Self-healing approaches for the preventive repair of concrete structures: SARCOS COST Action

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ABSTRACT

The SARCOS Action is focused on the preventive repair concept, with the objective of sealing small cracks at the earliest stage of damage, both for new and existing structures, and on looking for standardized methodologies to evaluate the mechanical and durability performance of the treated structures, with continuous feedback from the modelling of self-healing mechanisms. The present contribution aims to give a general vision on the advances achieved within the SARCOS Action, including the revision of the state-of-the-art of the different aspects addressed within the Action: self-healing approaches, techniques for characterizing self-healing performance and self-healing mechanism modelling.

Keywords: Preventive repair, self-healing approaches, self-healing performance, self-healing modelling

1. INTRODUCTION

The imperative need of incorporating sustainable strategies into the construction industry practices requires developing innovative solutions able to provide an answer to transversal challenges such as improving and guaranteeing the construction performance, optimizing efficiency and promoting the minimum consumption of energy and natural resources during each stage of the whole service life. Working on the preventive repair concept, based on the treatment of incipient cracks both in new and existing constructions, is required for addressing such transversal challenges [1]. The preventive repair of small cracks in concrete will avoid further loss of performance and functionality in the long term. For new constructions, self-healing approaches appear as promising innovative solutions for repairing the concrete cover just after the occurrence of damage without requiring any external intervention. In the case of existing constructions, developing external repair methods compatible with the existing cementitious substrate, and in case employing self-healing materials, becomes a highly interesting solution for improving the durability and efficiency of traditional surface treatments.

SARCOS COST Action deals with these new concepts and advanced solutions, taking into account not only the development of innovative approaches for the preventive repair of concrete structures but also looking for characterization techniques allowing the comparative assessment of their performance and efficiency. Furthermore, modelling the healing mechanisms taking place for the different designs and predicting the associated service life improvement will help to consolidate the implementation of these preventive repair approaches. In this framework, the scope of the SARCOS Working Groups is defined as follows:

a. WG1: comparative analysis of the different solutions developed for the preventive repair of concrete structures: self-healing concrete approaches and external repair methods;

b. WG2: implementation of comparative characterization techniques for assessing the performance recovery associated with the preventive repair approaches;

c. WG3: development of models to simulate self-healing processes and the evaluation of the service life extension.

The present manuscript summarizes the state-of-the-art concerning the preventive repair approaches for both new and existing constructions (WG1) and the characterization techniques for evaluating structures' health and healing effectiveness (WG2).

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2. PREVENTIVE REPAIR APPROACHES

2.1 Self-healing approaches

Incorporating self-healing functionalities in concrete appears as a promising sustainable alternative for extending the service life of new structures, lowering maintenance costs and avoiding complicated repairs by filling cracks at the earliest stage of damage [2,3]. Two main approaches for self-healing in concrete are distinguished: autogenous and engineered healing [4].

2.1.1 Autogenous self-healing approaches

This is a natural process, intrinsic to the fundamental constituents of the material, mainly caused by the continuous hydration of cement and by the calcium carbonate precipitation when water is available. The autogenous healing ability of concrete can be improved through different approaches [5]:

a. Restricting the crack width by using High Performance Fibre Reinforced Cementitious Composites (HPFRCCs) [6,7].

b. Providing additional water by adding superabsorbent polymers (SAP) during concrete casting [8].

c. Promoting the deposition of crystals inside the crack by adding mineral agents [9,10] such as crystalline admixtures, expansive additives, geomaterials, …

Combined use of two among the aforementioned techniques has been also reported, with synergic benefits [11,12].

2.1.2 Engineered self-healing approaches

Both chemical adhesives and biological agents can be added during concrete casting to improve the healing properties of concrete [4]. The effectiveness of these approaches can be enhanced by protecting the healing agents in capsules that will be activated only when the damage appears [10]. The real challenge of such technology is to obtain capsules able to survive during mixing and casting of concrete. Furthermore, the capsule must be broken when crack hits it. The mechanical properties of the capsule shell and the bonding between the capsule and the bulk cementitious matrix will govern the capsule breakdown when intercepted by a propagating crack. The probability of a crack hitting capsules will depend on the dosage, size and aspect of the capsules.

Several solutions with encapsulated chemical agents have been proposed, from the incorporation of microcapsules containing the healing agent [13] during concrete mixing to the design of hollow fiber systems incorporating the adhesive agents [14]. Encapsulated chemical agents with different nature, i.e. epoxy, methylmethacrylate (MMA), cyanoacrylate, have been added to the fresh concrete as self-healing solutions [15]. Adhesive agents heal cracks by bonding strongly the crack surfaces, even allowing a certain recovery of mechanical properties. Adhesive agents with one-component have shown higher sealing efficiency than two-component and multi-component agents [2]. Microcapsules with both silica and organic shell have demonstrated to be stable during concrete mixing and to be able to act when the trigger appears [16]. Also vascular systems have been proposed for releasing liquid adhesive sealers for concrete self-healing [17].

