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Self-healing of microcracks in Engineered Cementitious Composites under sulfate and chloride environment

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HIGHLIGHTS

- ECC is durable under aggressive sulfate and chloride ions environment.
- Self-healing of microcracks within ECC material were observed.
- ECC heal faster and more completely in such environment than in water.

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ABSTRACT

Hydraulic structures are subject to high risk of deterioration associated with cracking and sulfate-chloride attack. Application of Engineered Cementitious Composites (ECC) with self-controlled tight microcracks and self-healing capacities could potentially lead to enhanced durability performance of hydraulic structures even after the formation of cracks under combined environmental and mechanical loadings. This research experimentally investigated the self-healing behavior of ECC under aggressive sulfate and chloride conditions. Resonant frequency (RF) and mechanical properties including stiffness, first cracking strength, ultimate tensile strength and tensile strain capacity were experimentally determined for ECC specimens that were preloaded to 1% strain and exposed to sulfate and sulfate-chloride solutions to simulate the service environment of hydraulic structures. The performance of ECC was found not to be adversely affected by the aggressive solutions. Instead, self-healing of the microcracks was observed leading to partial recovery of the mechanical properties. It was also found that ECC tends to heal faster and more completely in sulfate solutions than in water. These results demonstrate that ECC material remains durable under sulfate-chloride environment, which is beneficial for improving the long-term performance of hydraulic structures in such aggressive environments.

1. Introduction

Sulfate attack is a common deterioration mechanism for concrete hydraulic structures in western China and the “alkali flats” of the arid western United States. According to the report from Dam safety office [1], it is listed among the top three deterioration mechanisms for hydraulic structures, and hydraulic structures in such environment can be severely deteriorated within a few years after construction, which is far below the expected service life. The mechanism for sulfate attack of concrete is that sulfate ions penetrate into concrete, especially through cracks, and react with calcium hydroxide and calcium aluminate hydrates to form expansive products including gypsum and ettringite, resulting in internal pressure and associated cracking and deterioration of concrete [2]. Sulfate attack could happen alone, or in more common cases, e.g. in Northwestern China and marine environments, sulfate attack and chloride attack can occur simultaneously [3,4]. The effect of sulfate-chloride environment on concrete is different from that of sole sulfate environment, since the presence of chlorides limits the formation of ettringite, thereby the deterioration of concrete caused by sulfate attack is impeded. Therefore, resistance to

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sulfate and sulfate-chloride attack have both to be considered for hydraulic structures.

Sulfate and sulfate-chloride attack can be accelerated when cracks exist in hydraulic structures. Chemical attack, restrained shrinkage, thermal deformations, mechanical loads and many other factors in field conditions can all lead to concrete cracking [5]. Cracks connect the pores and form a path for aggressive ions (sulfate and chloride ions) to penetrate into the concrete, which drastically accelerates the deterioration of concrete structures. It is also found that the diffusivity of aggressive ions increases significantly with increasing crack width [6]. Therefore, it is critical to control the crack width of concrete hydraulic structures in order to achieve satisfactory long-term durability performance under sulfate and sulfate-chloride environments.

Engineered Cementitious Composites (ECC) is a class of high performance fiber reinforced cementitious composites featuring high tensile ductility and self-controlled tight cracks [7–10]. Unlike normal concrete or conventional tension-softening fiber reinforced concrete (FRC), ECC shows a strain-hardening behavior under uniaxial tension accompanied by multiple microcracks. The tensile strain capacity of ECC typically ranges from 2% to 5%, which is 200–500 times that of normal concrete. Moreover, the cracks formed in ECC are typically less than 60 μm wide. As demonstrated in previous studies [6,11,12], with such tight crack widths, the permeability and diffusivity of cracked ECC specimens remains comparable to that of uncracked concrete, which greatly delays further deterioration of the structure.

The durability study on ECC under sulfate and sulfate-chloride environment has been investigated by the authors earlier [13]. In that paper, compressive and tensile behavior of ECC under sulfate and sulfate-chloride conditions were experimentally characterized. Micromechanical study was also carried out to investigate the microscopic mechanisms underlying the composite level behavior of ECC under those aggressive environments. The experimental results obtained in [13] demonstrated that ECC remains more durable than normal cementitious materials under sulfate and sulfate-chloride environment, suggesting the potential to apply ECC as a protective surface layer for new hydraulic structures or as surface repairs for damaged hydraulic structures for enhanced long-term performance of these structures.

