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Assessment of influence of self-healing behavior on water permeability and mechanical performance of ECC incorporating superabsorbent polymer (SAP) particles

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HIGHLIGHTS

- SAP particles can enhance the tensile ductility in ECC.
- SAP particles can absorb H_2O from high RH condition and sustained release H_2O during low RH conditions.
- The self-healing ability of ECC can be enhanced by the addition of SAP particles.
- The self-healing process of ECC can enhance the recovery of mechanical properties.

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ABSTRACT

The self-healing behavior of a series of pre-cracked engineered cementitious composites (ECC) incorporating superabsorbent polymers (SAP) with relative low crack width is investigated in this paper, focusing on water permeability and recovery of mechanical performance. Self-healing in ECC with different pre-cracked levels and different curing conditions (high/low relative humidity (RH) cycle and 95% RH) was studied. The water permeation test and uniaxial tensile test both were conducted to evaluate the influence of self-healing on water permeation and mechanical performance in ECC incorporating SAPs. Meanwhile, the process of self-healing and products both were measured by using Environment scanning electron microscope (ESEM) and energy dispersive X-ray spectroscopy (EDS). The test results, together with ESEM and EDS observations, further confirmed that when exposed to high/low relative humidity conditions, the self-healing process of ECC was accelerated by the help of SAPs which can absorb H_2O from high RH condition and sustained release H_2O during low RH conditions and more self-healing product was formed in crack. The findings of this study can be used to promote self-healing of ECC with SAPs in infrastructure application.

1. Introduction

Engineered cementitious composites (ECC) is a special type of high performance fiber reinforced cementitious composites (HPFRCC) and developed by Li [1,2] in the 1990s. ECC has an extreme tensile ductility of 3–5% while maintaining very tight crack width with 60 μm. Self-healing ability of ECC materials has been researched for many years, significantly regaining the mechanical properties of material by self-healing when limited crack width occurs in concrete [4–6]. Self-healing phenomenon in cement concrete was observed on an Amsterdam bridge in the 1800s, where tights cracks were found and self-healed by recrystallization of calcite [7]. These phenomenons indicate that under some special conditions (for example, when rainwater and CO_2 is available) cement-based materials can heal its own cracks with healed products.

Self-healing in cement-based materials has been widely studied by researchers until now [8]. Self-healing means the cracks in concrete can be filled by some chemical compositions from itself. One importantly mechanism is the formation of $CaCO_3$ as the results of reaction between Ca^{2+} and air CO_2 [9,10]. Continuous hydration of unhydrated cement-based materials is another self-healing mechanism [11]. Therefore, C-S-H and $CaCO_3$ were determined as the mainly self-healing products [12]. As pointed by previous researches [13,14], crack width was a critical factor for the occur of self-healing due to limited healed products. The crack width below 100 μm, especially lower than 50 μm [15,16], was beneficial

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to promote self-healing. Moreover, ECC possesses a typical characteristic with tight crack width below 60 μm.

Yao et al. [17] studied the performance of ECC incorporating SAPs as the controlling pre-existing flaws. Adding SAPs to ECC can improve tensile ductility and toughness of ECC. Meanwhile, drying shrinkage was reduced and retrained. Yang et al. [18] analyzed the effects of wet-dry cycles on self-healing behavior. After self-healing, the initial resonant frequency value of pre-cracked ECC can be recovered 76–100% and can still retain a high tensile strain value, from 1.8% to 3.1%. Qian et al. [19] found that the bending capacity of pre-cracked ECC curing in water can recover by 65–105% compared to virgin specimens. Zhu et al. [5] concluded that freeze–thaw cycles can weaken the mechanical properties of pre-cracked ECC. Meanwhile, the healing degree of pre-cracked ECC in water freeze–thaw cycles is higher than that in deicing salt freeze–thaw cycles. Snoeck et al. [20] investigated the self-healing ability of cementitious materials with SAPs to promote the internal curing upon crack formation. Ma et al. [21] founds that the pre-cracked ECC cured in water/air cycle could obtain faster self-healing behavior. Lower pre-damage deformation level of specimens at 28 days could also have better mechanical recovery.

