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Rheological and mechanical properties of hybrid fiber reinforced cement mortar

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HIGHLIGHTS

- A new hybrid fiber system containing both micro- and macro-fiber was employed.
- Rheological properties and mechanical response were presented.
- Good fresh properties and best flexural toughness were achieved.

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ABSTRACT

A new hybrid fiber system containing steel fiber, polyvinyl alcohol fiber (PVA fiber) and calcium carbonate ($CaCO_3$) whisker was employed to further improve hardened properties and reduce engineering cost of cement mortar. In this paper, the rheological properties, flow rate and flow spread were measured to evaluate the workability of hybrid fiber reinforced mortar in fresh state. Mechanical strength and flexural toughness of mortars were tested in hardened state. The results indicated that, flowability of fresh hybrid fiber reinforced mortar decreased after substituting PVA fiber for steel fiber and further $CaCO_3$ whisker for PVA fiber in mortar. This is mainly due to the flexibility of PVA fiber and large specific surface area of $CaCO_3$ whisker. The hybrid fiber reinforced mortar shows promising mechanical strength and flexural toughness due to the multi-scale crack resistance formed by micro- and macro-fibers. M5 specimen (1.5% steel fiber + 0.4%PVA fiber + 1.0% $CaCO_3$ whisker) exerts the best flexural performance and relatively higher compressive strength, exhibiting an obviously positive hybrid effect of fibers.

1. Introduction

Under tension load condition, inherent brittleness of concrete was documented to directly lead to the deficiencies in toughness, tensile strength and dynamic mechanical properties. Incorporation of short, randomly distributed fibers would contribute to the improvement of ductility and toughness of cementitious composites [1–3]. However, the reinforcement efficiency of single fiber has been proved to be limited compared with the synergetic fibers with different lengths, diameters or aspect ratios [4,5]. The occurrence of micro-crack in the cement hydration product or paste and their subsequent propagation and coalescence usually leads to the rupture of cement composites. Therefore, the primary effort for delaying the initiation and propagation of micro-cracks is to realize micro-scale reinforcement by introducing smaller fibers [6,7]. Then, larger fibers take the role in bridging macro-cracks and transferring load back to the matrix that uncracked to trigger multiple crack behavior. Therefore, the enhanced tension strength and toughness can be achieved by utilizing hybrid fiber reinforcement.

Studies have demonstrated that the structures of cementitious composites can be mainly divided into four scales i.e. cement hydration product, cement paste, mortar and concrete [8,9]. Cracks with micro- and macro-size may occur consistently with various scales of cementitious composites. Although the studies on hybrid fiber reinforced cementitious composites have been flourished, they are mainly concentrated on the various sizes of fiber in terms of steel fiber, PVA fiber and carbon fiber etc. Meanwhile, traditional fibers listed above can hardly satisfy the reinforcement demanded in cement hydration product because of their relatively larger length and diameter [10]. In this case, $CaCO_3$ whisker with 20–30 μm length and 0.5–2 μm diameter is applied with steel and PVA fibers to fulfill the reinforcement of cementitious composites in both micro and macro scale [11]. In our previous study, $CaCO_3$ whisker has been demonstrated to be high-performance and easy

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dispersion in cementitious composites [12]. In addition, partial replacement of PVA fiber with$CaCO_3$ whisker in cementitious composites can also reduce the engineer cost, which has been demonstrated with a classical and widely-accepted method called TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) [13]. In TOPSIS, the compressive strength, flexural strength, flexural toughness, equivalent flexural strength and mid-span crack number are considered in combination with the fiber cost. And the closeness coefficient r^* shows a decreasing tendency with the addition of $CaCO_3$ whisker, indicating a reduced engineering cost.

The incorporation of fibers can notably reduce the workability of fresh cementitious composites [14], which is detrimental to the compactness, porosity and density of cementitious composites in the hardened state. In this paper, the rheological properties, slump flow and flow rate of the fresh hybrid fiber reinforced cement mortars were conducted to evaluate the effect of hybrid fiber on the fresh properties of cement mortar. In addition, the mechanical properties in terms of compressive strength and flexural toughness with different proportion of hybrid fiber in reinforced cement mortar were investigated.

2. Experimental procedure

2.1. Materials

Ordinary cement (P.O 42.5R) and its chemical constituents are shown in Table 1. The particle size distribution of siliceous sand is plotted in Fig. 1. Properties of fibers used in this study are tabulated in Table 2 and the micro-morphology of $CaCO_3$ whisker is shown in Fig. 2. Super plasticizer (Polycarboxylic acid based, water reducing ratio 32%) was used in all mortars.

2.2. Mix proportion

Mix proportions of fibers used in this study are shown in Table 3. The ratios of water to cement and sand to cement were fixed at 0.3 and 0.5, respectively. Superplasticizer at a dosage of 0.5% by weight of cement was used in each cement mortar. The total content of single steel fiber and the hybrid of steel and PVA fiber were kept at 2% by volume and then PVA fiber was partially replaced by $CaCO_3$whisker. A mortar without any fiber was used as control.