In addition to the superior cracking control ability and durability of ECC, potential self-healing of microcracks of ECC could further delay the deterioration of ECC and extend the service life of the structures. Self-healing refers to the phenomenon that cracks diminish autogenously in width over time. Self-healing of cracks in concrete material in the presence of water is a complex chemical and physical process. The healing of concrete cracks has been attributed to the hydration of unreacted cement, swelling of C—S—H, crystallization of calcium carbonate, closing of cracks by impurities in the water and closing of cracks by spalling concrete particles [14]. Based on previous studies [15–17], self-healing extent is inversely related to crack width. It is for this reason that ECC with tight microcracks could promote self-healing, and therefore recovers the transport properties, and in some cases even the mechanical properties of the concrete material, greatly improving the durability of the concrete structures [17–19].

The self-healing of ECC under various environments have been studied by many scholars. Precipitation of calcium carbonate and continuous hydration of unreacted cement are considered the two major contributors to self-healing of microcracks in ECC [19]. Both Yang et al. [18] and Kan et al. [19] found that wet/dry cycles are beneficial for promoting self-healing of ECC. Herbert and Li [20] reported that the self-healing of ECC is not limited to controlled laboratory environment, but is also observed in a natural environment with variable temperature and precipitation. Zhu et al. [21] studied the self-healing of ECC under freeze-thaw cycles. Sahmaran and Li [22] proved that ECC could heal sufficiently under freezing and thawing cycles in the presence of de-icing salt. Li and Li [23] and Sahmaran and Li [24] investigated self-healing of ECC in chloride and high alkaline environment, respectively. Their results show that ECC, both cracked and uncracked, remains durable under those environment exposures, and self-healing of microcracks were observed under all investigated environments, further contributing to the high durability. In addition, Qian et al. [25] and Sisomphon et al. [26] explored the influence of curing condition (air curing, water curing, cyclic wet/dry curing and 3% CO_2 concentration curing) on the self-healing of ECC incorporating different cementitious materials.

Despite the growing body of literature on self-healing of ECC, little research has been carried out on the self-healing behavior of ECC under sulfate and sulfate-chloride environment. In order to fully evaluate the potential of applying ECC in hydraulic structures, research is needed to characterize the mechanical and self-healing performance of ECC under such aggressive environments. Since typical sulfate and chloride attack involve cracking due to formation of expansive substance, the use of fly ash, the high tensile strength and ductility of ECC may help resist such failure and result in higher performance. In addition, the formation of ettringite/gypsum associated with sulfate attack may even facilitate healing of cracks through tighter sealing. These hypotheses need to be experimentally validated. This investigation together with the prior study by the authors [13] form a comprehensive experimental system for understanding the performance of ECC under sulfate and sulfate-chloride environment.

In this study, the mechanical property and self-healing of microcracks in ECC under sulfate, and sulfate-chloride environments were experimentally investigated. Specifically, ECC specimens were pre-tensioned to 1% strain level to simulate the formation of cracks in field conditions, and then exposed to sulfate and sulfate-chloride solutions for a time period of 30, 60 or 120 days. The resonant frequency and residual mechanical properties of ECC including ultimate tensile strength and strain capacity, stiffness and first cracking strength were measured after the environmental exposure to assess the performance of ECC. The research findings are expected to provide new knowledge for future application of ECC in hydraulic structures exposed to aggressive environments.

2. Experiment investigation

2.1. Materials

The same ECC mixture used in the previous study [13] was adopted in this investigation. The mix proportion of this ECC is shown in Table 1. The raw materials include Type I Portland cement, Class-F fly ash, fine silica sand, water, poly-vinyl alcohol (PVA) fibers, and a high range water-reducing admixture (HRWRA). The chemical composition of cement, fly ash and the properties of the PVA fiber used in this study are listed in Tables 2–4 respectively. Previous studies [12,13] have proved the feasibility of using this ECC mix to enhance the long-term performance of hydraulic structures.

The preparation of the mixture follows a typical ECC mixing procedure as detailed in [27]. After mixing, the fresh mixture was casted into 9 in. × 3 in. × 0.5 in. coupon specimen molds. All specimens were demolded after 24 h and air cured under laboratory conditions at a room temperature of 23 ± 3 °C and 20 ± 5% RH for 28 days.

2.2. Specimen preloading and environmental exposures

In order to investigate the durability performance and self-healing of cracked ECC under aggressive environments, ECC specimens were preloaded to 1% strain using uniaxial tensile test as shown in Fig. 1 to introduce cracks. Prior to tensile testing, four aluminum plates were glued to the ends of the specimen to facilitate gripping. The test was carried out using a 25 kN capacity testing frame under displacement control at 0.5 mm/min. Two linear variable displacement transducers (LVDTs) were mounted to the specimen to monitor the specimen extension. When