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Stress strain behavior of hybrid steel-PVA fiber reinforced cementitious composites under uniaxial compression

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HIGHLIGHTS

- Hybrid steel-PVA fiber reinforced cementitious composites tested under axial compression.
- Hybrid fibers can greatly increase the compressive strength and toughness of cementitious composites.
- A stress strain model is proposed for hybrid steel-PVA fiber reinforced cementitious composites.

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ABSTRACT

It is well understood that the inclusion of fibers into concrete can reduce the weakness and increase the performance of concrete. Hybrid fibers can achieve more performance gain compared with single fiber reinforced concrete. Fiber reinforced cementitious composites are a breed of high performance concrete containing fibers but without coarse aggregate. This study investigated the axial compressive behavior of cementitious composites with hybrid steel-polyvinyl alcohol (PVA) fibers. A total of 24 cementitious composites of different fiber content and compressive strength were investigated. The failure modes, peak stress, peak strain, elastic modulus, toughness index, as well as stress strain curves of the cementitious composites were obtained and carefully interpreted. Based on the test results, a stress strain curve with satisfactory accuracy was proposed for cementitious composites with hybrid steel-PVA fibers.

1. Introduction

It is well known that concrete is a brittle material with high compressive strength and low tensile strength. One way to increase the tensile strength and the tensile strain of concrete is to add randomly distributed fibers into concrete, which forms fiber reinforced concrete (FRC). Many different fibers have been considered for inclusion into concrete, such as steel fibers, glass fibers, carbon fibers and natural fibers [1]. Depending on the type and amount of fibers adopted, the compression strength of FRC may increase or decrease when compared with plain concrete of the same mix proportion, while the deformation capacity of FRC in compression is generally better than its plain concrete counterpart.

While the benefit of single fiber may be limited, hybrid fibers have been investigated to achieve better performance. For example, when both stiff and ductile fibers are included, stiff fibers can provide strength increment while ductile fibers can increase the deformation capacity (or toughness) of FRC [1–4]. Alternatively, short and long fibers of the same type can be used at the same time [5], where short fibers are used to control microcracks at earlier loading stage and long fibers are used to control macrocracks. Many studies have been conducted to investigate the behavior of hybrid fiber reinforced concrete and cementitious composites [2–4,6], including both tensile and compressive behavior. However, the study on hybrid steel-PVA fiber reinforced cementitious composites is rare.

In this study, the axial compressive behavior of normal strength hybrid steel-PVA fiber reinforced cementitious composites were explored. The major parameters studied including water/binder ratio, fiber content and combination. The test results were carefully analyzed and a stress-strain model was also proposed to predict the compressive stress-strain curve of hybrid steel-PVA fiber reinforced cementitious composites.

2. Experimental program

2.1. Mix proportions and material properties

The present study was conducted in two series (i.e. A and B) with different basic mix proportions, as shown in Table 1. The cementitious composites were prepared by ordinary Portland cement (P.O 42.5), fly ash, silica fume, river sand, fresh water

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Table 1
Basic mix proportions of cementitious composites.

	W/B	Material dosage (kg/m^3)					
		Cement	Fly ash	Silica fume	Sand	Water	S.P.
A	0.45	393.6	118.1	59.1	1263.5	256.9	12.2
B	0.38	484.2	145.3	72.6	1134.3	266.8	15

Note: S.P. = superplasticizer.

Table 2
Properties of steel and PVA fibers provided by manufacturer.

	Diameter (mm)	Length (mm)	Ultimate tensile strength (MPa)	Elastic modulus (GPa)	Rupture strain (%)	Specific gravity (kg/m^3)
Steel fibers	0.2	13	2800	200	/	7800
PVA fibers	0.04	12	1560	41	6.5	1300

Table 3
Fiber content/combination of different mix numbers.

Mix No.	Steel fiber content V_{sf} (%)	PVA fiber content V_{pf} (%)	Mix No.	Steel fiber content V_{sf} (%)	PVA fiber content V_{pf} (%)
1	0	0	7	1.0	0
2	0	0.5	8	1.0	0.5
3	0	1.0	9	1.0	1.0
4	0.5	0	10	1.5	0
5	0.5	0.5	11	1.5	0.5
6	0.5	1.0	12	2.0	0

