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# Mechanical properties of polypropylene hybrid fiber-reinforced concrete

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# ABSTRACT

This paper investigates the mechanical properties of polypropylene hybrid fiber-reinforced concrete. There are two forms of polypropylene fibers including coarse monofilament, and staple fibers. The content of the former is at 3 kg/m<sup>3</sup>, 6 kg/m<sup>3</sup>, and 9 kg/m<sup>3</sup>, and the content of the latter is at 0.6 kg/m<sup>3</sup>. The experimental results show that the compressive strength, splitting tensile strength, and flexural properties of the polypropylene hybrid fiber-reinforced concrete are better than the properties of single fiber-reinforced concrete. These two forms of fibers work complementarily. The staple fibers have good fineness and dispersion so they can restrain the cracks in primary stage. The monofilament fibers have high elastic modulus and stiffness. When the monofilament fiber content is high enough, it is similar to the function of steel fiber. Therefore, they can take more stress during destruction. In addition, hybrid fiber-reinforced concrete can effectively decrease drying shrinkage strain.

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# 1. Introduction

There are many kinds of fibers, no matter metallic or polymeric, widely used in concrete engineering for their advantages [1–4]. In fact, no single fiber-reinforced concrete has the perfect mechanical properties. Recently, many researches have an orientation to discuss the mechanical properties of the hybrid fiber-reinforced concrete, such as a proper proportion between carbon fibers and polypropylene fibers [5], glass fibers and polypropylene fibers [6], or carbon fibers and glass fibers to concrete [7,8]. Although their studies are related to the hybrid fiber-reinforced concrete with different kinds of fibers, the majority of the researches focus on the steel–polypropylene fiber-reinforced concrete [9–15].

The steel fibers have high elastic modulus and stiffness so they can improve compressive strength and toughness of concrete [1]. On the other hand, the polypropylene fibers have good ductility, fineness, and dispersion so they can restrain the plastic cracks [16]. Therefore, proper mixture of these two complementary fibers can make better mechanical properties of concrete. Adding steel fibers to concrete can improve the properties of concrete, but the fiber content must be high. It increases structure weight of concrete and has balling effect during mixing so the workability will be lowered. In addition, steel fibers easily basset and rust, and it also has the problem of conductive electric and magnetic fields. If steel fiberreinforced concrete is used in the runway of airport, high-speed railway systems, and nuclear power plant, it may have the safety problem [17].

In order to overcome the above-mentioned disadvantages, this study proposed that the coarse synthetic monofilament polypropylene fibers could be a potential replacement for steel fibers. The experiment mixes staple fibers at 0.6 kg/m<sup>3</sup> with coarse synthetic monofilament fibers at 3 kg/m<sup>3</sup>, 6 kg/m<sup>3</sup>, and 9 kg/m<sup>3</sup> to concrete, respectively. It explores the properties of polypropylene hybrid fiber-reinforced concrete, such as workability, compressive strength, splitting tensile strength, flexural properties, and drying shrinkage strain.

# 2. Experimental program

# 2.1. Materials

The materials used for the nonfibrous control concrete mixture consisted of the normal Type I Portland cement, the gravel having a maximum size 2.54 cm, and the river sand having a fineness modulus of 2.86. The mix proportion of cement:water:gravel:sand was 300:192:850:1050 kg/m<sup>3</sup>. The additives are coarse monofilament fibers and staple fibers, and they are showed in Fig. 1. The diameter of monofilament fibers is 1 mm, the length is 60 mm, the elastic modulus is 5.88 GPa, and the tensile strength is 320 MPa. The staple fibers have a various length between 10 mm and 25 mm, denier is 2.5, elastic modulus is 4.2 GPa, and tensile strength is 550 MPa.

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M. Hsie et al. / Materials Science and Engineering A 494 (2008) 153-157



Fig. 1. Photos of polypropylene fiber.

