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Review

A review of intrinsic self-healing capability of engineered cementitious composites: Recovery of transport and mechanical properties

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HIGHLIGHTS

- Self-healing capability of ECC is examined depending on literature survey.
- Factors governing intrinsic self-healing capability of ECC are discussed.
- Assessment of self-healing by transport and mechanical properties are emphasized.
- Results of different experimental studies are collected and summarized.

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ABSTRACT

The need for viable materials in sustainable infrastructures is driving the creation of multifunctional strain-hardening cementitious composites that combine brittle cementitious matrices with fibers. Unlike conventional concrete, these materials typically show multiple microcracking behavior with strain-hardening response under tensile loading. Even with tight widths, however, crack formation is a critical problem that reduces the mechanical performance of structures and accelerates the ingress of water and aggressive substances. As part of a class of cement-based composites exhibiting strain-hardening response, engineered cementitious composites (ECCs) have a high likelihood of preventing water and harmful chemicals from penetrating by sealing existing cracks and regaining original mechanical and durability properties through self-healing. This promises to contribute to the development of a new generation of highly durable, damage-tolerant structures. ECCs are potentially excellent for intrinsic self-healing due to tight crack widths and high amounts of supplementary cementitious materials in their mixture proportions. This paper details the parameters governing self-healing efficiency and the effect of self-healing on the residual mechanical and transport properties of cementitious composites. Test methods measuring the effect of these parameters on healing efficiency are also described.

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1. Introduction

Concrete has been the most popular construction material since its first practical use for industrial purposes in the late nineteenth century. Its versatility, combined with the wide availability of raw materials for production, have only made it more popular in the intervening centuries. Due to industrialization and ever-increasing population, it is also estimated that production will continue to grow. Despite its popularity in the construction industry, however, the material is not perfect; relatively low tensile strength (compared to strength in compression) stands in the way of universal use. Today, steel embedded inside concrete (reinforced concrete) is used in most construction practices around the world. However, although steel and concrete have synergistic interaction, problems related to the durability and mechanical properties of conventional concrete (generally due to relatively low tensile load carrying capacity and low ductility) impact structural serviceability, leading to the need for urgent repair and/or renovation in infrastructures with crack-originated damage.

To illustrate this situation, the annual cost in the USA to maintain existing bridges is around $5.2 billion [1], with an estimated budget of $20 billion to $200 billion for reconstruction [2–3]. In the UK, nearly 45% of the budget allocated for the construction and building industry is spent for repair and maintenance applications [4]. Countries in the European Union face a similar situation, with an annual disbursement of over $1 billion for bridge maintenance and an estimated $20 billion for the maintenance of all infrastructure types [5].

As a result, self-healing is a topic of significant interest in civil engineering. Although it was observable in civil infrastructures as long as a century ago [6–7], studies related to it have only started to appear in the last two decades [8–9]. Civil infrastructures that use concrete-like materials lack quality, durability and serviceability, requiring repeated inspection and repair. Self-healing of damage (e.g. cracks) in concrete structures could result in reduced deterioration rates, lower repair frequency, minimized costs and extended ultimate service life [8]. In addition, self-healing with no external human interference allows self-repair in places that are not reachable due to structural restrictions, especially in the case of large infrastructures.

Given their beneficial effects on structural serviceability, self-healing methodologies have been used by a number of researchers over the years. Invaluable information related to these emerging self-healing techniques has already been summarized in several papers [8–12]. Those methodologies included hollow fibers [13–22], chemical encapsulation [23–26], bacteria-based biological self-healing [27–30], expansive agents and mineral admixtures [31–34], shape memory materials [35–38] and self-healing triggered by self-controlled tight microcracking [39–46]. Each unique methodology holds great promise for future applications. However, each technique also has its drawbacks, so it is not easy to decide which one is the most efficient. However, Van Tittelboom and De Belie [9] suggest that the future self-healing research is more likely to concentrate on more innovative approaches such as hollow fiber utilization and encapsulation, since the autogenous healing (intrinsic healing due to the composition of the cementitious matrix) of cement-based materials will always depend on tight crack widths, the chemical composition of the matrix, time of cracking and so on. On the other hand, for the time being, intrinsic self-healing favored by the formation of tight microcracks seems to be more robust compared to other methodologies [8].

2. Engineered cementitious composites for tight microcracking

Engineered cementitious composites (ECCs) were first introduced by Li et al. twenty years ago, and research related to these materials is growing every day [47]. The most important characteristic that separates ECC from conventional fiber reinforced cementitious composites is its strain-hardening behavior under excessive tensile loading conditions. Strain-hardening behavior, which accompanies superior tensile ductility, is based on micromechanics-based material design theory, using a synergistic interaction between individual components (e.g. fibers, matrix and the interface between the two) rather than relying on high fiber content. It is realized by the formation of many closely spaced multiple microcracks with widths of less than 100 μm. This performance is obtained with 2% fiber volume, although production with lower or higher fiber volumes is possible depending on structural requirements. The standard ECC mixture (also known as M45), which has the broadest published dataset in literature, utilizes CEM I 42.5 type standard Portland cement, low calcium Class-F fly ash, fine silica sand, polyvinyl alcohol fibers (PVA), water and superplasticizer. The typical stress–strain curve of an ECC specimen tested under uniaxial tensile loading is shown in Fig. 1-a, multiple microcracks forming due to strain-hardening response are shown in Fig. 1-b [48,49].

Among the parameters with the greatest influence on the formation of effective self-healing, tight microcracking is significant due to its direct effect on the amount of self-healing products generated by the cementitious system to plug the crack. As might be expected, larger widths require higher volumes of products to be formed, and this situation is likely to accelerate self-healing kinetics due to higher space availability for newly formed products and easier ingress of necessary substances into the cracks for self-healing to occur [50]. Although wider cracks accelerate self-healing kinetics, they may result in inadequate plugging of the total crack opening, and may not be sufficient to retrieve a material's original durability and mechanical properties. Although it is more logical to think that narrower cracks would be healed more easily, maximum allowable crack opening values that could be healed intrinsically vary dramatically in different studies. For example, Jacobsen et al. [51] suggest that cracks should have maximum widths of 5–10 μm to be sealed completely. According to Ismail et al. [52], however, maximum sealable crack width is 53 μm. Reinhardt and Jooss [53], Edvardsen [54], Aldea et al. [55] and Clear [56] all state that for complete sealing, crack widths should not exceed 100 μm, 200 μm, 205 μm and 300 μm levels, respectively. Given the fact that ECCs exhibiting crack widths as