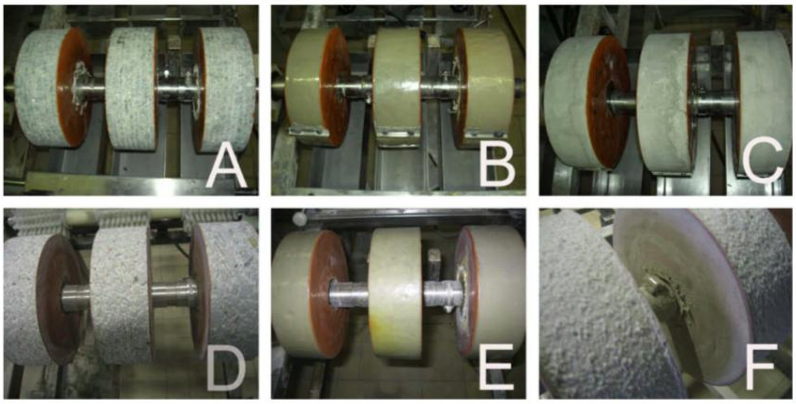

Figure 13. Overview of the visual aspect of the sewer pipe reference concrete (A, D), polyurea lining (B, E) and cementitious coating (C, F) cylinders mounted on the TAD apparatus before (A-C) and after (D-F) 10 cycles of chemical exposure tests [179]. See Image D for the position of the brushes.

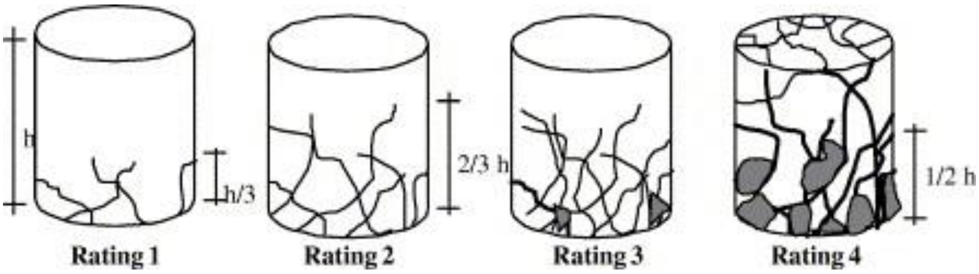

Figure 14. Damage rating based on visual inspection [180].