Self-healing of engineered cementitious composites in the natural environment

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Abstract. This research investigates the self-healing behavior of Engineered Cementitious Composites (ECC) in the natural environment. ECC specimens were damaged to 0.5% tensile strain and allowed to heal outdoors, under random and sometimes extreme environmental conditions. Resonant frequency measurements and uniaxial tensile tests were used to quantify the rate and robustness of self-healing, while photo documentation was used to obtain visual evidence of self-healing products. It was found that there was a significant recovery of resonant frequency and stiffness in the damaged specimens after they were exposed to the natural environment. Specimens were able to recover up to 90% of their original, pre-damaged, resonant frequency values and up to 31% and 68% of their initial stiffness after one and three months of exposure. Photo documentation also showed self-healing in cracks up to 20 μm in width. This suggests that ECC is not only capable of self-healing in controlled laboratory conditions, but also in the natural environment.

1. Introduction

Cracks are unavoidable during the lifetime of a concrete structure. Structures directly exposed to the natural environment are susceptible to cracking not only from factors such as excessive loading and restrained shrinkage, but also from harsh environmental conditions. Cracking lowers the durability of concrete structures by creating pathways for harmful agents to penetrate the structure and potentially attack the reinforcing steel or the surrounding concrete. Cracks may also weaken the structure by negatively impacting the mechanical properties of the concrete. Therefore, the development of a concrete that can heal itself and regain this loss of performance due to cracking is highly desirable.

Studies have shown that cracked cementitious materials have the ability to heal themselves over time when exposed to water. It has been found that there is a gradual reduction in the permeability of damaged cementitious materials as water is allowed to flow through the cracks. This decrease in permeability is due to diminishing crack widths as cracks are filled with healing products. In some extreme cases with small crack widths, cracks may heal completely, thus increasing the durability of the damaged material [1-3]. However, this is rare since most cementitious materials are brittle and incapable of achieving crack widths small enough to undergo self-healing.

ECC is a fiber reinforced cementitious composite that has been optimized through the use of micromechanics to achieve high tensile ductility and tight crack widths. ECC has a tensile strain capacity of 3-5% and develops extremely small microcracks (< 60 μm) under loading [4-6]. These tight crack widths are an intrinsic material property of ECC and promote robust self-healing behavior that is not easily attainable in brittle concrete with uncontrolled crack widths. It has been found that self-healing can occur in ECC under controlled laboratory conditions [7-8], and this study builds on that research by allowing ECC to heal outdoors, in the natural environment, under random and sometimes extreme environmental conditions.

2. Experimental investigation

2.1 Mix proportion and raw materials

The ECC mix proportion used in this study is given in Table 1. Type I ordinary Portland cement, Class F normal fly ash conforming to ASTM C618 requirements, fine silica sand with an average particle size of 110 μm, a polycarboxylate-based high range water reducer (ADVA® Cast 530), and polyvinyl alcohol (PVA) fibers were used to prepare the ECC material. The PVA fibers account for 2% of the total mix volume and are 12 mm in length with an average diameter of 39 μm. The fibers have a tensile strength of 1600 MPa, a density of 1300 kg/m^3, an elastic modulus of 42.8 GPa, and a maximum elongation of 6%. Also, the PVA fiber manufacturer coated the surface of the fibers with an oiling agent (1.2% by weight) to reduce the fiber/matrix interfacial chemical bond caused by the strong hydrophilic nature of the PVA fiber [4, 9].

Table 1. Mix proportion of ECC

Component	Cement	Fly Ash	Sand	Water	HRWRA[a]	Fiber
Weight %	27	33	22	16	0.4	1.3

[a] HRWRA: High Range Water Reducing Admixture

2.2 Specimen preparation

A batch of ECC was prepared using a force-based Hobart mixer with a 20L capacity. Coupon specimens measuring 300 x 76 x 12.5 mm were then cast and covered with wet plastic sheets. Specimens were demolded after 24 hours and cut down to 200 mm in length to minimize bending stresses caused by misalignment during tensile loading. Specimens were then air cured at laboratory temperature and humidity (20 ± 1°C, 50 ± 5%) until testing. The day prior to testing, aluminum plates were glued to the ends of the coupons to facilitate gripping within the load frame.