During the last decades there have been important advances on bio-concrete development, that is, to use microorganisms to seal microcracks when they appear [18,19]. These biological agents need suitable protection from the high alkalinity of the aqueous phase of concrete and also in order to provide the microorganisms with the necessary space for their development and to protect them. Solutions based on the microencapsulation of the biological agent or on the impregnation of porous granules with the microorganism have been proposed [20].

2.2 External surface treatments for preventive repair

2.2.1 Traditional surface treatments

The preventive repair of existing constructions is also possible when surface treatments are applied just after the first signs of damage are appearing. Traditionally, the European standards propose three different surface treatments [21]:

a. Surface coating: physical barrier that avoids the penetration of aggressive agents such as chlorides into the cementitious matrix. Several types of surface coatings can be distinguished: polymer coatings, polymer/clay coatings, cementitious coatings. The ageing of the coating and the low penetrability are the main drawbacks of these treatments.

b. Hydrophobic impregnation: this type of treatment penetrates through the concrete pores and makes the surface hydrophobic, avoiding the water penetration. The most commonly used are silane, siloxane and mixtures of them. These products are able to chemically react with the cementitious substrate although no-sealant ability can be expected.

c. Pore-blocking surface treatment: Silicate-based solutions and fluosilicate have shown to be effective in blocking the capillary pores in concrete surfaces, increasing the hardness and impermeability of the concrete's surface layer.

2.2.2 Innovative surface treatments with healing ability

During the last few decades, the use of nanoparticles as concrete surface treatment has gained great interest. It has been shown that the electro-kinetic transport of pozzolanic nanoparticles is able to reduce the porosity of the repaired interface, with associated enhancement in strength and reduction in the permeability [22]. Nano-SiO_2 particles have demonstrated to be able to penetrate through concrete pores when applied on the surface [23] and to interact with the cementitious matrix, modifying the calcium/silicon ratio [24]. Nano-SiO_2 surface treatments promotes a refinement of the capillary pores of concrete [23,24], increasing the impermeability of hardened cement pastes.

Nowadays, the trend is looking for multifunctional surface treatments which reduce concrete permeability while exhibiting a hydrophobic effect, such as penetration of silane-clay nanocomposites or TEOS. Adding organoclay nanocomposites to polymeric surface treatments with epoxy and silane improves the resistance of the treated surface against moisture penetration and chloride ingress [25]. TEOS has shown being able to enhance the quality of concrete surfaces when applied by brushing or immersion as can penetrate deeply into concrete substrate and reacts with calcium hydroxide forming C-S-H gel [26]. Innovative solution based on the bio-mineralization of the concrete surface allows incorporating the self-healing functionality also in surface treatments [27]. Ureolytic bacteria have shown to effectively increase the resistance of cementitious materials against aggressive agents by nucleating calcium carbonate crystals. The effectiveness of the biofilm in improving the durability of the treated surface has been reported to depend on the efficiency of the bacterial culture in precipitating the carbonate crystals [19].

3. SELF-HEALING CHARACTERIZATION

3.1 Sample pre-conditioning for healing testing

The sample pre-cracking is generally carried out before testing the effectiveness of the self-healing approach. Generally, one main crack across the sample is created after the curing period using different mechanical tests, including three- or four point bending, tensile splitting and direct tension tests, also as a function of the employed material and of the stability of its response under the applied pre-cracking loads. Pre-damaging through compression tests has been also reported, e.g. for mortars. The healing effectiveness is evaluated through the recovery of durability and/or mechanical performance, the last being generally performed applying the same mechanical test after self-healing occurs. The visual inspection of the sample surface makes it possible to identify the crack pattern and to determine the crack width. The different experimental conditions for promoting self-healing development, such as the environment and the time of exposure or the crack width, make it difficult to determine in a comparative way the healing ability of the different existing approaches. Anyway the consistency of the proposed approach can be assessed by correlating the measured recovery of the mechanical properties of interest with the measured crack closure [27].

3.2 Analysis of healing products and their properties

The sealing ability of the different preventive repair approaches described in the previous section has been characterized from the macroscopic level to the nanoscale. By visual inspection it is possible to assess if the repair treatment has been able to fill the micro-cracks at superficial level. Using microscope and digital imaging, the crack width can be determined [29]. The X-Ray Computed Tomography has been employed to assess the ability of healing agents to fill the cracks inside the material bulk [30]. Several characterization techniques have been applied to identify the healing products [4]: Scanning Electrode Microscope (SEM), Field Emission Scanning Electron Microscope (FESEM) and X-Ray Diffraction. The composition has been analyzed by EDX coupled to SEM, Thermo-Gravimetry Analysis and Raman Spectroscopy.