#### 2.2. Mixing and curing

The mixing process started with the dry mixing of the coarse and fine aggregates for 1 min. The cement was added; the dry mixing kept for another 1 min, and then added water and mixed for 2 min. After the former process, the specified amount of fibers was added to the wet concrete. The mixture was mixed for 3 min to ensure that the fibers can evenly disperse throughout the concrete. The fresh concrete was filled in  $150 \text{ mm} \times 300 \text{ mm}$  cylinder molds and 150 mm  $\times$  150 mm  $\times$  530 mm rectangle molds. The former is for the tests of compressive and spilt tensile strengths, and the latter is for modulus of rupture (MOR) and toughness index. Both molds were removed after 24 h, and the specimens were allowed to cure in a water cabinet at  $23 \pm 1$  °C. Property tests were performed after the samples had cured for 28 days. In addition, the fresh concrete was filled in  $100 \text{ mm} \times 100 \text{ mm} \times 500 \text{ mm}$  drying shrinkage test molds. The mold was removed after 24 h, and initial values of test specimens were measured. After that, the specimens were placed in cabinets maintaining conditions of 23 °C and 50%R.H. Shrinkage strain was measured after the specimens had been cured for 40 days. In this study, every test result consisted of the average of six replicate tests.

### 2.3. Test methods

The ASTM C39 test method was used to determine the compressive strength of cylindrical specimens [18]. The cylindrical specimens were placed in an all-purpose hydraulic testing machine, and the load was increased at a rate of 0.3 MPa/s until the specimens failed. The ASTM C496 test method was used to measure the splitting tensile strength of cylindrical specimens [19]. The continuous load was increased at a rate of 0.9 MPa/s until the specimens failed.

The flexural strength (MOR) test, conducted using test beam under third-point loading, followed the ASTM C1018 test for flexural toughness and first-crack strength of fiber-reinforced concrete [20]. The mid-span deflection was the average of the ones detected by the transducers through contact with brackets attached to the beam specimen. The testing machine ran to increase the deflection at a constant rate; the load–deflection relation recorded using an X–Y plotter. The ASTM C157 method was used to test drying shrinkage [21].

#### 3. Results and discussion

### 3.1. Slump

Table 1 shows the slump of the fiber-reinforced concrete. The slump changed due to the different fiber content and form. For

pure concrete, the slump is 16.5 cm. When adding monofilament fibers at 3 kg/m<sup>3</sup>, 6 kg/m<sup>3</sup>, and 9 kg/m<sup>3</sup>, the slump fell down to 15.4 cm, 14.2 cm, and 13.1 cm, respectively. When adding staple fibers at 0.6 kg/m<sup>3</sup>, the slump slightly decreased to 15.9 cm. The slump of polypropylene hybrid fiber-reinforced concrete deceased more than the other specimens, and the slump losses were 14.9 cm, 13.6 cm, and 12.8 cm, respectively. The reason of lower slump is that adding hybrid fibers can form a network structure in concrete, which restrain mixture from segregation and flow. Because of the high content and large surface area of fibers, fibers are sure to absorb more cement paste to wrap around, and the increase of the viscosity of mixture makes the slump loss [11].

#### 3.2. Compressive strength

Table 1 presents the compressive strength, splitting tensile strength, and modulus of rupture of polypropylene hybrid fiber-reinforced concrete. The strengths improved to different extents in response to the fiber content. Fig. 2 shows the increase of compressive strength of polypropylene hybrid fiber-reinforced concrete. Comparing with pure concrete, adding monofilament fibers at 3 kg/m<sup>3</sup>, 6 kg/m<sup>3</sup>, and 9 kg/m<sup>3</sup> can increase 4.65%, 9.12%, and 13.24%, respectively. Adding staple fibers at 0.6 kg/m<sup>3</sup>, the improved percentage is 3.15%. The improved percentages of hybrid fiber-reinforced concrete are 14.60%, 15.24%, and 17.31%. The compressive strength improvement of polypropylene hybrid fiber-reinforced concrete ranged from 14.60% to 17.31%, comparable to the augmentations of 12.3% to 15.89% for steel–polypropylene hybrid fiber-reinforced concrete [22]. The polypropylene hybrid fiber-reinforced concrete has better compressive strength increase.



Fig. 2. Compressive strength-effectiveness of polypropylene hybrid fiber-reinforced concretes.

