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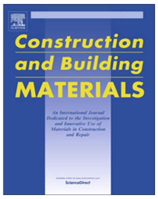

The effects of age, cement content, and healing time on the self-healing ability of high-strength concrete

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HIGHLIGHTS

- High-resolution scans and computer image processing analysed self-healing concrete.
- Some cracks completely heal for initial crack widths below 460 μm.
- Efficiency of self-healing is affected by the density of the cement matrix.
- The healing process exhibits localized variability.
- Various forms of calcium carbonate were identified as products of self-healing.

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ABSTRACT

Our study assessed the self-healing process in high cement content, low water-to-binder ratio composites. Two different compositions were aged 2 and 20 months. Mechanically induced cracks up to 800 μm wide were analysed by an automated method based on high optical resolution scanning and computer image processing. For composites aged for 2 and 20 months, the maximum detected width of healed cracks was 460 μm and 388 μm, respectively. The healing process exhibited localized variability and was affected by crushed material in cracks. Crack width analysis coupled with microscopy and EDS indicated that a dense cement matrix may reduce self-healing efficiency.

1. Introduction

Self-healing of cracks in cement-based composites is one means for increasing the durability of cement composite structures [1]. In this context, the self-healing ability describes a condition where a cracked cementitious material can partially or totally restore itself to the original structural integrity, limiting the ingress of aggressive environmental factors into the composite. Often, very complex self-healing processes are initiated in cement composites exposed to water and atmospheric gases in response to the existing damage to the material.

This type of self-healing ability, based on the natural properties of the cement-based composite, has been tested, discussed, and documented in a large number of publications [2–7]. Studies show that the autogenous self-healing ability is significantly limited by several factors, including its dependency on the crack width. Yang et al. [6], Li & Yang [8] claim that complete healing is possible only for crack widths < 50 μm, while partial healing is possible for crack widths up to 150 μm. For similar conditions, Van Tittelboom et al. [9] conclude that complete healing is possible for crack widths up to 200 μm. Other authors specify this crack width boundary to be 300 μm. For these reasons, fibre-reinforced self-healing composites containing steel, glass or polymeric fibres have been developed that control the crack width in cement composites. A dispersed reinforcement of adequately selected deformational parameters allows single, large-width cracks occurring under a load to be replaced with a net of smaller-width cracks that feature a stronger self-healing ability [10].

For Portland cement-based composites, self-healing of cracks occurs at a rate of 15 μm/day, according to Van Tittelboom et al. [9]. In the tests conducted by the above-mentioned authors, substituting Portland cement with binders such as fly ash or blast furnace slag does not facilitate any material changes in this regard. In fact, significant amounts of pozzolan binder consume calcium, leaving insufficient amounts of $Ca(OH)_2$ and improves the continued hydration, but the effect on autogenous self-healing depends on external conditions [9].

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In general, studies of different types of self-healing properties have employed testing methods that rely on visual inspection and on simple crack width measurements [11]. One common method for observing changes in crack widths is the use of charge-coupled device (CCD) cameras for directly observing a sample surface [12], as well as computer tomography [11,13,14] or electron microscopy [11,15]. Very often, crack widths are evaluated manually by an operator at arbitrarily selected points on the sample surface, causing the objectivity and accuracy of such tests to be questioned. Berrocal et al. [16] published a more advanced method for determining the nature of cracks in composites that employs a threshold processing of binary images from a stereoscopic microscope with a CCD camera. However, the subjective values in threshold processing determine the geometrical nature of the crack image [17]. Moreover, the subjective selection of the crack measurement point also distorts the results of the width measurements and healing level. Most importantly, guidelines and standards regulating testing of self-healing ability have yet to be established.

In an earlier work [17], we presented an automated crack width measurement method based on computer processing and analysis of digitally recorded images of cement composite surfaces. A series of experiments on concrete specimens and cracks in various measurement conditions (crack orientations, locations, moisture, and brightness levels) were performed to evaluate the features of this method and the measurement uncertainty. None of the cement composites in these experiments exhibited a self-healing ability. However, a brief example of application was presented to illustrate the method.

This crack width measurement method was used in the research presented in this paper to estimate crack width change and to quantitatively assess self-healing progress. Even though the measurement method was developed and evaluated previously, this is the first time it was used for the purpose of studying the self-healing process.

The research presented here is based on a series of experiments investigating the self-healing process for different cement hydration times and cement contents. A large dataset of crack width measurements while undergoing self-healing were gathered together with SEM and EDS analyses. An attempt was made to verify data presented in the literature concerning the limitations of this type of self-healing.