All specimens were preloaded to 0.5% tensile strain at an age of 3 days. Uniaxial tensile loading was applied using a load frame (MTS Model 810) with a 25 kN capacity under displacement control and a loading speed of 0.0025 mm/s. Two Linear Variable Displacement Transducers (LVDTs) were attached to the specimens during loading to measure tensile deformation. When the tensile strain reached 0.5%, the tensile load was released and the samples were unloaded and removed from the load frame.

2.3 Natural environment exposure

After preloading, specimens were placed outdoors in a location where they would be fully exposed to all environmental conditions. Since this experiment took place in Michigan between February and May, the samples were exposed to rain, snow, and temperatures ranging from -14 to 28°C.

2.4 Self-healing evaluation methods

2.4.1 Photo documentation

In order to obtain visual evidence of self-healing, images of cracks in the preloaded specimens were taken once a week. Specimens were chosen for photo documentation based on crack width data in hopes of determining the largest crack width capable of self-healing in the natural environment.

2.4.2 Resonant frequency

Resonant frequency (RF) measurements based on ASTM C215 for the longitudinal mode were used to monitor the rate of self-healing in the preloaded specimens. Although the RF measurement technique is commonly used to evaluate concrete damage after exposure to freezing and thawing cycles, it has proven to be a useful method for determining the rate and extent of self-healing in ECC [8]. RF measurements were taken before and after preloading the specimens to quantify the amount of damage, and then twice a week throughout the duration of natural environment exposure to evaluate the rate of self-healing.

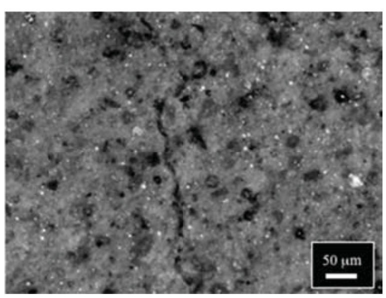
2.4.3 Uniaxial tensile test (reloading)

To assess the robustness of the self-healing products, mechanical properties were measured under uniaxial tensile loading once the specimens were allowed to heal in the natural environment. After damage was induced during preloading, the specimens were placed outdoors and allowed to heal under various natural environment conditions. Specimens were then reloaded using uniaxial tensile tests and these mechanical properties (primarily stiffness) were then compared to those measured during preloading to determine the level of recovery. Two sets of specimens were used for reloading: one set was reloaded after 1 month of natural environment exposure, and the other was reloaded after 3 months of exposure. These reloading tests were conducted using the same method as described in Section 2.2 for preloading, but the specimens were reloaded until failure.

3. Experimental results and discussion

3.1 Photo documentation

Fig. 1 shows a 10 μm crack before and after self-healing was allowed to occur. This crack healed gradually over time as various precipitation events occurred and, after 1 month of natural environment exposure, the crack appeared to be completely healed. This gradual type of healing was found to be typical of cracks that were 10 μm or less in width.

a) 

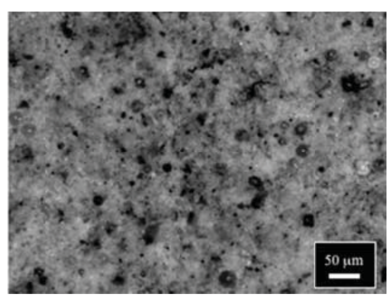
b) 

Fig. 1. 10 μm crack (a) after preloading to 0.5% and (b) after 1 month of natural environment exposure (48.3 cm of precipitation)

