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A "fracture testing" based approach to assess crack healing of concrete with and without crystalline admixtures

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HIGHLIGHTS

- Effects of crystalline admixtures on the self healing of concrete have been investigated.
- Effects of self healing on the recovery of mechanical properties have been evaluated.
- Under water concrete autogeneously heals; crystalline admixtures promote self healing in air.
- Self healing was quantified through indices load and damage recovery.
- A crack closure above 70–80% is necessary to start recovery of stiffness and load bearing capacity.

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ABSTRACT

In this paper a methodology of characterization of both autogenic and engineered self-healing of ordinary concrete, with or without a crystalline admixture, has been assessed. The employed crystalline admixture consists of a mix of cement, sand and active silica and is added to the raw concrete constituents before mixing.

The effects of the self healing phenomena on the recovery of stiffness and load-bearing capacity have been evaluated by means of 3-point bending tests performed up to controlled crack opening and up to failure, respectively before and after conditioning. Different exposure conditions have been considered, such as water immersion, air exposure and accelerated temperature cycles. Moreover, Ultrasonic Pulse Velocity tests and microstructural observations have been carried out. On the basis of the results, self-healing related indices have been also defined.

1. Introduction

Worldwide increasing consciousness for sustainable use of natural resources has made "overcoming the apparent contradictory requirements of low cost and high performance a challenging task" [1] as well as a major concern. The importance of sustainability as a requisite which has to inform structure concept and design has been also recently highlighted in Model Code 2010. In this context, the availability of self-healing technologies, by controlling and repairing "early-stage cracks in concrete structures, where possible", could, on the one, hand prevent "permeation of driving factors for deterioration", thus extending the structure service life, and, on the other hand, even provide partial recovery of engineering properties relevant to the application [1,2].

As pointed out by Lauer and Slate already in 1956 [3] "if the mechanism of the action is understood, and means can be found for accelerating it, a great stride will have been made in effectively retarding" the rate of degradation of concrete and corrosion of embedded steel reinforcement, which are among the major problems of the concrete durability [4].

Discovered as early as in 1836 by the French Academy of Science, and attributed to the transformation of calcium hydroxide ($Ca(OH)_2$) into calcium carbonate ($CaCO_3$) as a consequence of exposure to the carbon dioxide (CO_2) in the atmosphere, autogeneous healing of concrete was also later observed by Abrams [5], who attributed it to the "hydraulicity" of residual un-hydrated cement, as well as by Loving [6], who, on inspection of concrete pipe culverts, found many healed cracks filled with calcium carbonate.

As a matter of fact, besides the availability of CO_2 in the exposure environment, the age of concrete at the time of cracking also governs the mechanism with the highest autogenous healing

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Table 1
Mix composition of investigated concretes (dosages in kg/m^3).

Constituent	Without additive	With additive
Cement type II 42.5	300	300
Water	190	190
Superplasticizer (lt/m^3)	3	3
Fine aggregate 0–4 mm	1078	1080
Coarse aggregate 4–16 mm	880	880
Crystalline additive	=	3

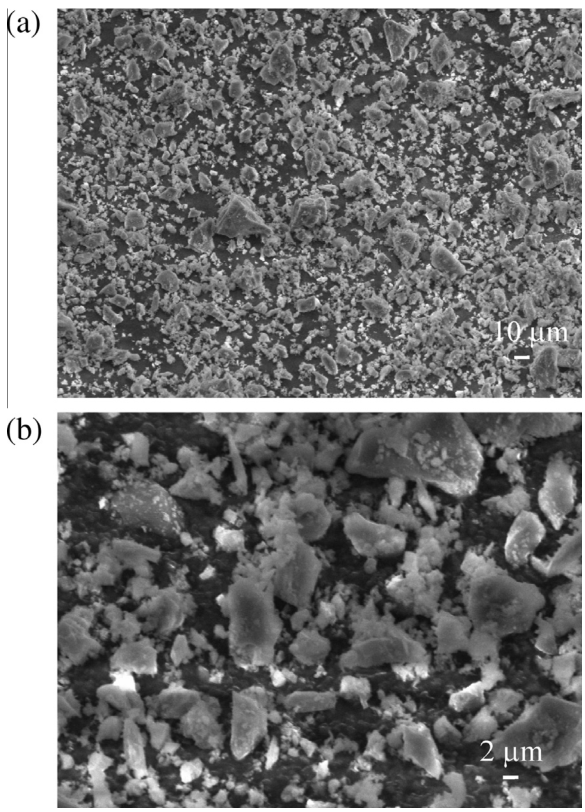

Fig. 1. SEM images of a powder sample of crystalline additive observed at different magnifications (a) e (b).