2. Materials and methods

Two concrete compositions (Table 1) were mixed, cast into cylindrical moulds, and aged for 2 or 20 months in water. The cement content in M1 and M2 mixes is 2.1 and 2.8 times higher by mass, respectively, than in normal strength concrete. These compositions were chosen in order to study the differences in self-healing of high-strength concrete as a function of cement content. To reduce the water content, a high-range water-reducing admixture was used at the highest dosage permitted by the manufacturer. The significant reduction in water content in combination with large quantities of cement provided a fraction of non-hydrated cement in the cured concrete, constituting only a micro-filling of the cement matrix. Consequently, when water eventually penetrated the cured structure through the mechanically created microcracks, this non-hydrated portion hydrated and acted as a cement binder. These hydration products, including C–S–H, a calcium carbonate from carbonated Portlandite $Ca(OH)_2$, and crystallized Portlandite, filled the microcracks and restored the integrity of the material and possibly restored its strength.

Table 1
Composition of concrete mixes and their content [kg/m^3 of concrete].

Composition of concrete mixes	M1	M2
CEM I 42.5R	626	823
0–2 mm sand	658	576
dolomite crushed-stone aggregate 2–8 mm	1117	979
water	157	165
SP (3% m_{binder}) – CHRYSO® Fluid Optima 185	19	25
water-binder ratio	0.28	0.23

The test procedure consisted of the several steps. First, cylindrical samples 100 mm diameter by 200 mm height and 150 mm diameter by 300 mm height were prepared from the concrete mixes and deposited in an air-conditioned room at 20 ± 2 °C and a relative humidity of 90 ± 5%. Then the samples were unmoulded after 2 days of curing. Unmoulding after 1 day was impossible because of the low strength of the samples caused by the significant delay of cement hydration due to the high amount of superplasticizer used. The samples were cured for 28 days by full water immersion at a temperature of 20 ± 2 °C, and then for an additional 1 month or 19 months they were exposed to air at a temperature of 24 ± 2 °C and relative humidity of 60 ± 5%. Then the samples were sliced into dimensions of 100 mm diameter by 50 mm height and 150 mm diameter by 75 mm height and wrapped by glass fibre-reinforced tape along the circumference. Every two outer parts of the sliced cylinders were discarded. These reinforced cylindrical samples were subjected to single or multiple static loads in a splitting scheme (Brazilian test) to achieve cracks with widths in the range of 0–800 μm. Tests were performed under controlled loading conditions at a loading speed of 25 kPa/s. The cracked samples were subjected to the self-healing process under full water immersion conditions at a temperature of 24 ± 2 °C for a testing period of up to 28 days. The condition of the sample surfaces within the crack area have been regularly documented using an optical microscope and a high-resolution scanner, having previously evaporated water from the sample surface at an air temperature of 24 ± 2 °C and relative humidity of 60 ± 5%. Finally, the effectiveness of the self-healing process was evaluated using measures of relative and absolute crack healing.

The effectiveness of the self-healing process was assessed using the method described in [17]. Surface images of the sample slices were recorded digitally by an Epson Perfection V600 Photo scanner with a CCD matrix possessing a 6400 dpi optical resolution and an optical density of 3,4 D_{max}. Crack areas were scanned at intervals over the course of their self-healing, grouped and processed using a Scale-Invariant Feature Transform (SIFT) transformation along with proprietary macrocodes in the ImageJ software [18]. Using the procedures described in [17] the cracks were automatically covered with a net of intersecting lines, along which the degree of brightness was determined and the respective crack widths were estimated. Observing crack widths at predefined time intervals allowed us to determine changes with time and to evaluate the effectiveness of the self-healing process. The standard uncertainty of the described method for measuring the average crack width is approximately 8 μm [17].

This method for analysing sample surfaces does not allow for the evaluation of the progress of self-healing at larger depths inside the crack, especially in areas inaccessible to visible light. It constitutes a very good alternative to manual measurements often employed in similar tests, but it cannot replace physical examinations such as gas or water permeability tests.

As the main part of the tests, a total sample area of 2175 cm^2 of 16 samples was digitally recorded at the cracked regions, correlating to 3289 locations of intersecting lines and crack width measurements. Samples were immediately scanned after cracking (time point t = 0) and after t = 2, 4, 7, 14 and 28 days of the self-healing process. Data was analysed at crack width intervals of 50 μm and 100 μm, with a range of up to 800 μm. They were also