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Tailoring Engineered Cementitious Composites with local ingredients

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HIGHLIGHTS

- ECC with tensile strain capacity of 3–6% can be developed based on local ingredients.
- The Ca-content and particle size play an important role in ECC development.
- The inclusion of crumb rubber can be effective in enhancing tensile ductility in ECC.

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ABSTRACT

Engineered Cementitious Composites (ECC) is a kind of High Performance Fiber Reinforced Cementitious Composites (HPFRCC) with a low fiber volume content of 2%. The unique properties of tensile strain hardening behavior and tight multiple cracks ensure that ECC can meet the stringent requirements of resiliency and durability of concrete infrastructures. While there are strong initiatives for the adoption of ECC in China, wider applications will require localization of material ingredients. In this paper, ECCs with local ingredients, including domestic PVA fibers, fly ash and crumb rubber, were developed under the guidance of micromechanics model for ECC. The fiber/matrix interface parameters and matrix parameters from single fiber pullout test and fracture toughness test respectively, were obtained for the tailoring of domestic ECC. The experimental results indicated that cost-effective ductile ECCs can be designed successfully using local material ingredients. These composites show an ultimate tensile strength of 4–5 MPa and tensile strain capacity of 3–6%.

1. Introduction

Engineered Cementitious Composites (ECC), a special type of High Performance Fiber Reinforced Cementitious Composites (HPFRCC), has been researched widely since it was developed by Li and coworkers [1] in the 1990s. ECC is designed through tailoring of the fiber, matrix, and interface properties, based on the theory of micromechanics and fracture mechanics [2,3]. ECC possesses an extreme tensile ductility, in the range of 3–5% (300–500 times that of concrete or FRC) [4,5]. A typical uniaxial tensile stress–strain curve is shown in Fig. 1. After first cracking the tensile load capacity continues to rise, resulting in a macroscopic strain-hardening phenomenon accompanied by multiple micro-cracking. The crack width development is also shown in this figure, which reveals that crack widths increase steadily up to about 60 μm, at about 1% strain. Between 1% and 5% strain, the crack width stabilizes and tends to remain constant at 60 μm while the number of cracks increases [6]. Unlike most concrete and fiber reinforced concrete materials, crack width in ECC is an intrinsic material property, independent of structural size, steel reinforcement, or the load applied to a structure built with ECC. These special properties ensure that ECC can meet the stringent requirement of resiliency and durability in infrastructures. ECC has been successfully applied in bridge deck link slab [7], bridge deck overlays, dam repair and coupling beams in high rise buildings [8,9].

Typical ECC material consists of controlled quantities and types of cement, sand, fly ash, water, additives, and short, randomly oriented polymeric fibers (e.g. Polyethylene, Polyvinyl Alcohol). Fiber volume fractions are minimized ($V_f = 1.5–2\%$) for ease of construction execution and economic feasibility in infrastructure applications [10,11]. For broader adoption of ECC in large-scale applications, the use of local materials is preferred, both for economic reasons as well as to enhance infrastructure sustainability.

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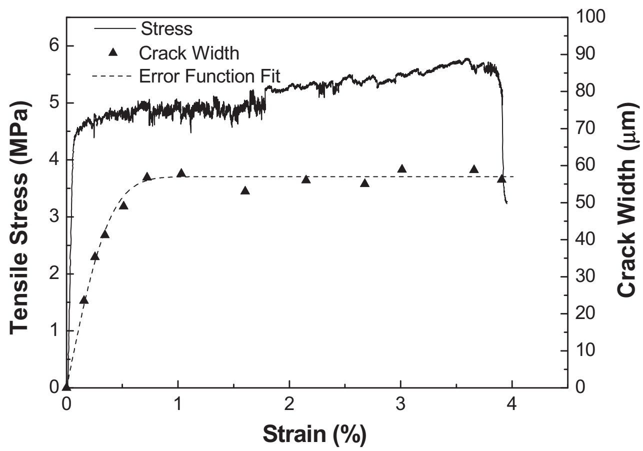

Fig. 1. Typical uniaxial tensile stress–strain–crack width curve of ECC [17] showing high tensile ductility and tight crack width.

Domestic ECCs using local raw materials and Kuraray's PVA fiber have been developed by a number of researchers with success, including Mechtcherine and Schulze [12] in Germany and da Silva Magalhães et al. [13] in Brazil. In China, ECCs with domestic PVA fibers and other local raw materials were researched by Zhang and Qian [14], Qian and Zhang [15] and Pan et al. [16]. Zhang and Qian analyzed the feasibility of Engineered Cementitious Composites with local ingredients through four-point bending test; using domestic PVA fiber at 1.6% by volume content. Pan et al. developed ECC with a combination of domestic and imported (Kuraray Co. Ltd.) PVA fibers.