M. Hsie et al. / Materials Science and Engineering A 494 (2008) 153-157

Mixture no.	Fiber dosage		Slump (cm)	Compressive s	strength	Splitting tensi.	le strength	Modulus of ru	ıpture	Increased costs
	$P1^{*}$ (kg/m <sup>3</sup> )	$P2^{*} (kg/m^{3})$		Measured (MPa)	Strength–effectiveness (%)	Measured (MPa)	Strength–effectiveness (%)	Measured (MPa)	Strength-effectiveness (%)	per cubic meter (US\$)
M-0	0	0	16.5	27.974	I	2.399	I	4.583	I	I
M-1	ŝ	0	15.4	29.275	4.65	2.425	1.08	4.869	6.24	19.35
M-2	9	0	14.2	30.525	9.12	2.463	2.67	5.227	14.06	38.70
M-3	6	0	13.1	31.678	13.24	2.601	8.42	5.504	20.10	58.05
M-4	0	0.6	15.9	28.855	3.15	2.502	4.30	4.699	2.53	3.87
M-5	ŝ	0.6	14.9	32.058	14.60	2.612	8.88	4.995	8.99	23.22
M-6	9	0.6	13.6	32.237	15.24	2.677	11.59	5.403	17.90	42.57
M-7	6	0.6	12.8	32.816	17.31	2.719	13.35	5.710	24.60	61.92

Table 1

(3) = (3) + (3)

Polypropylene fiber is US\$6.45 per kilogram.

The increased labor fee is negligible because the hybrid fiber-reinforced concrete can be mixed at regular concrete batching plants.



Fig. 3. Splitting strength-effectiveness of polypropylene hybrid fiber-reinforced concretes

The reason is monofilament fiber has the high Young's modulus and stiffness for the rough shape, and when these fibers are at high content, similar to effectiveness of function the steel fiber, therefore they may withstand more resistant to compression capacities. Moreover, the staple fibers have good fineness and various lengths. As it mixes with monofilament fibers, they can easily form the network structure, and lower the concrete stress concentration at the cracks tip and thus increase compressive strength [23].

# 3.3. Splitting tensile strength

Fig. 3 shows the increase of splitting tensile strength of polypropylene hybrid fiber-reinforced concrete. Compared with the pure concrete, as the fiber content increases, the splitting tensile strength of polypropylene hybrid fiber-reinforced concrete rises by 8.88%, 11.59%, and 13.35%, respectively. Also, the hybrid fiberreinforced concrete increases more splitting tensile strength than the single fiber-reinforced concrete does. In primary stage of cracking of concrete, there are numerous staple fibers bridging the microcracks and preventing the expansion. When the tensile stress kept ruins the specimens, the stress was transferred to the monofilament fibers, which are coarser and stronger, so it can arrest the propagating macrocracks and substantially improve the splitting tensile strength.

# 3.4. Modulus of rupture

Fig. 4 shows the increase of modulus of rupture of polypropylene hybrid fiber-reinforced concrete. The order of the increase of



Fig. 4. Modulus of rupture of polypropylene hybrid fiber-reinforced concretes.

M. Hsie et al. / Materials Science and Engineering A 494 (2008) 153-157



Fig. 5. Fracture faces of polypropylene fiber-reinforced concretes.

Table 2

MOR is staple fibers, monofilament fibers, and hybrid fibers. Comparing with pure concrete, the augmented percentages of MOR of polypropylene hybrid fiber-reinforced concrete are 8.99%, 17.90%, and 24.60%. When the load put on the beams, the hybrid fibers can withstand the tensile stress in the tensile zone below the neutral axis. When fine staple fibers fail, coarse monofilament fibers can keep bridging and disperse the stress of macrocracks until they cannot sustain. Therefore, hybrid fiber-reinforced concrete has higher MOR. Fig. 5 shows the fiber distribution on the fracture surface of polypropylene hybrid fiber-reinforced concrete specimen. Because the monofilament fibers have high elastic modulus and stiffness, the major parts of fibers are pulled out. This fracture model is similar to steel fiber on concrete.

# 3.5. Toughness index

Toughness index is used to measure the energy absorbed in deflecting a beam at specified amount, being the area under a load–deflection curve in three-point bending. Fig. 6 shows the load–deflection curves including the additions of monofilament fibers at 9 kg/m<sup>3</sup>, staple fibers, and hybrid fibers. It was found that for the pure concrete, the material demonstrated its brittleness, the load decreases rapidly with increase of specimen deflection after peak load (curve 1). However, for the hybrid fiber-reinforced concrete, the decrease trends were flatter (curve 2), indicating that the addition of polypropylene fibers really changed the toughness and hybrid fibers provided the larger toughness. Table 2 shows the values of toughness index of fiber-reinforced concrete. The toughness indexes of pure concrete are  $I_5$  at  $3\delta$ ,  $I_{10}$  at  $5.5\delta$ , and



Fig. 6. The load-deflection curves of polypropylene fiber-reinforced concretes.

