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A methodology to assess crack-sealing effectiveness of crystalline admixtures under repeated cracking-healing cycles

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HIGHLIGHTS

- A methodology to analyze the self-sealing capacity is used.
- The influence of a crystalline admixture as a healing stimulator was studied.
- Specimens were subjected to repeated cracking (DEWS tests) and healing cycles.
- The crack closure was analyzed with image processing methods.
- The effect of the crystalline admixture persists up to one year.

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ABSTRACT

This paper analyzes the autogenous and stimulated self-sealing capacity of steel fiber reinforced concretes, with and without crystalline admixtures, under repeated cracking and healing cycles. To this purpose, the performance under cracking and healing cycles was investigated on $150 \times 150 \times 50\ mm^3$ specimens, cracked by means of an indirect tensile test called Double Edge Wedge Splitting (DEWS) test. Two concrete mixes (with and without crystalline admixtures) and three healing exposure conditions were investigated: water immersion, open-air exposure and wet/dry cycles. Initially, the specimens were cracked up to a crack opening of 0.25 mm and were then subjected to the different aforementioned exposure conditions for 1, 3 and 6 months. At the end of each period, the specimens were cracked again and were subjected to the different exposure conditions for an additional 1 or 2 months, repeating the cracking and healing procedure up until a total duration of one year. The crack closure was analyzed using image processing methods. The results show that, for the same healing period, the specimens immersed in water reached the largest crack closures. In addition, it was observed that the crystalline admixture may favor long-term self-sealing capacity under repeated cracking and healing events.

1. Introduction

The increasing concern about a responsible use of raw materials and the need to guarantee a higher and tailored level of material and structural performance in engineering applications for longer times has promoted a huge amount of research on the challenging topic of self-healing (cement-based) construction materials. RILEM TC 221 [1] defines self-healing as "any process by the material itself involving the recovery and hence improvement of a performance, after an earlier action had reduced the performance of the material".

It is well known that, by itself, concrete has some moderate self-healing capabilities (autogenous healing). This is closely related to the fact that, in most concretes, approximately 20–30% of the cement particles remain anhydrous. When a crack appears, such anhydrous particles come into contact with water or moisture and react with it creating hydration products that contribute to the closure of the crack [2–5]. Moreover, $Ca(OH)_2$ particles produced by cement hydration may release calcium ions which, reacting with carbonate ions in water or carbon dioxide in air, form calcium carbonate precipitates, also contributing to close the cracks. This type of self-healing is known as "autogenous healing", which occurs when cracks are healed by usual constituents of the cementitious matrix and, therefore, materials that are not specifically added to the same matrix for self-healing purposes (this is, own generic materials) [1,6–9]. On the other hand, the healing process is called "engineered healing" when specific engineered additions designed to promote it are purposely added to the concrete mix-design [10–16]. Tailored additions such as silica fume [17],

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crystalline admixtures [11,12,18–21] and superabsorbent polymers [8,22–24] have been used to stimulate the autogenous self-healing capability of concrete mixtures.

In turn, the synergy between fiber reinforced cementitious composites (FRCCs) and self-healing techniques is giving rise to solutions with great potential [10] since fibers can improve the self-sealing process because of their ability to control the width and propagation of the cracks [4,6,7,12,18,25,9,14,26]. In fact, FRCCs are characterized by enhanced toughness due to the crack-bridging effects provided by fibers [27–37]. The test results indicate that the use of fibers reduce the maximum and average crack width, as well as the crack spacing [29,30].