This study focuses on developing ECC with all domestic raw materials including cement, silica sand, fly ash, crumb rubber and PVA fiber. According to ECC design theory, the strain hardening behavior of ECC is largely governed by matrix fracture toughness, fiber bridging capacity and initial flaw size distribution. In this study, to tailor domestic ECC, matrix fracture toughness and fiber/matrix interfacial bond were adjusted with the addition of fly ash and crumb rubber while fiber bridging capacity was adjusted with different fiber content. The relevant parameters were obtained through single fiber pullout test and matrix fracture toughness test. In addition, the mechanical properties were assessed through compressive and uniaxial tensile test.

2. Micromechanics-based analytical models

The fundamental requirement of ECC with tensile strain hardening lies in the steady state propagation of micro-cracks emanating from material matrix defects under tensile load. The design theory of ECC was proposed by Li and coworkers [1,3,18] based on the early works of Marshall and Cox [19] on flat crack analyses of ceramics matrix composites reinforced with continuous aligned fibers. Li's micromechanical model was further improved by Lin et al. [20], Yang et al. [21] and Kanda and Li [22]. According to this design theory, two criteria, strength criterion and energy criterion, must be satisfied for flat crack propagation to prevail over the more common Griffith crack propagation mode. First, strength criterion must be met in order to ensure an adequate fiber bridging capacity upon micro-crack initiation from a defect site. Specifically, it requires that the first cracking strength σ_{fc} controlled by matrix fracture toughness and initial flaw sizes to be less than fiber bridging capacity σ_0 on any given potential crack plane. That is

$$\sigma_{fc} \leq \sigma_0 \tag{1}$$

Furthermore, the steady-state crack propagation criterion requires the energy balance as shown in (2) [23].

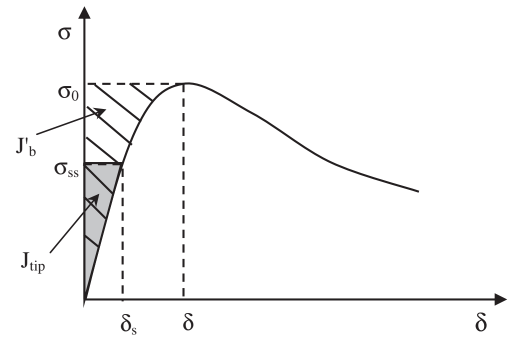

Fig. 2. Typical curve of fiber bridging stress σ – crack opening width δ.

$$\sigma_{ss}\delta_{ss} - \int_0^{\delta_{ss}} \sigma(\delta)d\delta = J_{tip} \tag{2}$$

where σ_{ss} is the steady state cracking stress; δ_{ss} is the flat crack opening corresponding to σ_{ss} (Fig. 2); J_{tip} is the crack tip toughness, which can be approximated as the cementitious matrix toughness if fiber volume fraction is less than 5%, calculated as in (3); σ_0 is the maximum bridging stress which corresponds to the crack opening δ_0.

$$J_{tip} = \frac{K_m^2}{E_m} \tag{3}$$

where K_m is the matrix fracture toughness and E_m is the matrix Young's modulus. Since the left hand side of (2) has the upper limit of

$$\sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J'_b \tag{4}$$

it follows that a necessary condition for steady state cracking is

$$J_{tip} \leq J'_b \tag{5}$$

The strength criterion governs the range of flaw sizes that can be initiated to form part of the multiple micro-crack population during strain-hardening while the energy criterion governs the steady-state flat crack propagation. Tensile strain-hardening behavior could be achieved if both criteria are satisfied. Otherwise, the tension-softening behavior of common fiber reinforced concrete prevails. In addition, considering variability of fiber and flaw size distribution, Kanda and Li [24] recommended that $J'_b/J_{tip} > 3$ and $\sigma_0/\sigma_{fc} > 1.45$ to ensure robust strain-hardening behavior.

3. Experimental programs

3.1. Raw materials and mixture proportions

The raw materials used in this study were all produced by local manufacturers. The ordinary Portland cement (PII 42.5R cement [25]) and fly ash (Type I [26]) meet Chinese standards. Five kinds of fly ash from different coal-fired power plants were screened for use in the investigation. The chemical compositions of the cement and fly ash are listed in Table 1. The fine silica sand of 106–212 μm has a mean size of 150 μm. The crumb rubber has a size of 180 μm and a density of 1.19 g/cm^3. The grain size distribution of aggregates and cementitious materials are presented in Fig. 3. Two domestic PVA fibers (produced by Wanwei High-tech Co. Ltd (WW) and Bao Hualin Co. Ltd (BHL) in China) were used in this research program. As control, a PVA fiber often adopted in ECC studies (REC-15 fiber with a surface oil coating of 1.2% by weight, produced by Kuraray Co. Ltd in Japan) was included in this