Without water, cracks in ECC will not show self-healing. So this paper considered adding superabsorbent polymers (SAPs) into ECC to improve the self-healing capacity. SAP particles possesses an extreme ability to absorb and retain water from a humid environment. The use of SAP particles into ECC has major mechanisms. First, SAP particles can swell due to water absorbed during mixing and shrink during hardening ECC, leaving macropores into matrix at last [17]. These macropores can decrease the matrix fracture toughness and promote the formation of multiple cracking in ECC. Second, SAP particles are very helpful for self-healing of ECC due to absorbing water in wet period and releasing water in dry period, which is important for regaining mechanical properties of ECC. Meanwhile, SAP can also seal the crack in concrete and promote the recovery of water-tightness in structure. Therefore, the uptake of harmful substances in concrete will lower, enhancing the long-term durability and reducing the maintenance costs [17,22,23].

The effect of self-healing on mechanical properties of ECC has been studied by a large number of researchers [5,19,21,24]. However, there has been little research on self-healing of ECC with SAPs in regions without rain or not exposed to direct rainfall. Thus, this paper focus on clarify the influence of self-healing on water permeability and mechanical properties of ECC incorporating SAPs. Firstly, the ECC mixtures with different SAPs types and different SAPs content were produced. Then, the permeability and tensile properties of pre-loaded ECC were conducted by rapid penetration test and uniaxial tensile test. The mechanical properties including compressive strength, first cracking strength, ultimate tensile strain, ultimate tensile stress, elastic modulus and tensile stiffness.

2. Research significance

The large production of concrete material driven by infrastructure application and the lack of durability of structures have effect on economic, social, and environmental. However, current self-healing of ECC is focus on the presence of water. This paper reports a new method to enhance the self-healing behavior of ECC without water. Meanwhile, the addition of SAPs can improve the deformability and limit crack width. The resulting compressive strength, tensile ductility, and water permeability of ECC incorporating SAPs are expected to contribute to fast self-healing behavior with a reduced dependence on water.

3. Experimental program

3.1. Materials and preparation

Three ECC mixtures with different SAPs content were investigated in this paper. Mix composition is listed in Table 1. The used sand is quartz sand with a mean size of 160 μm. Two sizes of SAP particles, with a mean size of 550 and 75 μm and both adding 2% and 4% by weight of cement, were prepared in this investigation. The composition of SAPs is both acrylamide and sodium acrylate, and provided by local producer. The SAPs used in this paper is in a dry state. In order to get a consistent and uniform state after adding water, more high range water reducer (HRWR) is need to add in mixtures, due to high absorb ability of SAPs, conducted by slump flow test, detailed in Ref. [25]. In previous paper [25–27], most of water-SAP ratio is from 10:1 to 30:1 to get good flow properties to meet the needs of requirement. In this paper, in order to achieve consistent rheological properties of fresh ECC, the average water uptake of SAPs with 550 and 75 μm is approximately 1 g/g and 0.5 g/g respectively under mixing conditions. During mixing, SAPs swell due to absorbing part of water, it can increase the bulk of SAPs and densify matrix [26]. The volume swollen SAPs in ECC1-2, ECC1-4, ECC2-2 and ECC2-4 both increase, up to 1.5%, 3.5%, 0.9% and 2.1% respectively (seen in Table 3). The PVA fiber was used in this paper both with content of 2% by total volume. The detailed properties of PVA fiber were listed in Table 2.

The raw materials are firstly mixed in a planetary mixer with 10 L capacity for 2 min at low speed, followed by the addition of water and HRWR. Mixing continuous for another 6 min. Then, fibers were slowly added into mixtures and mixed for 8 min. The fluidity of fresh mixtures was tested by jumping table before molding. After

Table 1
Mix proportion of ECC mixtures by weight (kg/m^3).

Mixture ID	Cement	FA	Sand	Water	SAP-1	SAP-2	HRWRA	Fiber	W/B	W/B*
ECC0	509	763	462	318	0	0	10	26	0.25	0.250
ECC1-2	509	763	462	318	10.2	0	12	26	0.25	0.242
ECC1-4	509	763	462	318	20.4	0	16	26	0.25	0.234
ECC2-2	509	763	462	318	0	10.2	10	26	0.25	0.246
ECC2-4	509	763	462	318	0	20.4	12	26	0.25	0.242

* Excluding water absorbed by SAP.

Table 2
Properties of PVA fiber.

Length	Diameter	Tensile strength	Elastic modulus	Density	Maximum elongation	Manufacturer
12 mm	39 μm	1620 MPa	42.8 GPa	1.2 g/cm^3	7%	Kuraray (Japan)