INVESTIGATION OF THE DURABILITY OF SELF-HEALING CONCRETE

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ABSTRACT

The durability of buildings is impaired when certain conditions or environments promote deterioration of the concrete, compromising the performance and integrity of the structure. Cracks are pathological manifestations of degradation agents, such as chlorides and sulfates. Reinforced concrete requires maintenance operations that, in appropriate periods, intervene in actions that increase or maintain performance in service. Self-healing concrete is an alternative for reducing expensive maintenance and repair actions, but its durability needs to be investigated. The objective of this research is to investigate the durability of self-healing concrete when subjected to degradation agents. The proposed methodology is the mapping of research published in Brazilian and international literature on the durability of self-healing concrete exposed to chlorides. The results showed that the self-healing concrete maintains its durability when exposed to chloride. However, it is not yet possible to certify its lifespan over time.

Keywords: durability, self-healing concrete, degradation agents, chlorides, cracks.

INTRODUCTION

The durability of concrete structures is an indispensable property of the elements in supporting the conditions provided by the designer during their lifespan. Reinforced concrete has an exceptionally low tensile strength. During construction or during use, cracks in the structure can occur due to the nature of the material, the method of construction, environmental conditions, and load effects.

Cracks in reinforced concrete allow water and degradation agents to enter, a process that can lead to unwanted corrosion of the steel and deterioration of the concrete structure. According to ABNT NBR 15575-2 [1], cracks can be classified as active (variation of the opening due to hygrothermal or other movements) or passive (constant opening). In this sense, self-healing concrete is a concrete capable of repairing its own cracks. Thus, this material becomes attractive when looking for durability of reinforced concrete structures when exposed to degrading agents, such as chlorides and sulfates.

There are certain conditions or environments that can lead to deterioration of the concrete, compromising the performance and integrity of the structure. A concrete is considered durable when it can withstand the deterioration process to which it will be exposed, thus guaranteeing a necessary resistance and a condition of use for a specified time or an expected lifespan.

The main objective of this study is to investigate the durability of self-healing concretes that used the healing approach when exposed to chlorides.

DURABILITY OF CONCRETE STRUCTURES AND THE EFFECTS OF CHLORIDE IONS

Concrete is considered durable when it can support the deterioration process to which it will be exposed. So it is essential that each concrete structure continues to perform its intended functions, that is, maintain required strength and condition of use for a specified time or a traditionally expected service life [2]. The quality of concrete structures depends mainly on three properties: strength, permeability, and resistance to aggressive agents. During operation, concrete structures often suffer cracks, which leads to a deterioration in quality and a reduction in expected service life [3].

Once the cracks in the concrete start, they create paths for the transport of oxygen and water, facilitating the entry of degradation agents, such as chlorides, carbonates, sulfates, and acids in the concrete. ABNT NBR 6118 [4] defines limits for the maximum characteristic crack opening, as long as it does not exceed values of the order of 0.20 mm to 0.40 mm, under the action of frequent combinations, it has no significant importance in the corrosion of passive reinforcements.

For Wang *et al.*[5] when the crack opening is less than 50 μm, they have little effect on the permeability of the concrete. As for crack openings from 50 to 200 μm, the permeability of concrete increases rapidly and when an opening is bigger than 200 μm, the water permeability rate increases steadily.

The presence of cracks provides a preferential path for the diffusion of aggressive agents and moisture, significantly increasing the permeability of concrete structures and in this way the structural system loses performance.

Aggressive ions, especially chlorides and sulfates, move by diffusion in the pore water.It is in the pore water that reactions occur with the hydrated cement paste, so that ionic diffusion is important in relation to attack on concrete by sulfates and attack on reinforcement by chlorides. Ionic diffusion is more effective when the pores of the hardened cement paste are saturated, but it can also occur in partially saturated concrete [2].

The penetration of chloride ions is one of the main mechanisms of deterioration of reinforced concrete structures, since there is the possibility of reaching the steel reinforcements, causing corrosion. One form of prevention that can be applied to reduce the entry of degradation agents in the concrete is the use of self-healing concretes, which induce the effect of filling the pores, minimizing the penetration of the chloride ion.

One of the most serious problems of reinforced concrete structures, corrosion of steel reinforcement, can occur due to the action of chloride ions. Such ions are introduced into the concrete in several ways: through the contamination of water or fine aggregate or even being absorbed from environments that contain it. The ways of finding chloride ions in concrete are fixed when chemically combined with the aluminum-ferritic phases to form chloroaluminates or adsorbed to the pore walls through C-S-H and free when dissolved in the aqueous phase of the concrete.

