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Coupled effects of crack width, slag content, and conditioning alkalinity on autogenous healing of engineered cementitious composites

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ABSTRACT

Engineered cementitious composite (ECC) is a unique group of fiber-reinforced strain-hardening cementitious composites exhibiting crack self-healing. Due to the absence of coarse aggregates in the ECC mix design, high amount of supplementary cementitious materials (SCM) are generally used to reduce the cement content. The inclusion of slag not only changes the chemical compositionss of the matrix but also alters the crack width of ECC. Both may influence the autogenous healing potential of the slag-based ECC. This paper systematically investigates the influence of the individual factor, i.e. slag content, crack width, and environmental alkalinity, on the autogenous healing efficiency of ECC. Specifically, single-cracked ECC specimens with different slag content and crack width were conditioned under water/dry or NaOH/dry cycles. The autogenous healing performance was evaluated based on crack width reduction, resonant frequency recovery and microstructure analysis. The results show that autogenous healing is determined by a couple effect of physical properties (crack width), chemical compositionss (slag content), and environmental conditions (conditioning alkalinity). At a given slag content and certain alkalinity, there exists a maximum allowable crack width for complete healing, beyond which only partial or no healing would happen. The dominant healing product for the water/dry conditioning is $CaCO_3$ while the NaOH/dry cycles promote slag hydration and results in the formation of C–S–H and $CaCO_3$ as main healing products. It is concluded that $CaCO_3$ precipitation is more effective to engage autogenous healing than the formation of C–S–H. The concept to associate allowable crack width and slag content is proposed, which would guides ingredients selection and component tailoring to engage robust autogenous healing in ECC in the future.

1. Introduction

Infrastructures, for public transportation, energy harvesting, and commercial activities, are vital to the economic well-being of a nation and life quality of the citizens. While the importance of infrastructures in economic development is well recognized, the disrepair, especially of concrete structures, is reaching an alarming level. In most developed countries, concrete maintenance and rehabilitation cost about 50% of the outlay on infrastructures [1]. While the effort in maintenance is undoubtedly important, improving the durability of concrete is the only fundamental solution in the long term.

Deterioration of concrete infrastructure, such as corrosion of reinforcing steel, is associated with the formation of cracks. Reinforced concrete members could crack under structural loading, but more often due to constrained shrinkage/thermal deformations, which are practically inevitable [2]. Cracks in concrete become the pathways for various aggressive agents to penetrate, which accelerates deterioration of reinforced concrete structures; they also reduce the load capacity of some unreinforced concrete members such as plain concrete pavement [3] and concrete railway sleepers [4]. As a result, it is highly desirable to engage self-healing in concrete, i.e. the cracks being healed in natural environment without human interference.

The phenomenon of self-healing in cement-based material has been known for many years. It was observed that cracks of some old concrete structures were lined with white crystalline material, which demonstrated that concrete itself is capable of sealing the

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cracks with certain new substance, which were chemically formed in presence of water from the rain and carbon dioxide in the air. A number of studies [5–7] investigated water permeation through cracked concrete, also noted a gradual reduction of permeability over time, which again demonstrated the capability of the cracked concrete to seal itself.

Two approaches have been developed to promote self-healing in concrete. The first approach, referred to as autonomic healing [8], embeds capsules or packets containing self-healing compounds to the concrete matrix [9–13]. In the encapsulation-based approach, the capsules contain chemical compounds, either two-part adhesives or additional matrix resins [14,15]. When the capsules are broken by the propagating crack, the compound is released exclusively into the damaged location, resulting in immediate and efficient repair. Despite the obvious advantage in self-healing efficiency, the amount of required healing compound increases rapidly as crack grows and widens, which causes very high cost [16].

The second approach relies on the self-healing ability of the concrete matrix itself. It is usually referred to as autogenous healing [17]. This approach relies on the homogenous and pervasive distribution of healing compounds, e.g. free calcium ions and unhydrated cement particles in concrete matrix [18,19]. Upon cracking, these compounds are activated by contacting water and carbon dioxide present in the natural environment and form healing products to fill cracks. Such healing products normally take the form of calcite precipitates and/or additional hydration products. Autogenous healing turns the deteriorating environmental agents into beneficial healing reagents. Despite the relatively lower healing efficiency compared to encapsulation-based approach, autogenous healing offers great potential for long-term functionality, and requires relatively lower cost [20,21]. However, lack of reliability is the major obstacle to achieve robust autogenous healing. For instance, while some of the cracks in old concrete structures were healed, more of them remain unhealed [20]. It has been reported that crack width control is essential to form healing products within cracks [5–7]. Finer crack width, which helps to maintain the relatively high alkalinity for calcite precipitation, is more likely to induce autogenous crack healing [5]. Unfortunately, such tight cracks are often difficult to achieve in normal reinforced concrete structures [22].