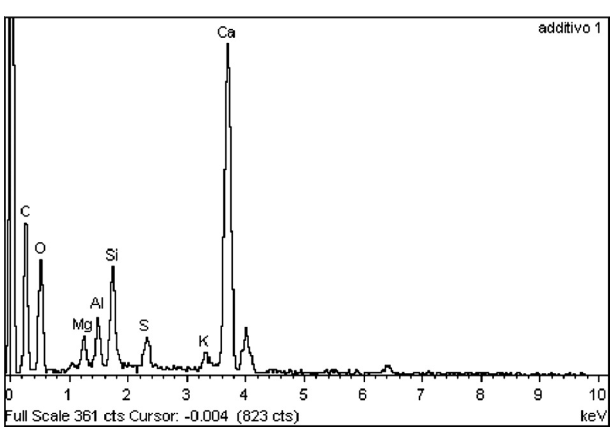

Fig. 2. EDS analysis of the additive particles shown in Fig. 1.

capacity. Due to its relatively high content of unhydrated cement particles, ongoing/delayed hydration is the main healing mechanism in young concrete [7–9], whereas at a later age, calcium carbonate precipitation becomes the major one.

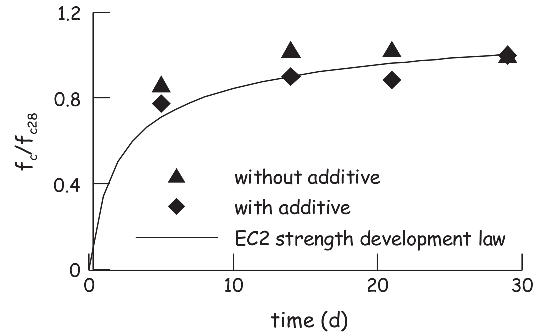

Fig. 3. Strength development of concrete with and without crystalline additives vs. EC2 provisions (fc28 = 29.9 N/mm^2 and 27.4 N/mm^2 for concrete without and with the crystalline additive respectively – each data point average of two nominally identical tests).

The action of autogeneous healing may have "practical value in several applications (...) namely: (...) repair of precast units cracked during early handling; sealing against corrosion and re-knitting of cracks developed in concrete piles during their handling and driving; sealing of cracks in concrete water tanks; and the regain, after loss, of strength of "green" concrete disturbed by vibrations" [10]. Further evidence of the effects of crack healing on the recovery of mechanical properties was reported by Whitehurst [11], who observed an increase in the dynamic modulus of field structures during a wet spring, following a winter of freezing and thawing. Anyway, whereas significant reduction in water permeability was observed because of crack healing [12–14], reported recovery of mechanical properties [3,14,15] was not so spectacular. With reference to the maximum crack width that can be healed without any external intervention, a wide range of openings has been reported by different authors (i.e. from as low as 5 to as high as 300 µm) [16–18].

Consensus among the international community has been achieved about the engineering significance of the problem, which has resulted in state-of-the-art reports to be compiled as well as into a clear terminology definition. The RILEM TC-221-SHC "Self-healing phenomena in cement based materials" [1], distinguishes:

- based on the result of the action, between self-closing and self-healing, whether only closure of the cracks or also restoring of the mechanical properties is observed;
- based on the process of the action, between "autogenic" (or natural) and "autonomic" (or engineered) self closing/healing, whether the crack closure or restoration of material properties is due to either the concrete material itself or some engineered addition.

In the very last decade a huge amount of research work has been dedicated to "engineered" self-healing, along different main directions of investigation: self healing engineered with fibre reinforcement [20–28], mineral-producing bacteria [29], super absorbent polymers [30], healing agents contained in shell and tubular capsules [31,32] and other proprietary chemical admixtures [33], such as alumino-silicate materials and various modified calcium composite materials. In the latter case, the self-healing action is mainly due to the filling of the crack width, swelling and expansion effects and to improved hydration and re-crystallization. The supply of water (moisture) is essential, especially in the case of addition of chemical agents able to promote the deposition of crystals inside the crack, but "since most infrastructures are exposed to rain or underground water, usually this is an easily satisfiable requirement" [33].