Autogenous Healing of Engineered Cementitious Composites Under Wet-Dry Cycles

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1.0 Introduction

Cracks can occur during any stage of the life of a concrete structure. They can be due to the concrete material itself as in the case of restrained shrinkage, or due to external factors such as excessive loading, harsh environmental exposure, poor construction procedures, or design error. Cracks have many negative effects on the mechanical performance and durability of concrete structures. The development of concretes that can automatically regain this loss of performance is highly desirable. Along this line, self-healing of cracked concrete, commonly known as autogenous healing, is an often studied phenomenon. Experimental investigation and practical experience have demonstrated that cracks in cementitious materials have the ability to seal themselves.

The effects of various parameters on self-healing include crack width, water pressure, pH of healing water, temperature, water hardness, water chloride concentration, and concrete composition. The mechanism of autogenous healing in concrete can be different such as, further hydration of the unreacted cement, expansion of the concrete in the crack flanks (swelling of C–S–H), crystallization (calcium carbonate), closing of cracks by solid matter (impurities) in the water and closing of cracks by loose concrete particles resulting from crack spalling. Among these, the crystallization of calcium carbonate within the crack is the main mechanism for self-healing of mature concrete.

The crack width is the dominating factor for any of the above mentioned five mechanisms of self-healing to be effective. Therefore, the need of crack width control is very important for autogenous healing.

2.0 ECC an Autogenous Healing Material

Engineered Cementitious Composite (ECC) is a unique type of high-performance, fiber reinforced cementitious composite. ECC features high tensile ductility (tensile strain capacity) with moderate fiber content, typically 2% by volume. Of special interest is the capability of ECC materials to deform to high tensile strains under load, commonly over 3%, while maintaining a tight crack width of about 60 μm up to failure, as shown in Figure 1. ECC with self-controlled crack width as low as 20 μm have been developed. This steady state crack width can be seen as an inherent material property of ECC, similar to compressive strength or elastic modulus. With this characteristic, ECC material is expected to have good potential to achieve self-healing in a variety of environmental conditions, even when the composite is tensioned to several percent strains. It appears that self-healing in ECC looks to improve the long-term ductility and durability of ECC after cracking, and establishes a much more durable civil engineering material.

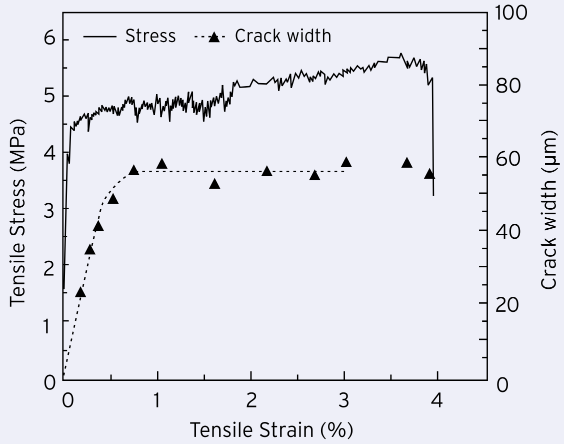


Fig. 1: Typical tensile stress-strain-crack width curve of ECC

The tight crack width in ECC is a result of its ability to experience flat crack propagation with much of the crack flank maintaining constant (steady state) crack width as the crack length increases indefinitely. Unlike normal concrete or fiber reinforced concrete, this feature of ECC allows self-control of crack width independent of steel reinforcing ratio and structural dimensions. Given this characteristic, the small crack width in specimens for laboratory investigation is identical to that in full-scale structures. When combined with the tensile strain-hardening response in ECC, desired small crack width can be easily imposed on ECC specimens for examining rehealing of crack damage, without the need for feedback control as in the case of controlling cracks in tension-softening normal concrete or fiber reinforced concrete.

While knowledge of the process of self-healing in concrete is available, specifics with regard to self-healing in ECC are limited, especially in the case of exposure to various environmental conditions. These conditions can vary greatly and include: the drying action of wind and sun; rain-water containing dissolved sulphurous compounds from industrial pollutants (i.e. acid rain); bridge-deck run-off or freezing and thawing action; sulphate attack and carbonation. This paper highlights on the self-healing of pre-damaged mature (six months of age) ECC materials under cyclic wetting and drying.