Technical standards prescribe strict limits regarding the chloride content in concrete from any source. BS 8110 [6][1] and BS EN 1992-1 [7] limit the total chloride content in reinforced concrete to 0.40 % of the cement mass. ACI 318-56 [8] limits the chloride content in reinforced concrete to 0.15 % of the cement mass. In Brazil, ABNT NBR 12655 [9] limits the chloride content according to the exposure class shown in Table 1.

Table 1: Maximum chloride ion content to protect concrete reinforcement.

Class of aggressiveness	Risk of deterioration of structure	Structure service conditions	Maximum ion content chloride (Cl-) in concrete % on cement mass
All	All	Prestressed concrete	0.05
III (strong) IV (extraordinarily strong)	Big High	Reinforced concrete not exposed to chlorides in structure service conditions	0.15
II - Moderate	Small	Reinforced concrete not exposed to chlorides in structure service conditions	0.30
I - Weak	Insignificant	Reinforced concrete in mild conditions exposure (dry or protected from moisture in structure service conditions)	0.40

Also, the sulfate ion chemically reacts with the cement compounds and forms expansive products, causing the cracking and disintegration of concrete, in order to put its performance, durability and safety at risk, significantly reducing its lifespan [10].

In the extensive literature on experimental evaluation of self-healing functionalities in concrete-based materials, a relatively small number of studies have addressed the effectiveness of curing in reducing chloride diffusion [11].

SELF-HEALING CONCRETE

The pioneering study Dry [12] applied to pavement works on a bridge in central Illinois (USA), incorporated hollow polypropylene fibers filled with methyl methacrylate adhesive as a healing agent, and thus, as cracks spread, the fibers broke and activated the adhesive that heals cracks.

This type of healing is considered autonomous according to the Technical Committee 221-SHC of RILEM [13], as they comprise microcapsules filled with healing agents or in the vascularization of hollow tubes that pump healing agents into cracks. Another autonomous internal self-healing mechanism is the precipitation of calcite produced by microorganisms introduced into the concrete [3]. The width of the crack and the type of cement can directly interfere in the self-healing process [14].

There is also the possibility of producing self-healing concretes where self-healing is said to be autogenous, as the curative capacity is intrinsic, that is, caused by components of the cementitious material present in the concrete dosage. The phenomenon of self-healing

attributed to the dissolution and deposition of hydrates induced by active catalysts, must be differentiated from the phenomenon of autogenous clogging, which is due to the continuous hydration of non-hydrated materials with $CaCO_3$ calcite nucleation and subsequent crystal growth [15].

The crystalline catalyst as a self-healing agent is a synthetic cementitious material classified as hydrophilic waterproofing or also as a admixture that reduces hydrostatic permeability [16]. The process is based on the precipitation of a chemical reaction, promoted by the catalyst, between the hydration by-products of water and cement, forming a new insoluble crystalline structure of calcium silicate hydrate, calcium carbonate, crystals of apatite and enstatite crystals [16].

Self-healing concrete types employ crystallizing and mineral admixture that increase the alkalinity power of water, in addition to those that incorporate bacteria into the concrete. In the case of self-healing concretes produced with crystallizing admixture, the penetration of water activates the crystalline catalyst, and exposes on the internal faces of these cracks a new surface formed by sub-hydrated cements and non-activated slags [15]. This crystalline catalyst increases the alkalinity of water, inside the cracks, which favor the formation of stable hydrated products on the internal faces of static cracks with an opening of up to 0.40 mm.

Wang *et al.* [5] comments that the characteristics of self-healing products at different fissuring times, curing mode and crack width influence self-healing concrete. The microstructure in dry conditions has a small number of crystals and gels formed. More crystals are formed in a humid environment and the structure is denser. The greater the crack width, the greater the size of the self-healing product produced, but there is a limit to the increase in crack width, as many self-healing products are not sufficient to compensate for the great effect of the crack width.

According to Sisomphon, Copuroglu and Koenders [17] crystalline products can only occur when sufficient moisture is present, since the crystalline catalyst in solution with reactive silica forms a hydrophilic crystallizing waterproofing, thus reactive components react with $Ca(OH)_2$ to form crystalline products that disconnect pores and fill cracks in the concrete. In other words, the condition of exposure to water plays an important role in the self-healing process. Reinforcing the chemical reactions of precipitation and continuous hydration.

It is possible that self-correction of small width cracks occurs in the case of conventional concretes, emphasizing the study by Sahmaran *et al.* [18], which evidenced in pre-fissured concrete mortars with a crack width less than 50 μm exposed to saline solution, at the end of exposure period of one month, the presence of calcite promoting self-healing.

Many researchers have studied the use of calcite produced by bacteria to increase the lifespan of concrete structures, eliminating cracks, increasing concrete strength, reducing permeability and reducing water absorption [3]. The possibility of completely sealing cracks created artificially with a width of 0.30 mm and a depth of 10 mm, noting that the permeability of concrete has become much lower. They add that when calcite is of microbiological origin, the compressive strength of the treated samples can be restored by 84 % [3].