Fig. 2 shows another 10 μm crack that experienced a slightly different form of healing than the crack in Fig. 1. Fig. 2 (a) and (b) show the crack before environmental exposure and after the crack appears to be completely healed. However, in Fig. 2 (c), the crack becomes much more visible and, after 2 more weeks of environmental exposure, appears to be completely healed again in (d). Based on these images, it seems as though healing products are being washed out of cracks during heavy rainfalls. Although other studies [8, 10] have found that healing products are most likely a combination of calcium carbonate and C-S-H gel, these would not easily dissolve during large precipitation events. Therefore, it is believed that the healing products being washed out are calcium hydroxides (CH) which are formed during cement hydration. CH would normally be consumed during pozzolanic reactions, but these reaction kinetics are slow and a precipitation event could occur before the reaction is complete and dissolve the CH between the crack faces. This type of washout was not seen in all cracks, but more detailed studies will be required to confirm the chemical composition of the healing products.

Although most self-healing was visible in cracks that were 10 μm or less in width, healing products were seen in cracks as large as 20 μm. It has been found that crack widths must be below 150 μm for self-healing to occur under controlled laboratory conditions [8], however, no significant amount of healing products were observed in cracks larger than 20 μm when healing was allowed to occur in the natural environment.

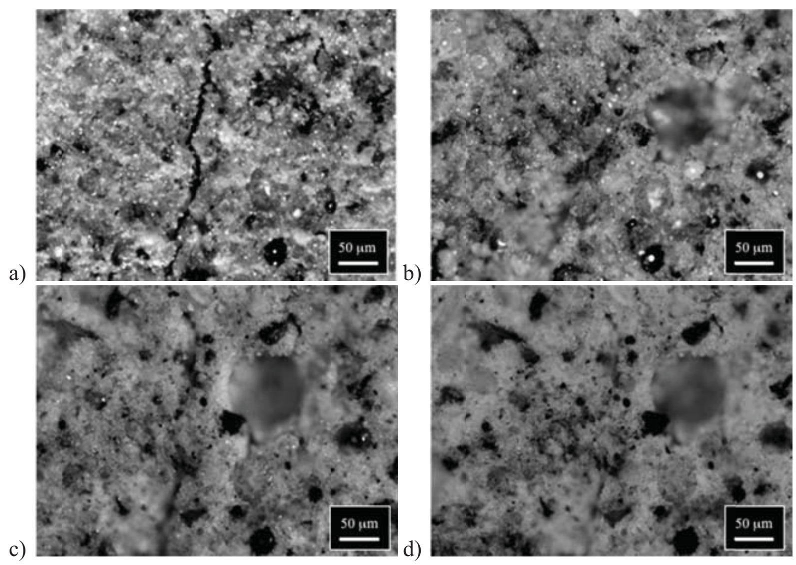


Fig. 2. 10 μm crack (a) after preloading to 0.5%, (b) after 2 weeks of natural environment exposure (22.2 cm of precipitation), (c) after 1.5 months (50.9 cm of precipitation) with possible washout of healing products, and (d) after 2 months (54.3 cm of precipitation)

3.2 Resonant frequency

In addition to self-healing, continued hydration creates an increase in RF values. Therefore, the RF data in Figs. 3 and 4 has been normalized to account for the effects of continued hydration and these graphs represent the true RF recovery from self-healing. Due to the formation of cracks within a sample during loading, there was a large drop in RF values after samples were preloaded. However, it is clear that the RF values recover greatly even after only 1 month of natural environment exposure (Fig. 3). As shown in Fig. 4, the rate of self-healing drastically decreases after 1 month of natural environment exposure, but most samples were able to recover up to 90% of their original, pre-damaged, RF values.