and superplasticizer (S.P.). The fly ash adopted was grade II fly ash according to Chinese code GB/T 1596 [7]. River sand with fineness modulus of 2.97 was adopted as aggregates. The superplasticizer was polycarboxylate in powder form. Two different type of fibers were adopted, namely copper-coated micro steel fiber and PVA fiber. The diameter and length of the micro steel fiber are 0.2 mm and 13 mm, which are much smaller than the steel fibers used in normal FRC [8]. Micro steel fiber has been adopted in the production of ultra high performance concrete [9–11], which can greatly increase the compressive strength of concrete. Under the same fiber dosage, the number of micro steel fibers will be much larger, which is anticipated to lead to more uniform distribution of fibers and better performance. The diameter and length of the PVA fiber are 0.04 mm and 12 mm respectively. PVA fiber has been widely used in the production of engineered cementitious composites (ECC) [12], which can greatly improve the ductility of concrete. The mechanical properties of micro steel fiber and PVA fibers provided by manufacturer are listed in Table 2. By the hybridation of stiff steel fiber and ductile PVA fiber, both the strength and ductility of cementitious composites are anticipated to be greatly increased.

The water/binder ratios for series A and B are 0.45 and 0.38, respectively. Two relatively large and close water binder ratios were chosen as only normal strength cementitious composites were considered in the present study. The bulk density of series A and B is a little more than 2100 kg/m^3, which is relatively smaller than normal concrete (i.e. 2300–2500 kg/m^3) due to the absence of coarse aggregate and relatively high mortar fraction. The density of the cementitious composites is comparable with previous studies on cementitious composites (i.e. 2075 kg/m^3) [12].

For each series (i.e. A and B), 12 mixes with different fiber volume content/combination were further investigated. The steel fiber and PVA fiber content/combination of each mix number were summarized in Table 3. The volumetric content of steel fiber varied between 0% and 2%, and that of PVA fiber varied between 0% and 1.5%. In total, 24 different mix proportions were investigated. The name of each mix consists of a letter "A" or "B" indicating the basic mix proportion and a digital number indicating the content and combination (from 1 to 12 as shown in Table 3) of two different fibers. For example, the mix 'B8' represents the cementitious composite produced by basic mix B (Table 2) together with 1.0% steel fiber and 0.5% PVA fiber (see Table 3).

2.2. Test set-up and loading procedure

For each mix proportion, three standard concrete cylinders (150 mm × 300 mm) were cast. The cylinders were tested following ASTM C39 [13] and ASTM C469 [14] to obtain their elastic moduli and axial compressive stress-strain curves. In total, 72 cylinders were prepared and tested. All specimens were cured in standard fog room for 28 days before testing. For each cylinder, four foil type strain gauges were attached uniformly at the mid-height section in longitudinal direction. The gauge length of strain gauges was 100 mm. In addition, two linear variable displacement transducers (LVDTs) were used to measure the shortening of the 150-mm mid-height region of the specimen. The LVDTs were fixed to the cylinder by a compressometer as shown in Fig. 1.

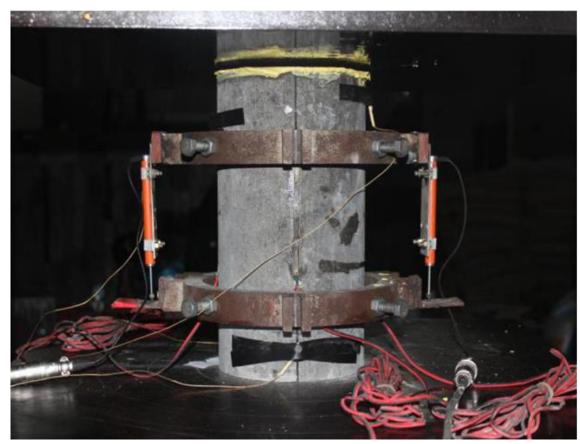

Fig. 1. A photo of the test set-up.

All the tests were conducted on a hydraulic loading machine with load capacity of 5000 kN. The tests were conducted by following steps: (1) strain gauges were glued to the specimens at least one day before testing; on testing, the specimens were carefully mounted at the center of the lower platen of the machine; the top surfaces of the specimens were then capped flat with a thin layer of high strength gypsum; (2) three loading-unloading cycles were applied with the maximum load being about 30% of the peak load to obtain the elastic modulus; the loading rate at this step is 4.5 kN/s following ASTM C469 [14]; (3) load the specimen from zero to about 80% of ultimate load at a constant loading rate of 4.5 kN/s; (4) load the specimen at a constant displacement loading rate of 0.18 mm/min until the post-peak load capacity was reduced by 50%.

3. Test results and analysis

3.1. General behavior

The key test results were summarized in Table 4, including peak stress ($f_{co}, f_{co,f}$) and corresponding strain ($\varepsilon_{co}, \varepsilon_{co,f}$), elastic modulus ($E_c, E_{c,f}$) and toughness index ($TI$). The subscript '$f$' represents specimens containing fibers. It should be mentioned that all test results