METHODOLOGY

The proposed methodology is a systemic literature review involving case studies related to self-healing concrete studies under the action of chlorides and sulfates. The research was raised in studies on the google academic website and ScienceDirect. The keywords used in the search for durability, self-healing concrete, degradation agents, chlorides, sulfates, in addition to the combination of these words.

REVIEW ANALYSIS

The main cause of corrosion in reinforced concrete structures is the attack of chloride ions. It is also recognized that cracks allow chlorides to enter the concrete, this effect being more pronounced when the crack width is greater than 135 μm [18]. Crack widths from 100 μm to 300 μm can cause a reduction of the useful life of reinforced concrete by around 80 % [19]. However, when the crack width is less than 50 μm, a significant amount of self-healing is observed in the cracks exposed to the sodium chloride solution for 30 days [18].

Chloride penetration tends to decrease with time when using self-healing concrete [20]. Fact observed when using crystalline catalyst, which is effective in improving the mechanical properties and permeability of self-healing concretes by mechanical loading, with a reduction in the chloride migration rate in self-healing concretes between 28 % to 35 %[21].

In addition, the use of crystalline catalyst reduces the penetration of chloride ions by up to 30 %, which represents an increase in useful life by up to 34 % [16]. The curing agent based on polyurethane encapsulated in glass capsules reduces the chloride entry rate by up to 75 %, extending the useful life of self-healing concrete slabs in marine environments by up to 60-94 years, as opposed to only seven years for conventional cracked concrete [22].

It is noteworthy that the amplitude of the mechanical properties of loss by cracking and recovery by healing is due more to the characteristics of the type of cement, where CP III and CP II-E show greater recovery at older ages [15]. The effect of the crystalline catalyst increases the compressive strength of cracked and healed samples by 5.90 % in CPIII cement, 5.80 % in CPII and 3.70 % in CPV [15]. In addition, the percentage reduction in the diffusion of chloride ions in concretes, after 28 days of healing, when using CP V-ARI cement + crystalline catalyst presents a greater percentage reduction (52 %) [15].

The effect of crystalline catalyst is beneficial in concretes in relation to self-healing, as it is efficient in reducing water penetration, especially when using blast furnace cement. Moreira [14] found a reduction in the height of the water rising by up to 44 % in relation to the reference when he used the cement mixture CP III combined with crystalline catalyst.

In this sense, mention is made of the case study carried out in Brasilia, capital of Brazil, where an underpressure slab located in the basement of a building [23] was built to guarantee the tightness of the slab. Thus, a waterproofing system was designed with the use of permeability-reducing additive (PRA), due to the outcrop of the water table, and by municipal legislation that did not allow the use of suction pumps [23].

As for the ability to seal cracks in self-healing concrete, the use of the crystallizing additive guarantees the greatest capacity for sealing cracks, especially in thicknesses up to 0.30 mm, when compared to the use of complementary cementitious materials (fly ash and active silica) in self-healing concrete [24].

The use of self-healing concrete with autonomous self-healing, incorporating curing agent based on polyurethane encapsulated in glass capsules promotes a beneficial effect on resistance to the diffusion of chlorides. However, in about one third of the cracks, the healing mechanism can fail, probably due to the displacement of the tubes, which do not break properly and due to extremely high capillary forces in the tubes. But, even so, on average, the useful life of the structures produced with self-healing concrete increases by about 100 % and in the most appropriate healing situation, there is an increase in the useful life from 150 to 550 [19].

Pre-cracked samples and then cured for 1, 3 or 6 months, permanently immersed in 16.5 % NaCl solution, present the beneficial effects of the crystalline mixture for larger cracks (0.50-

1.00 mm) [11]. However, in the case of smaller cracks (<0.40 mm), the concrete samples with the curing agent reached the sealing capacity after 3 months of curing, unlike conventional concrete; 6 months later [11].

In the case of samples subjected to wetting and drying cycles, these have a generally lower healing capacity compared to submerged samples. This is because there is probably no corrosion in dry concrete at a relative humidity below 60 % [2]. There is no corrosion in concrete fully immersed in water, except when water can carry air. The optimum relative humidity for corrosion is between 70 and 80%, and at higher relative humidity, the diffusion of oxygen in the concrete is considerably less [11].

CONCLUSION

The use of crystalline catalyst increases the durability of self-healing concrete, however, after the analyzes carried out in national and international studies, it is highlighted that there is still a need for research applied in real cases for a long period of time to certify its useful life. The relevance of the self-healing ability depending on the width and depth of the cracks has not yet been exhausted, as most studies focus on the area of materials used in the production of self-healing concrete, showing that there is still a need to explore the performance of concrete after self-healing.

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