Engineered cementitious composite (ECC) is a unique group of fiber-reinforced strain-hardening cementitious composites exhibiting ultra-high ductility of several percent with the formation of multiple fine cracks [23–25]. Fig. 1 illustrates the relationship between tensile stress, strain, and average crack width in a typical polyvinyl alcohol (PVA) fiber-reinforced ECC. As can be seen, the crack width increases gradually with the increase of tensile stress and stabilizes at around 60 μm after tensile strain of 1%, i.e. the crack width in ECC is self-controlled and can be regard as an intrinsic property of the material [17]. Autogenous healing are more likely to happen in such tight cracks in PVA-ECC [17,26–28], but the degree of healing of ECC is still highly affected by the crack width. As shown in Fig. 2, Yang et al. [17] found that for the typical PVA-ECC, the smaller cracks are more likely to heal. Specifically, the maximum allowable crack width to obtain complete resonant frequency recovery through autogenous healing was around 50 μm; partial recovery was observed for cracks between 50 and 150 μm; cracks beyond 150 μm did not show any recovery.

Ground granulated blast furnace slag (GGBS) is often used as a supplementary cementitious material (SCM) in concrete [29]. GGBS can be activated in the alkaline environment in concrete, contributing to the compressive strength in a long-term [29,30]. The inclusion of slag changes the autogenous healing efficiency of normal concrete. Van Tittelboom et al. [35] have shown that under continuous water conditioning, replacing cement with blast furnace slag at 50% led to the highest crack closing rate compared to the 0% and 85% replacement. Huang et al. [36] concluded that the blended slag cement paste (66% wt.) had higher autogenous healing potential than Portland cement paste.

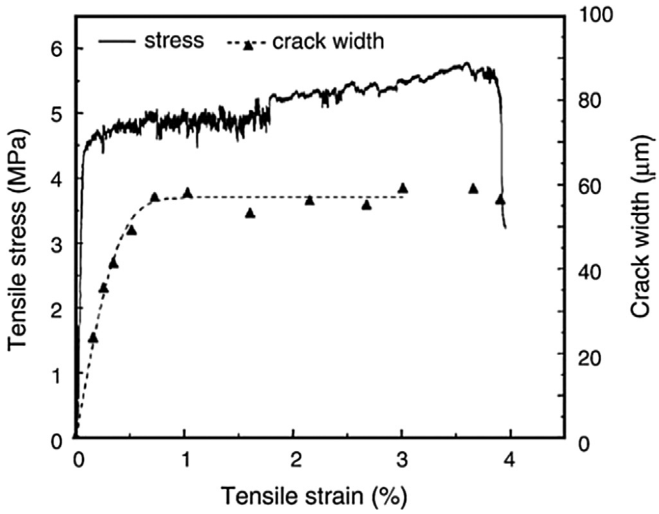

Fig. 1. Typical tensile stress-strain-crack width curve of ECC [17].

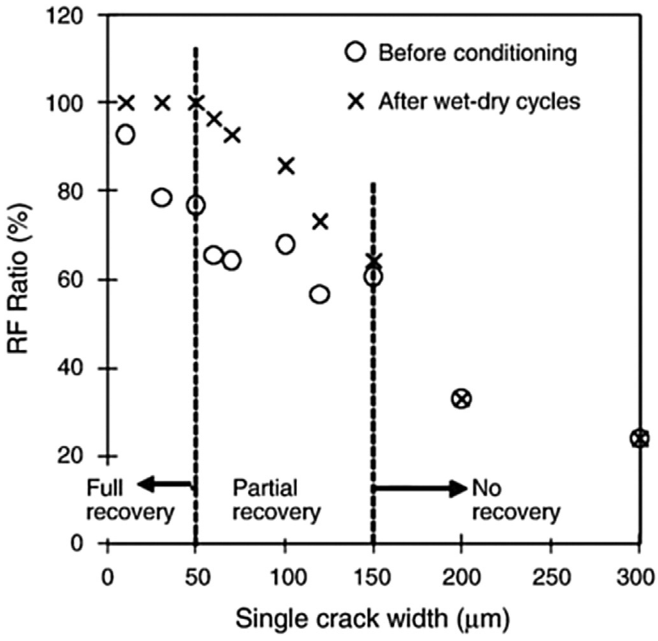

Fig. 2. Resonant frequency (RF) ratio as a function of crack width [17].

In ECC mix design, due to the absence of coarse aggregates, the cement content is much higher than conventional fiber-reinforced concrete. As a result, GGBS is often suggested as cement replacement in ECC mix design [31–34]. Qian et al. [32] studied the self-healing behavior of ECC adopting high slag content and concluded that the healing efficiency was comparable with that of ECC that has zero slag. Sahmaran et al. [37] found that in slag-rich ECC, cracks up to 100 μm were completely sealed after 60 days of continuous water conditioning. All results reported in the previous studies; however, were the combined effects from changes of chemical compositionss of matrix and crack width of composite due to the addition of slag. All study failed to separate the