Toughness index	of hybrid	fiber-reinforced	concretes

Mixture no.	$I_5$	I <sub>10</sub>	I <sub>30</sub>	
M-0 M-1 M-2 M-3 M-4 M-5 M-6 M-7	1.00 2.27 2.76 3.26 1.15 2.79 3.47 3.58	1.00 4.30 4.86 5.48 1.57 4.44 5.68 6.91	$ \begin{array}{r} 1.00\\ 10.26\\ 12.51\\ 13.36\\ 2.50\\ 11.36\\ 14.06\\ 15.23\\ \end{array} $	$\begin{bmatrix} Pe & A & C & E & G \\ \hline g & D & F & H \\ 0 & 3 & 3 & 5.5 & 15.5 & \delta \\ Deflection \rightarrow & 15.5 & \delta \\ I_{3} = \frac{OACD}{OAB} & I_{30} = \frac{OAGH}{OAB} \end{bmatrix}$ The graph of toughness index

 $I_{30}$  at 15.5 $\delta$  [24]. All these three indexes reached unity, assuming that the nonfibrous-reinforced concrete matrix is elastic-brittle. The three toughness indexes of staple fiber-reinforced concrete are 1.15, 1.57, and 2.50. The values are slightly increased comparing with the toughness index of pure concrete. The monofilament fiber-reinforced concrete and hybrid fiber-reinforced concrete have greater index values. For the hybrid fiber-reinforced concrete, the more the fiber content is, the more destructive energy can absorb, and thus it increases more toughness index. When the monofilament fiber content is at  $9 \text{ kg/m}^3$ , the values of  $I_5$ ,  $I_{10}$ , and  $I_{30}$  are 3.58, 6.91, and 15.23, respectively. They point out that the monofilament fibers have potential improve the toughness of concrete.

# 3.6. Drying shrinkage strain

Table 3 shows the drying shrinkage strain of hybrid fiberreinforced concrete. The value of pure concrete is set to 1. The values of all the fiber-reinforced concrete are below 1, and the value of polypropylene hybrid fiber-reinforced concrete is the smallest. When the fiber content is at  $3 \text{ kg/m}^3$ ,  $6 \text{ kg/m}^3$ , and  $9 \text{ kg/m}^3$ , the values are 0.871, 0.867, and 0.862, respectively. This indicates that the

Table 3
Drying shrinkage strain of hybrid fiber-reinforced concretes

Mixture no.	Drying shrinkage strain ( $\times 10^{-6})$	Relative drying shrinkage
M-0	596	1
M-1	554	0.930
M-2	530	0.889
M-3	524	0.879
M-4	519	0.871
M-5	519	0.871
M-6	517	0.867
M-7	514	0.862

more the fiber content is, the lower the drying shrinkage strain is. Because the hybrid fibers can be properly distributed throughout the mortar matrix, around the coarse aggregate particles, and even in boundary layers of concrete elements, this can effectively hinder drying shrinkage strain.

# 4. Conclusions

Polypropylene hybrid fiber-reinforced concrete utilizes two complementary fibers to improve the properties of concrete, and the performance of hybrid fiber-reinforced concrete is better than that of single fiber-reinforced concrete. Comparing with the strengths of pure concrete, the compressive strength of polypropylene hybrid fiber-reinforced concrete increased by 14.60-17.31%; the splitting tensile strength did by 8.88-13.35%; modulus of rupture did by 8.99-24.60%.

Adding polypropylene hybrid fibers to concrete can increase toughness index, and the more the fiber content is, the higher toughness index is. Adding monofilament fibers at 9 kg/m<sup>3</sup> to hybrid fiber-reinforced concrete, the values of  $I_5$ ,  $I_{10}$ , and  $I_{30}$  are 3.58, 6.91, and 15.23, respectively. In addition, polypropylene hybrid fiber-reinforced concrete also can lower drying shrinkage strain and ranged from 0.862 to 0.871.

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