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Tensile performance of sustainable Strain-Hardening Cementitious Composites with hybrid PVA and recycled PET fibers

Jing Yu[a,*], Jie Yao[a], Xiuyi Lin[b,c,*], Hedong Li[b,d], Jeffery Y.K. Lam[b], Christopher K.Y. Leung[a], Ivan M.L. Sham[b], Kaimin Shih[e]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China
[b] Nano and Advanced Materials Institute, Hong Kong Science Park, Shatin, Hong Kong SAR, China
[c] Department of Applied Physics, The Hong Kong Polytechnic University, Hung Hom, Hong Kong SAR, China
[d] Institute of Advanced Engineering Structures and Materials, College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, China
[e] Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong SAR, China

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ABSTRACT

Strain-Hardening Cementitious Composite (SHCC) is a type of advanced construction material that can enhance the resiliency and durability of structures. However, the high cost of the constituents limits the wide application of SHCCs. To reduce the material cost and improve the sustainability, this study explores the potential of replacing commonly-used polyvinyl alcohol (PVA) fibers by recycled polyethylene terephthalate (PET) fibers. The potential of fiber hybridization was first evaluated using micromechanical modeling, and the ultimate tensile strain of hybrid-fiber SHCCs was estimated using a semi-empirical method. Then the tensile performance of SHCCs after standard curing and accelerated aging was experimentally evaluated, and the crack pattern development with increasing tensile strain was recorded. Satisfactory mechanical performance can be achieved even when 50% of PVA fibers are replaced by recycled PET fibers with surface treatment. In addition, using recycled PET fibers in SHCCs can significantly reduce the material cost and environmental impact.

1. Introduction

Concrete is arguably the most important construction material in the modern world. From its early days, plain concrete has been well known as a material that is strong in compression, but fails under tension in a brittle manner with little warning. While the inclusion of steel reinforcement has made concrete highly effective for practical construction, improvement in the resiliency, durability, and sustainability of the infrastructure can be further enhanced if concrete can be made ductile [1]. To overcome the brittleness of concrete, advancements in material science and engineering have made possible the development of Stain-Hardening Cementitious Composites (SHCCs), which exhibit tensile strain-hardening and multiple cracking [2–4]. SHCC is also known as Engineered Cementitious Composite (ECC), Pseudo-Ductile Cementitious Composite (PDCC) or Ultra-High Toughness Cementitious Composite (UHTCC) in the literature. At the ultimate state under uniaxial tension, the strain of SHCCs can reach 3–8% [5–11] (Fig. 1), which is about 300 to 800 times the tensile strain capacity of ordinary concrete and fiber reinforced concrete (around 0.01%). In addition, the crack width can be controlled to $< 100\,\mu m$ [5–11] (Fig. 1), which results in excellent durability of SHCCs [12]. In this paper, SHCCs are defined as a specific type of High-Performance Fiber-Reinforced Cementitious Composites with the ultimate tensile strain no less than 1%. With high ductility, excellent crack control ability as well as high toughness, SHCCs have clear advantages over normal concrete for many construction applications [1,13,14].

However, compared to conventional concrete, ordinary SHCCs are costly, and intensive in energy and carbon footprint [15]. One possible solution to this issue is to partially or even totally replace the cement and/or fine aggregates with industry by-products and/or other low-cost alternatives, such as fly ash [16–20], ground granulated blast-furnace slag [21–24] and coarse sands [25–27]. Another more effective solution is to replace the commonly-used high-performance polyethylene (PE) or polyvinyl alcohol (PVA) fibers. Taking the typical SHCC M45 in Li [5] with PVA fibers for example, almost 80% of the material cost comes from the fibers [20]. Moreover, the cost of PE fibers is about 8 times that of PVA fibers on an equal volume basis [5]. Therefore, seeking for other fibers with lower cost but adequate performance for SHCCs is critical for practical applications of the material.

Many studies have reported the application of other types of

* Corresponding authors.
E-mail addresses: jyuad@connect.ust.hk (J. Yu), jyaoad@connect.ust.hk (J. Yao), xylin@polyu.edu.hk (X. Lin), lihedong@zju.edu.cn (H. Li), jefferylam@nami.org.hk (J.Y.K. Lam), ckleung@ust.hk (C.K.Y. Leung), ivansham@nami.org.hk (I.M.L. Sham), kshih@hku.hk (K. Shih).

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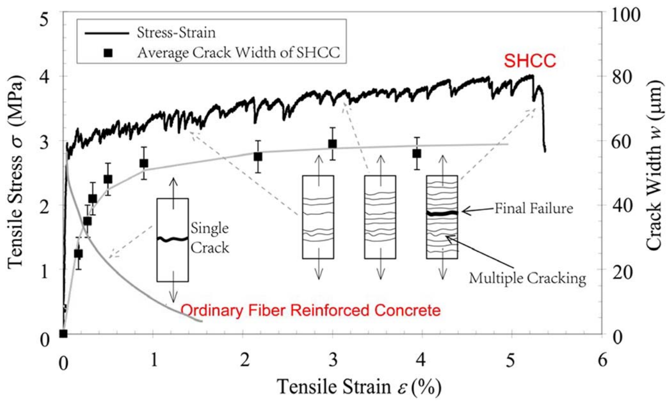

Fig. 1. Typical tensile stress-strain curve and crack width development of SHCCs (modified from Li [5]).