2.3. Test procedure

The flow rate and flow spread of fresh mortars involving different dosage of fibers were tested by mini V-funnel and mini-slump flow cone. The versions of testing instruments are illustrated in Okamura and Fung [15], as graphed in Fig. 3.

For the flow spread test, the mini-slump cone was first located in the center of a flat glass plate and filled up by the mortar. Then, the mini-slump cone was carefully lifted up vertically within five seconds and kept three minutes at least to allow the free spread of mortar. Two perpendicular diameters of the mortar patty formed after spread was measured and averaged. At last, the spread value was obtained by the subtraction of diameters between the averaged value and the cone bottom.

For the flow rate test, mixed mortars were first poured into the V-funnel until completely filled, during which the opening at the base of V-funnel kept closed. Then, unfold the opening at the bottom and the mortar was driven to flow out under its own gravity. The time from the moment of flowing start to the first light coming into the V-funnel from bottom opening was recorded as the flow time. The flow rate of mortars was calculated by the ratio between volume of mortar (1134 mL) and flow time with unit of mL/s.

Rheological property of fresh hybrid fiber reinforced cement mixtures was evaluated by the Brookfield RST-SST rotational rheometer with a paddle rotator of VT60-30, as illustrated in Fig. 4. Rheological measurement protocol consisted of two steps, as shown in Fig. 5. The first cycle referred to as pre-shear cycle, was conducted to obtain the same shear history of each mortar before measurement. Samples were then subjected to a data-logging cycle for actual measurements and one data per second was recorded.

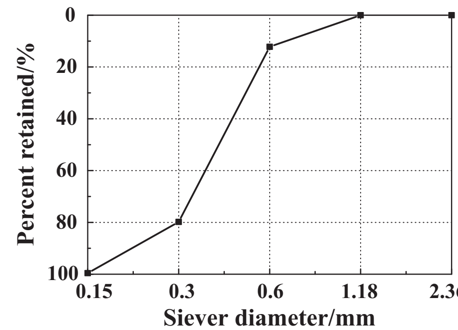

Fig. 1. Grading curve for the sand.

Table 2
Physical parameters of fibers used in the study.

Fiber type	Length (mm)	Diameter (μm)	Tensile strength (MPa)	E-modulus (GPa)	Aspect ratio
Steel fiber	13	200	≥2000	210	65
PVA fiber	6	35	1472	32.3	171
$CaCO_3$ whisker	20–30 μm	0.5–2	3 000–6 000	410–710	10–60

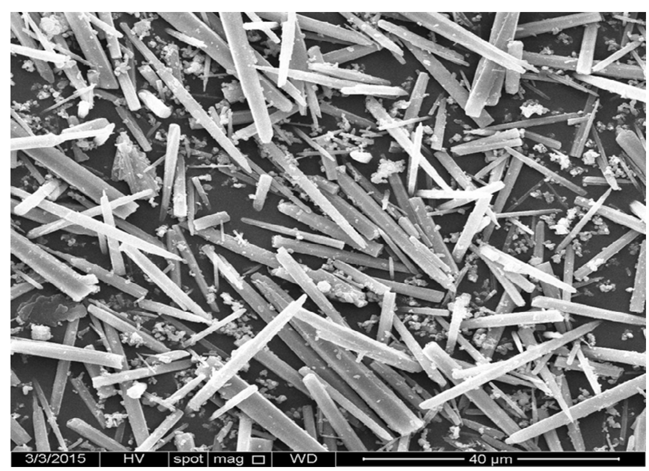

Fig. 2. Micro-morphology of whisker.

Table 3
Dosage of different fibers in the combination.

Groups	Volume fraction (%)			Fiber dosage(kg/m^3)		
	SF	PVA	CW	SF	PVA	CW
M0	0	0	0	0	0	0
M1	2	0	0	156	0	0
M2	1.75	0.25	0	136.5	3.2	0
M3	1.75	0.2	0.5	136.5	2.6	14.3
M4	1.5	0.5	0	117	6.45	0
M5	1.5	0.4	1.0	117	5.16	28.6
M6	1.25	0.75	0	97.5	9.7	0
M7	1.25	0.55	2	97.5	7.1	57.2
M8	1.0	1.0	0	78	12.9	0
M9	1.0	0.75	2.5	78	9.0	85.8

SF: steel fiber; PVA: polyvinyl alcohol fiber; CW: calcium carbonate whisker.

Table 1
Chemical constituent of cement (wt%).

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	CO_2	MgO	K_2O	SO_3	Na_2O	P_2O_5	MnO
	61.13	21.45	5.24	2.89	2.37	2.08	0.81	2.50	0.77	0.07	0.06