3.3 Characterization of performance recovery after preventive repair treatments

After the preventive repair treatment, both in new and existing constructions, the effectiveness in protecting the repaired concrete must be assessed. Different aspects must be analyzed to evaluate the quality of the repair, from its durability to the success of the treatment in recovering the concrete substrate performance. In this framework, two main aspects can be highlighted: mechanical and durability performance assessment, as detailed in next subsections.

3.3.1 Mechanical performance assessment

Different aspects of the mechanical performance of healed samples have been tested in the literature by applying non-destructive testing techniques and different mechanical tests. Ultrasonic measurements are proposed for the non-destructive evaluation of the healing effectiveness of several self-healing approaches, such as a bio-concrete with non-ureolytic bacteria-based healing agent [31], High Performance Fibre Reincorced Cementitious Composites (HPFRCCs), including Engineered Cementitious Composites (ECCs) [32] and concretes with supplementary cementitious materials [33], with crystalline admixtures [34], lightweight aggregates impregnated with a liquid self-healing mineral encapsulated in a polymer-based coating layer [35] and even lime mortars, to be employed in restoration of existing heritage buildings [36].

The recovery of the mechanical performance by the healed samples is, as said above, evaluated by means of the same experimental technique employed to pre-crack the same samples before starting the healing procedure. Flexural tests, either 3 or 4-point bending, have been widely employed to evaluate, through the recovery of post-cracking load-bearing capacity and, in case, flexural stiffness, the healing capacity of a wide variety of cement based materials, including HPFRCCs [11,28,29,37,38] and plain concrete with mineral additions [39], crystalline admixtures [34] and/or SAPs as water reservoirs [40]. However, a quantitative comparison between the different results is still a matter of concern as different testing techniques have been used in the different surveyed studies. The recovery of mechanical performance has been also determined through other parameters such as the compression strength, tensile splitting [41] and direct tensile strength [16,42-44], by using related experimental techniques, depending on the engineering performance of interest and type of material, mainly on the stability of its post-cracking response. As a relevant parameter to discriminate the efficacy of the investigated self-healing technique, the level of pre-cracking and/or pre-damage has to be quantified, which is generally dome by using, where possible, Crack Opening Displacement (COD) gauges, allowing a better control of the crack opening. For direct tensile tests on strain-hardening cementitious composites the level of pre-damage is usually quantified by means of the attained strain level [42, 45]; similarly, in the case of compression tests, the attained fraction of the compressive strength is assumed as a pre-damage quantification reference [36]. Furthermore, the mechanical performance of the healed samples has been also evaluated at the microscale level through nanoindentation on the healing surface [31]. For fibre reinforced cementitious composites quantification of healing on the fibre matrix bond has been also reported [11].

3.3.2 Durability performance assessment

The healing effectiveness of the different approaches for the preventive repair of concrete structures has been also evaluated by several durability indicators such as water permeability [12], capillary water absorption [45], and resistance against chloride penetration [46]. However, as in the case of the mechanical performance assessment, the main limitation to define in a quantitative way the effectiveness of a preventive repair approach is the variability between the different experimental tests proposed for evaluating the aforementioned durability indexes.

Different criteria have been adopted in the literature to quantify the effectiveness of the different self-healing approaches from water permeability tests (WPT). Homma et al. [46] and Lepech et al. [45] proposed to determine the permeability coefficient based on Darcy's equation as parameter for evaluating the autogenous healing ability of fiber-reinforced cementitious composites. Luo et al. [47] assessed the crack healing efficiency in a bacteria-based self-healing concrete determining the water permeation velocity under different curing conditions for promoting crack healing. Roig-Flores et al. [9,48] proposed measuring the water flow through the specimen under a known and constant pressure to characterize the autogenous healing ability of a concrete cast with crystalline additives.

In the case of surface treatments, the capillary water absorption has been often used for characterizing the repair effectiveness of both traditional and innovative surface treatments [23,26,49]. However, the diversity of concrete matrix used in different studies makes difficult a quantitative comparison between the surface treatments. Sorptivity test has been also proposed for evaluating the self-healing effectiveness of concrete with different encapsulated minerals [35]. The durability enhancement associated to the preventive repair methods has been often determined by characterizing the chloride transport through the concrete pores. Both for self-healing [8] and for external surface treatments [50], the rapid chloride permeability test, based on the standard ASTM C 1202, is a common method for evaluating the effectiveness of the different treatments against the chloride penetration.

4. CONCLUSIONS

The present manuscript includes an extended (although incomplete) overview of the literature concerning preventive repair solutions based on both self-healing approaches and on external repair methods. A high quantity of studies can be found, presenting different self-healing approaches, and a global overview comparing the different solutions is missing. Similar situation is observed when the methodologies for assessing the mechanical and durability performance of the different preventive repair methods is analyzed; although the characterizing methodologies are similar for the different approaches, a quantitative comparison of the reported effectiveness is hampered by the different experimental testing conditions. In this framework, the SARCOS COST Action established as main challenge the definition of common criteria and methodologies for evaluating in a comparative way the effectiveness, durability and performance of different approaches applied for the preventive repair of concrete.

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