3.0 Methods of Specimens Preparation and Testing

Wetting and drying can be used as an accelerated test method to simulate outdoor environmental conditions in which ECC structures are subjected to the drying action of wind and sun and wetting by rain. Specimen damage is imposed by tension loading to fixed amount of tensile strains, which can be simulated in a laboratory test by ponding the specimens for one day and air drying next day (CR1). This regime can be used to simulate cyclic outdoor environments such as rainy days and unclouded days. A second method of conditioning should be by ponding for one day and next day oven-drying at 55°C for 22h and air cooling thereafter (CR2). This is used to simulate cyclic outdoor environments alternating between rainy days and days with sunshine and high temperatures.

Table: 1 Mix proportions of ECC

Materials	Cement	Aggregate	Fly ash	Water	HRWR	Fiber
Unit weight (kg/m^3)	578	462	694	319	17	26

HRWR: High Range Water Reducer

The specimens were preloaded to different predetermined uniaxial tensile strain levels from 0.3% to 3%, at the age of 6 months. On unloading, a small amount of crack closure of about 15% can be observed. To account for this, all crack width measurements should be conducted in the unloaded state. Table 2 shows the average number of cracks within two pre-loaded specimen series and their corresponding crack widths over a gauge length of 100 mm. The maximum, rather than the average crack width, is reported here to highlight the extremely tight crack widths inherent in ECC as compared to concrete. While self-healing in structures will take place in the loaded state, this unloading is expected to have only a small impact on ECC self-healing capabilities. After unloading, these specimens were subsequently exposed to ten wet-dry cycles (CR1 or CR2).

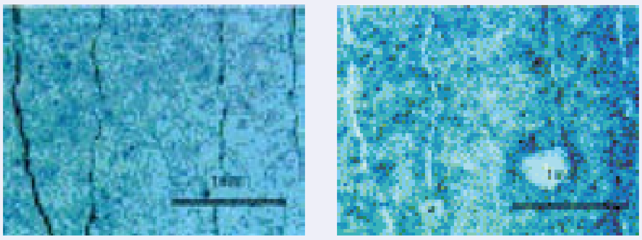
Table: 2 Crack characteristics of pre-loaded ECC

Tensile strain (%)	Number of cracks	Maximum crack widths (μm)
3	39	90
2	27	60
1	15	60
0.5	7	70
0.3	5	50

4.0 Healing Efficiency

The microstructures of ECC specimens before and after self-healing are shown in Figure 2 (a) and (b). It can be seen that abundant white residue is present along the crack lines after wet-dry conditioning cycles. It can be found out that the majority of the self-healed products are characteristic of calcium carbonate crystals.

Figure 3 shows an ECC specimen subjected to tensile loading after undergoing self-healing through the CR1 conditioning regime. This specimen was preloaded to 2% strain before being exposed to wet-dry cycles. Again, the distinctive white self-healed product can be observed in these pictures.



(a) Before self-healing (b) After self-healing

Fig. 2: Micro cracks in ECC before and after self-healing

As can be seen in Figure 4 new cracks and crack paths have been observed to form adjacent to previously self-healed cracks which now show little or no new cracking. The possibility of this event depends heavily upon the cracking properties of the matrix adjacent to the self-healing, and the quality of the self-healing material itself. However, this phenomenon serves as a testament to the real possibilities of full recovery of mechanical properties via self-healing within ECC material. Certainly, the rehealed crack shown in Figure 4 was transmitting a tensile load high enough to cause new cracking in its neighborhood.

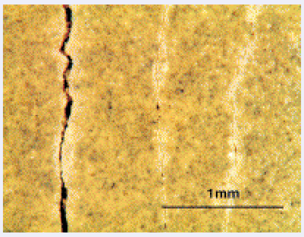


Fig. 3: Cracks through self-healed material due to reloading after wet-dry cycles

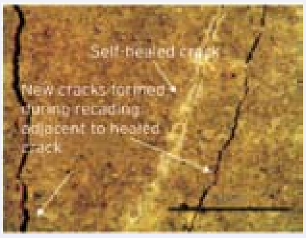


Fig. 4: Cracks through virgin ECC material adjacent to a self-healed crack held tight by self-healing material

5.0 Conclusion

The self-healing of ECC materials subject to wet-dry cycles can be used to enhance self-healing through design of cementitious materials (ECC). Also, self-healing in both transport property such as reduction in ingress of moistures, chloride ions and CO_2 etc. and mechanical properties such as strength, stiffness improves. The ECC materials should also under go some wet-dry cycles and the crack width should be li mited to 150 μm and preferably 50 μm for better efficiency.