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Review

Direct tensile properties of engineered cementitious composites: A review

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HIGHLIGHTS

- A comprehensive review of the fundamental factors influencing the tensile properties of ECC was conducted.
- The durability of ECC including the long-term tensile properties, the impact of high temperature, cyclic and fatigue loading was reviewed.
- The future directions of ECC have been pointed out.

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ABSTRACT

The high tensile strain capacity of engineered cementitious composites (ECC) is exceptional for cementitious material. In the present paper, a comprehensive review is conducted to summarize the fundamental information of factors that influence the tensile properties of ECC, specifically the fiber properties, specimen size and geometry, and strain rate. The extended durability of ECC, including the long-term tensile properties, the mechanical behaviors under the high temperature impact and the cyclic and fatigue loading, is also paid special attention. It is concluded that (1) fiber properties have a decisive effect on the tensile performance of ECC; (2) size and geometry effect exists in tensile test and needs further study; (3) high rate loading leads to a noticeable changes in the tensile properties of ECC; and (4) durability of tensile properties should be further investigated for the better application of ECC material.

Contents

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1. Introduction

Engineered cementitious composites (ECC, also referred to as strain hardening cementitious composites and pseudo strain cementitious composites) is the name for a special class of high-tensile-ductility concretes. Unlike the traditional trial-and-error material development methodology, ECC is designed based on micromechanical theory, resulting in a tensile strain capacity more than 3%, while keeping the fiber volume fraction no greater than 2% [32,38,60,35]. When subjected to tension, ECC exhibits multiple cracking and strain-hardening behaviors with crack width less than 100 μm, making it a highly durable material under environmental impacts (Sahmaran et al., 2007, [55]). A brief summary of major physical properties of ECC under static loading is given in Table 1.

It should be noted that ECC's properties are tailorable through the utilization of micro-mechanical tools. Even higher mechanical properties beyond those in Table 1 could be expected according to the demand and the improved technology in future.

Due to its excellent tensile strain capacity and special crack pattern, ECC has attracted the worldwide attentions. According to the statistics by Google scholar, there are approximately 10,000 relevant scientific articles published in the last two decades. These researches include the design theory of ECC [32,20], the effect of mineral admixtures on the mix proportion, the compressive and tensile properties together with their corresponding models [29,20,25], the shear properties ([58,34], the fracture properties [27,46], the effect of fiber interfacial treatment on the tensile properties [37], the durability and long-term tensile properties [59], the self-healing phenomenon [31,50,18,61,73], the simulation of cracking propagation [11,12], the nanoscale structure [57] and the reinforced ECC member and its structural application [19]. ECC using local material ingredients have been successfully produced in various countries, including Japan (Kanda et al., 2006), China [28,41,49,75], Europe [46,47,59], and South Africa [3], in addition to the US. It is noticed that there are already some practical applications in US [30], Japan [30], China [74], etc.

In the last two decades, several reviews on ECC have been conducted by Li [30] on its material properties and applications, by [59] on the durability of ECC under various environments, by [19] on its structural design and performance, and by [61] on its self-healing properties.

Since high tensile ductility is one of the most important characteristics in ECC material, the uniaxial tensile properties of ECC are always highlighted in the existing investigations. In recent years, researchers have studied the effects of fiber properties [1,7,68], specimen geometry ([43,44,77]), strain rates [3,8,40,43–45,69,70,53,6] and fatigue and cyclic loading [10,21,15,16,48]. In addition, the long-term tensile properties of ECC were paid special attention. Therefore, the present review tries to summarize the recent progress in these above-mentioned areas, to provide some insights and suggestions for further research and to facilitate the applications of ECC.

2. Fiber types used for ECC

Several kinds of fibers, including polyvinyl alcohol fiber (PVA), polyethylene fiber (PE) and steel fiber (SF) were monopoly or hybrid employed to produce ECC [36,64,66,67,40]. Due to its good dispersibility and proper interface properties, PVA fiber was most commonly utilized in producing ECC [37]. The property of normally used PVA fiber is listed in Table 2. To reduce the interfacial bond strength between fiber and matrix, oil coating (0.8–1.2% content by mass) on fiber surface was recommended to modify the hydrophilic nature of PVA fiber [37]. By this way, the maximum tensile strength of PVA-ECC ranged from 3 to 8 MPa with the corresponding tensile strain reaching 5% [30].

Recently, PE fiber with high strength and high Young's modulus was utilized to produce a high tensile strength and high ductility ECC. The property of PE fiber is listed in Table 2. [17] and [23] reported the mechanical properties of ultra-high-performance strain hardening cementitious composites (UHP-SHCC) with an average tensile strength of 10 MPa and an average elongation of 2.8%. [51] developed a high strength, high ductility concrete (HSHDC) with the direct tensile strength of around 15 MPa and the tensile strain between 3% and 4%. [5] used the PE fiber to reinforce alkali-activated slag-based composites (PE-AASC) which yielded an ultimate tensile strength ranging from 4.0 to 15.6 MPa with the corresponding the tensile capacity up to 7%. [66–68] and [76] developed the ultra-high ductility cementitious composites (UHDCC), with the maximum tensile strength reaching 20 MPa and the tensile capacity ranging from 8% to 13%. Unlike the hydrophilic PVA fiber, PE fiber is hydrophobic which needs no surface treatment to reduce the bond strength at matrix/fiber interface. Comparatively, the crack width of PE-ECC under and after tension is wider than that of PVA-ECC with the identical fiber volume fraction. Generally, the PVA fiber is suitable for producing moderate strength ECC with better environmental durability, while the PE fiber is more suitable for high strength ECC used as structural material.

Maalej et al. [40] developed an analytical model of hybrid PE and steel fiber to obtain ECC. The typical PVA-ECC, PE-ECC and steel/PE hybrid stress-strain curves from authors' own test results are shown in Fig. 1.

Table 1
Major physical properties of ECC.

Compressive strength (MPa)	First cracking strength (MPa)	Ultimate tensile strength (MPa)	Ultimate tensile Strain (%)	Young's modulus (GPa)	Flexural strength (MPa)	Density (g/ml)
20–150	3–10	4–20	3–12	18–40	10–50	0.95–2.3

Table 2
Properties of PVA and PE fiber.

Fiber type	Nominal strength (MPa)	Diameter (μm)	Length (mm)	Young's modulus (GPa)	Elongation (%)	References
PVA fiber	1620	39	12	42.8	6–8	Almost all the PVA-ECC
PE fiber	–	10	6.4	88	–	[21]
PE fiber	–	38	12.7	73	–	[22]
PE fiber	3000	28	12.7	100	3.1	Ranade et al. [51,52]
PE fiber	2900–3800	20–28	12–18	100–120	2–3	[66]
PE fiber	2700	12	18	88	–	[5]