Construction and Building Materials 114 (2016) 447–457

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of crystalline admixtures on the self-healing capability of early-age concrete studied by means of permeability and crack closing tests

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HIGHLIGHTS

- Self-healing is analyzed by permeability and crack closing in concrete specimens.
- Self-healing has been compared for two concrete classes healing underwater.
- Healing has been evaluated under water immersion at 15 °C, 30 °C and wet/dry cycles.
- The results are compared with previous tests, comparing a total of six exposures.

ARTICLE INFO

Article history:
Received 16 December 2015
Received in revised form 25 February 2016
Accepted 29 March 2016
Available online 5 April 2016

Keywords:
Concrete
Self-healing
Autogenous
Crystalline admixtures
Permeability
Durability

ABSTRACT

This paper analyzes the self-healing properties of early-age concretes, engineered using a crystalline admixture (4% by the weight of cement), by measuring the permeability of cracked specimens and their crack width. Two concrete classes (C30/37 and C45/55) and three healing exposure conditions have been investigated: water immersion at 15 °C, at 30 °C and wet/dry cycles. Specimens were pre-cracked at 2 days, to values of crack width in the range of 0.10–0.40 mm. The results show almost perfect healing capability for specimens healed under water at 30 °C, better than for specimens healed under water at 15 °C, while insufficient for the wet/dry exposure.

1. Introduction

Self-healing is the process through which a material is able to recover its properties, degraded after having suffered some damage, with little or no external help [1]. Some authors also differentiate between self-healing and self-sealing, depending on the recovered property [1,2]. The self-healing process is well-known in bones and trees, which are able to repair damage and recover their strength [3]. Structures built with self-healing materials will likely feature extended service life and lower maintenance costs, furthermore benefiting from the avoidance of complicated repairs all along their service life [4]. In the case of concrete, self-healing research has focused on the closing of cracks and the related recovery of properties, either mechanical or durability-based. The property that is sought after will depend on the specific type of structure. Sometimes the structure will require both mechanical and durability-based recovery, for example, in cases where water-tightness is needed for the structural stability to prevent the ingress of harmful substances that may activate or accelerate corrosion of reinforcement, thus leading to loss of load bearing capacity.

Though the popularity of self-healing concrete has strongly increased in most recent years, the mechanism has been known for years. Neville [5] already talked about the autogenous healing of concrete, and Fernández Cánovas [6] called it “cicatrization”. Moreover, it was observed in [7,8] that concrete water reservoirs and historical lime and lime-pozzolana mortars featured self-healing capabilities due to their composition. This phenomenon

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http://dx.doi.org/10.1016/j.conbuildmat.2016.03.196
0950-0618/

benefits from tighter cracks [9], as the volume that needs to be healed is smaller and thus the process is fastened.

Self-healing in concrete is caused by the following two main mechanisms [1,10,11]: autogenous healing and autonomous/engineered healing. Autogenous healing of small cracks in concrete is a natural process, intrinsic to the properties and the composition of the material itself. It is mainly caused by further hydration of cement and calcium carbonate precipitation, though other processes could also enhance it [12]. Autonomous healing is an engineered healing process designed to improve the self-healing properties of a concrete element. Furthermore, autonomous/engineered healing can be further divided into 'passive' and 'active' modes [1,11,13]. The 'active' mode requires some human help to activate the mechanism, while the 'passive' mode requires no human intervention. One of the methods for autonomous healing is the use of self-healing admixtures, such as crystalline admixtures.

The ACI TC 212 report [14] regards crystalline admixtures (CA) as a type of permeability reducing admixtures. Specifically, crystalline admixtures are hydrophilic, i.e., they react easily with water, in contrast to water-repellent or hydrophobic products. The behavior of these products is still partially unknown: in fact, the ACI TC 212 report [14] states that the concrete compounds reacting with CA are tricalcium silicates, while other authors [15] indicate calcium hydroxide as the reactive. The general process, according to [14], follows Eq(1), where a crystalline promoter, M_XR_X, reacts with tricalcium silicates and water to produce modified calcium silicate hydrates and a pore-blocking precipitate, $M_XCaR_X - (H_2O)_X$.

$$3CaO - SiO_2 + M_XR_X + H_2O \rightarrow Ca_XSi_XO_XR - (H_2O)_X + M_XCaR_X - (H_2O)_X \quad (1)$$