It has been shown that cracks smaller than 30 μm (and in some cases even 50 μm) can be healed completely [5,24,38]. Subsequently, the next step would be to analyze if the sealing mechanism is maintained over time after several cracking-healing cycles (self-healing repeatability). Compared to the large number of investigations on self-healing [6,7,10,11,18,19,20,9] among others, studies on the persistence of the healing capacity under repeated cracking and healing events of self-healing FRCC are less numerous [22,39–42] which has motivated this research. Among the cited studies on the persistence of the healing capacity under repeated cracking events, it is worth recalling the works by Snoeck et al. [22] and Sahmaran et al. [39]. Snoeck et al. [22] studied the ability of repeatable promoted autogenous healing in fiber-reinforced materials with and without superabsorbent polymers (SAPs). To this purpose, the mechanical properties of the specimens were compared after two cycles of loading under a four-point-bending test. Results showed that the healed specimens regained up to 75% of their mechanical properties and, a partial additional regain in mechanical properties up to 66% was observed even second reloading of healed specimens. On the other hand, Sahmaran et al. [39] studied the self-healing ability of engineered cementitious composites (ECCs). To generate microcracks on specimens, a repeatedly preloading up to 70% of their deformation capacities was applied by means of dynamic modulus tests based on ASTM C215, after the mechanical tests specimens were subjected to a cyclic wet/dry conditioning period. The extend and rate of self-healing under repetitive preloading conditions was determined by resonant frequency (RF) and rapid chloride permeability tests (RCPT). Results showed that ECC specimens can recover up to 85% of their initial RF values, even after six repeated cracking/healing cycles. In addition, the maximum crack width observed was 190 μm, even after nine cracking/healing cycles.

As a matter of fact, in the analysis of the crack sealing capacity of any material, the main issue remains the observation and measurement of the crack width and of its evolution in the investigated scenario. In the last decade, with the improvement of the photogrammetric and image processing methods, several crack-detection and characterization algorithms have been developed [43]. These procedures can yield high precision results especially on surfaces with homogeneous texture and illumination [44]. The detection algorithm starts with the application of filters that smooth the error and enhance the edges [45]. Subsequently, the procedure that allows the identification of the crack is applied. The most prominent methods today are the so-called binarization algorithms [46]. These methods perform a classification of each pixel into two categories; white or black (crack or non-crack), based on the definition of a radiometric threshold [47]. The result of this process is called "segmented image". Finally, additional filtering allows the elimination of outliers. Several authors, such as [48–55] have made use of these digital image processing methods for the detection and quantification of cracks in concrete. The procedure must be adapted according to the characteristics to be obtained: width, length, depth or area of the crack, the latter being the most frequently chosen for the study of the time evolution of cracking. The accuracy in detecting such crack parameters (i.e. estimated crack parameter versus measured crack parameter) using image analysis techniques varies from 75% to 95% compared to manual visual perception measurements [43].

The main objective of this work is to analyze the repeatability of the self-sealing of fiber-reinforced concrete and how it is influenced by the addition of crystalline admixtures. Crack width was measured by means of image processing methods. The crack sealing capacity was quantified through the definition of suitable indices under each of the analyzed conditions and along the investigated cracking-healing cycles.

2. Experimental program

2.1. Mix design, materials characterization and test set-up

A conventional fiber reinforced concrete (FRC) mix was used in this research, with the composition shown in Table 1. Besides a reference mix, another mix (denoted as C.A. concrete) containing 0.8% by cement weight of a crystalline admixture (Penetron Admix ®) used as healing promoter was also produced, leaving the mix proportions substantially unaltered. The objective of this research was to analyze a typical fiber reinforced concrete used for structural applications, containing a typical quantity of steel macrofibers. Both mixes contained 40 kg/m^3 hooked-end steel fibers 60 mm long and 0.9 mm in diameter (fiber aspect ratio equal to 65).

The employed crystalline admixture (Penetron Admix ®), consists of a blend of cement, sand and microsilica. It reacts with the moisture in fresh concrete and with the products of cement hydration producing a non-soluble crystalline formation which promotes crack sealing. This product was analyzed by means of SEM and EDS analysis (Section 3.2). A detailed description of its morphology and composition can be found in [19].

The mechanical properties of the investigated FRC were measured at 3, 7, 28 and 56 days by means of compressive strength test

Table 1
Concrete mix design.

Constituent [kg/m^3]	Reference Concrete (Without crystalline admixtures)	C.A. Concrete (With crystalline admixtures)
Cement type II 42.5	360	
Water	180	
Superplasticizer	3.5	
Coarse aggregate 4–16 mm	1077	
Steel fibers, Dramix 5D 65/60BG	40	
Fine aggregate 0–4 mm	814	811
Crystalline admixture (Penetron Admix ®)	0	2.9