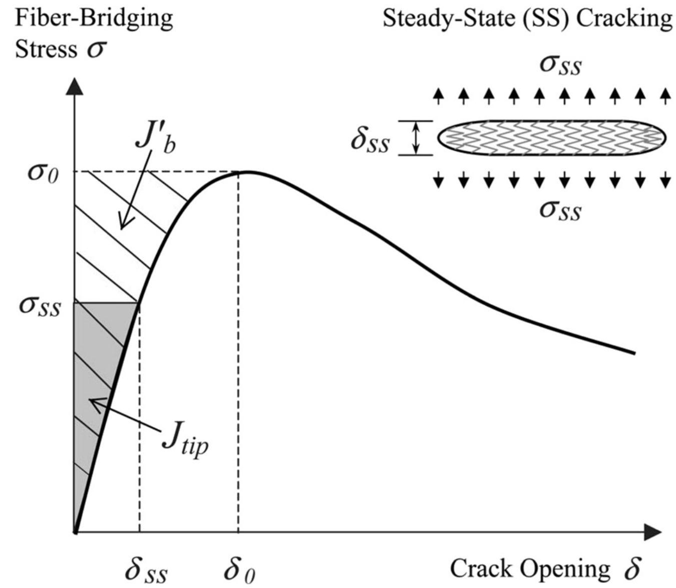

Fig. 2. Typical σ-δ constitutive relation of SHCCs (modified from Wang and Li [16]).

polymeric fibers in concrete for crack control and ductility enhancement [28,29]. However, most of these polymeric fiber reinforced composites showed tensile and/or deflection softening, or just very slight tensile strain hardening (< 0.5%) response at low fiber content (< 2 vol%). This is because the combination of the matrix, fibers and interfacial properties cannot fulfill the criteria for robust multiple cracking, according to the micromechanical theory proposed by Li and co-workers [2,3]. Limited studies have been reported on using fibers with lower cost to partially or even totally replace PE or PVA fibers in SHCCs. The fiber alternatives include polyethylene terephthalate (PET) fibers, high tenacity polypropylene (HTPP) fibers and ordinary polypropylene (PP) fibers. The fiber properties as well as the tensile characteristics of the resulting SHCCs are summarized in Table 1. Generally speaking, comparing to typical SHCCs (Fig. 1), the tensile performance (strength or strain) of SHCCs in Table 1 decreases when PE or PVA fibers are replaced. However, the achievable properties (e.g., ultimate tensile strain of 2% or above) are still useful for some practical applications.

Polyethylene terephthalate (PET), belonging to the polyester group, is a low-cost polymer that has been widely used in various plastic products, especially consumer packaged goods. However, the immense amounts of used PET commodities increase the burden on public landfills and lead to serious environmental issues. To reduce the cost and improve the sustainability of SHCCs through the use of recycled materials, this study explores the possibility of totally or partially replacing PVA fibers by recycled PET fibers, made from waste plastics. The potential of fiber hybridization was first evaluated by pseudo-strain-hardening (PSH) performance indices in micromechanical modeling, and the ultimate tensile strain of hybrid-fiber SHCCs was estimated with a new semi-empirical method. The tensile performance of SHCCs after both standard curing and accelerated aging was then experimentally evaluated. The crack pattern development with increasing tensile strain was recorded, and the effect of the PET fiber surface treatment was also studied. Finally, the influence of using recycled PET fibers on the material cost and environmental impact of SHCCs was quantitatively evaluated. The findings from this work can support the future development of sustainable SHCCs.

2. Micromechanical modeling of tensile performance of SHCCs with hybrid fibers

2.1. Basics of micromechanical modeling

The fiber-bridging σ-δ constitutive relation (Fig. 2) describes the relationship between fiber bridging stress σ transferred across a crack and the corresponding crack opening δ, which relates the material parameters (micro-scale) to the composite performance (macro-scale). Therefore, control of the σ-δ constitutive relation by tailoring material parameters is the key to successfully design of SHCCs, in terms of ultimate tensile strength and strain, as well as steady-state crack width in particular [30].

According to the micromechanical model of SHCCs [3], two criteria must be satisfied to ensure strain-hardening and multiple cracking. The strength criterion requires that the first-cracking strength σ_{fc} must not exceed the fiber bridging capacity σ_0 crossing that crack (Fig. 2), i.e.

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

The energy criterion requires that the crack tip toughness J_{tip} must be no more than the complementary energy $J_b^{'}$ (Fig. 2), i.e.

Table 1
Literature review on SHCCs with PVA or PE fibers partially or totally replaced.

Reference		Choi et al. [27]	Yang and Li [60] & Felekoglu et al. [61]	Zhang et al. [62]
Fiber parameters	Fiber type	Polyethylene terephthalate (PET)	High tenacity polypropylene (HTPP)	Polypropylene (PP)
	Length [mm]	10	10	12
	Diameter [μm]	33	10–12	36
	Elastic modulus [GPa]	11	6	5
	Tensile strength [MPa]	950	750–850	482
Fiber volume fraction [vol%]		PVA[a] 1.6 + PET 0.4	HTPP 2.0	PP 2.0
SHCC tensile strength [MPa]		2[b]	2–2.5	2.5[b]
SHCC ultimate tensile strain [%]		2.5[b]	2–4	3.5[b]
Remarks			Difficulty in processing due to the high aspect ratio of HTPP fibers	

[a] PVA: Kuraray™ K-II REC15 polyvinyl alcohol fibers.
[b] Approximate value from the figure in the corresponding literature.