There are relatively few recent publications concerning the effect of crystalline admixtures as promoters of self-healing. Jaroenratanapirom and Sahamitmongkol [16] focused on the visual observation of crack closing in mortar specimens healing under water. Their results show that CA provided the best behavior for small and early age cracks (under 0.05 mm and pre-cracked at 3 days and at 28 days), but were ineffective for larger cracks (around 0.3 mm) when compared to Ordinary Portland Cement (OPC) mortars. Similar results were obtained by Sisomphon, et al. [15], who also made reference to visual closing of cracks in mortar specimens with CA pre-cracked at the age of 28 days: only crack widths up to 150 μm were able to close completely when the samples were healed for 28 days under water. On the other hand, their water permeability tests showed rapid healing for mortars with CA during the first 5 days, but only a limited reaction for OPC mortars not containing the admixture. Afterwards, Sisomphon et al. [17] tested the recovery of mechanical properties of strain-hardening cementitious composites containing CA and reported hardly any benefit when compared with control specimens. However, the reaction for both kinds of specimens was enhanced when subjected to wet/dry cycles (immersion in tap water for 12 hours and drying in air for 12 hours) as compared to continuous water immersion. Later on, Ferrara, et al. [18] studied the effect of CA on strength recovery in normal strength concrete specimens, in their case made with concrete containing CA at a dosage of 1% by the weight of cement, under continuous water immersion and an exposure to open air and up to one year; this resulted in an improvement of the mechanical properties along the healing period.

Other studies [19,20] focused on the development of self-healing admixtures, by using expansive agents, geo-materials and chemical agents, in order to improve the chemical stability of rehydration products and the velocity of the reaction, which is fundamental for an effective healing.

All the aforementioned studies have anyway highlighted, once more, that presence of water is needed, even in a discontinuous way (as in the case of wet/dry cycles), to activate the healing reactions for both autogenous healing and CA-based healing. However, some discrepancies have been noticed when analyzing the autogenous healing capability of concrete: while some studies [21] showed improvement of the healing capability with increasing ambient humidity for early-age cracked specimens, others [22] concluded that exposures of high humidity levels do not activate self-healing reactions. To the knowledge of the authors, the majority of works so far have used continued water immersion as their healing exposure of choice. However, a few studies [23,17] have shown better behavior for both autogenous healing and CA-based healing under the exposure to wet/dry cycles than for continued immersion, which motivates specific analysis on this subject.

This work compares the effect of a crystalline admixture on self-healing behavior in early-age concrete, considering two classes of concrete under three different exposure conditions, all of them featuring the presence of water. The methodology used in this research is based on permeability tests and crack width evaluations, comparing their performance to evaluate self-healing, since some studies have registered correlations between permeability and crack width measurements [24–26]. The former method is based on the standard permeability test for uncracked concrete specimens and the methods for cracked specimens used by Edvardsen [24] and Sisomphon et al. [15].

2. Research significance

The results from this study will allow assessing the effect of a crystalline admixture on the self-healing properties of concrete at early ages through the analysis of water permeability and crack closing as healing parameters. This work studies the self-healing behavior in two commonly used concrete classes, one typical for precast concrete elements and/or civil engineering infrastructures (C45/55) and one standard class widely used for building constructions (C30/37). The influence of the environmental exposure on self-healing is also investigated by comparing three different exposure conditions and comparing their results with those of exposures from previous research [27], in order to widen the analysis data base and strengthen the conclusions. In all cases, the examined crack widths range between 0.10 and 0.40 mm, for the purpose of verifying the limits of healing effectiveness for each combination of experimental variables. This work aims to provide new perspectives on the use of crystalline admixtures as self-healing agents in engineering applications where watertightness is a key factor.

3. Experimental program and methodology

3.1. Experimental program

In this work, all specimens have been evaluated by means of a permeability-based method and the crack closing. Specimens were divided into eight testing groups to analyze the effect of concrete strength class, influence of exposure condition during healing and the presence of a crystalline admixture (CA) as a self-healing "promoter." Table 1 shows the experimental variables combination and the number of tested specimens for each of them, adding up to a total of 144 specimens tested in this study. Higher amount of specimens were tested for the "water immersion at 15 °C" groups, since they are the reference used for comparison.

The goal of the main set of these experiments is to compare the self-healing behavior of concrete with and without the crystalline admixture under three different exposure conditions: water immersion at 15 °C (WI_15), water immersion at 30 °C (WI_30), and wet/dry cycles (W/D). More detailed information on these conditions will be given in Section 3.3.