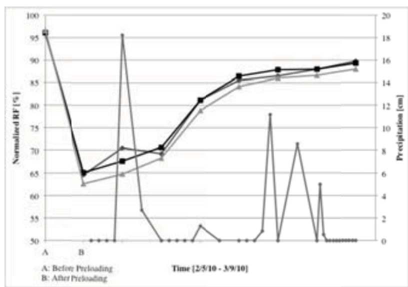


Fig. 3. Precipitation data and true RF recovery of samples reloaded after 1 month of natural environment exposure

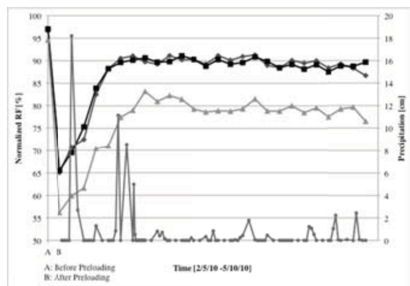


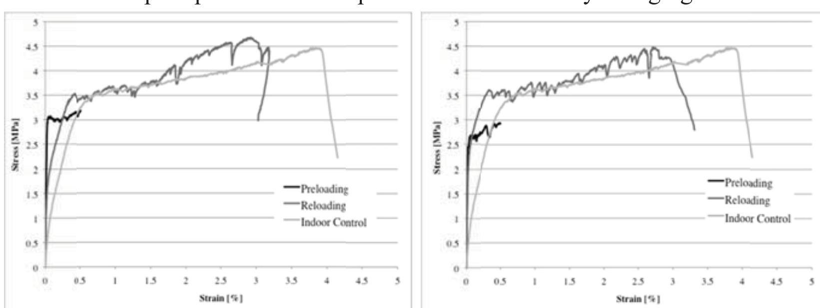
Fig. 4. Precipitation data and true RF recovery of samples reloaded after 3 months of natural environment exposure

Although most samples recovered to within 90% of their initial RF value, it has been seen that samples healed under laboratory conditions can recover up to 100% of their original value. Also, the rate of RF recovery seen in laboratory conditions is much more rapid than the rates seen in the natural environment [7-8, 10]. This is due to the fact that self-healing in the laboratory is achieved using consistent wetting and drying cycles, while self-healing in the natural environment is more sporadic and the duration of the precipitation events are usually much shorter than the duration of the wetting cycles used in laboratory conditions.

The RF data in Fig. 4 is fairly consistent after 1 month of natural environment exposure, but there are noticable fluctuations. These fluctuations correspond to precipitation events where the RF values decrease after one rainfall event and increase after the next. This is consistent with the observations made during photo documentation discussed in Section 3.1. The decrease in RF could be caused by the washout of healing products during heavy rainfalls, and the increase in RF would then be due to the reformation of healing products after the next precipitation event.

3.3 Uniaxial tensile test (reloading)

Fig. 5 shows the preloading and reloading curves of 2 typical ECC samples that were reloaded at 1 and 3 months of natural environment exposure. For comparison, each graph also includes a sample that was reloaded without any self-healing. It can be seen that the samples exposed to the natural environment recover some of their initial stiffness due to self-healing. Samples were able to recover up to 31% and 68% of their initial stiffness after 1 and 3 months of exposure. Although this is a significant regain in stiffness, samples healed under laboratory conditions were able to recover up to 90% of their initial stiffness values [8]. Like RF recovery, the greater stiffness recovery in laboratory samples is due to the fact that self-healing in the laboratory is achieved through consistent wet-dry cycles, while healing in the natural environment is more irregular since the amount of precipitation and temperatures are constantly changing.



(a) (b)

Fig. 5. Preloading and reloading curves for (a) samples reloaded after 1 month of natural environment exposure and (b) samples reloaded after 3 months of natural environment exposure.

4. Conclusions

(1) Self-healing can occur in damaged ECC samples exposed to the natural environment, under random and sometimes extreme environmental conditions.
(2) Through photo documentation, it was observed that the majority of healing products formed in cracks that were less than 10 μm in width. However, healing products were seen in cracks up to 20 μm in width.
(3) Washout of healing products is a possibility due to the slow kinetics of the pozzolanic reaction.
(4) Samples recovered up to 90% of their initial RF values.
(5) Samples recoverd up to 31% and 65% of their initial stiffness after 1 and 3 months of natural environment exposure.

(6) Although self-healing in the natural environment is promising, it is not as robust as the self-healing seen under controlled laboratory conditions.

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