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Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction

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Abstract

Concretes containing different types of hybrid fibers at the same volume fraction (0.5%) were compared in terms of compressive, splitting tensile, and flexural properties. Three types of hybrid composites were constructed using fiber combinations of polypropylene (PP) and carbon, carbon and steel, and steel and PP fibers. Test results showed that the fibers, when used in a hybrid form, could result in superior composite performance compared to their individual fiber-reinforced concretes. Among the three types of hybrids, the carbon–steel combination gave concrete of the highest strength and flexural toughness because of the similar modulus and the synergistic interaction between the two reinforcing fibers.

Keywords: Fiber reinforcement; Hybrid composite; Mechanical properties

1. Introduction

It is known that concrete is a relatively brittle material. Reinforcement of concrete with randomly distributed short fibers may improve the toughness of cementitious matrices by preventing or controlling the initiation, propagation, or coalescence of cracks [1–5]. The fibers used are mainly steel fibers, carbon fibers, and polymer fibers. Among the polymer fibers, polypropylene (PP) fibers have attracted most attention due to the outstanding toughness of concrete reinforced with them [6]. However, concrete is a complex material with multiphases. The phases include large amount of C-S-H gel in micron-scale size, sands in millimeter-scale size, and coarse aggregates in centimeter-scale size. Thus, the properties of concrete will be improved in certain level, but not whole levels if reinforced only by one type of fiber.

It has been shown recently [7–9] that by using the concept of hybridization with two different fibers incorporated in a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fiber enables the more efficient utilization of the potential properties of the other fiber. However, the hybrid composites studied by previous researchers were focused on cement paste or mortar. The mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction (0.5%) have not been studied previously. Therefore, the objective of this paper is to determine systematically the basic characteristics of the three types of hybrid fiber-reinforced concretes with carbon–steel, steel–PP, and PP–carbon fiber combinations in terms of compressive, splitting tensile, and flexural tests.

2. Experimental program

2.1. Materials

The cement used in all concrete mixes was normal Portland cement which corresponds to ASTM Type I. The sand used was local natural sand with specific gravity of 2.65. The coarse aggregate was crushed limestone with a maximum size of 15 mm and specific gravity of 2.70.

Properties of the carbon, steel, and PP fibers are shown in Table 1. The carbon and PP fibers were smooth and straight, while the steel fibers were hooked end.

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Table 1
Properties of carbon, steel, and PP fibers

	Carbon	Steel	PP
Length (mm)	5	30	15
Diameter (μm)	7	500	100
Density (g/cm^3)	1.6	7.8	0.9
Modulus (GPa)	240	200	8
Elongation at break (%)	1.4	3.2	8.1
Tensile strength (MPa)	2500	1500	800

Table 2 presents the control concrete mix proportions used in the testing program. For the concretes containing fibers, the dosage of superplasticizer was increased properly to maintain the slump around 160 mm. The mixtures were batched in 30-l vertical axis concrete mixer. The cement, sand, and fibers were dry-mixed for 30 s. This was followed by the addition of coarse aggregate, water, and the superplasticizer, with a mixing time of 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then placed in a curing room with 90% relative humidity and 23 °C for 27 days of curing. For 12 h prior to the tests, the specimens were allowed to air dry in the laboratory.

2.2. Testing procedures

For each mixture, nine specimens (six 100 × 100-mm cubes and three 100 × 100 × 500-mm beams) were prepared. The compressive and splitting tensile tests were carried out on the 100 × 100-mm cube specimens. The four-point loading flexural tests were carried out at a loading rate of 0.05 mm/min on the 100 × 100 × 500-mm beams according to the requirements of ASTM C 1018. During the flexural tests, the load and the midspan deflection were recorded on a computerized data recording system, and the load–displacement curve was drawn on a printer.

3. Test results

All test results are summarized in Table 3, while graphical representations of the results are displayed in Figs. 1 and 2. Each strength value presented in Table 3 is the average of three specimens. A total of 63 specimens were tested in this investigation.

Table 2
Concrete mix proportions

Material	Quantity
Type I cement (kg/m^3)	490
Sand (kg/m^3)	684
Crushed limestone (kg/m^3)	1024
Water (kg/m^3)	196
Superplasticizer (kg/m^3)	2.5
Slump (mm)	160

Table 3
Mechanical properties of fiber-reinforced concretes

Batch no.	Fiber volume fraction (%)			f'_c (MPa)	f'_{sp} (MPa)	MOR (MPa)	Toughness index		
	Carbon	Steel	PP				I_5	I_{10}	I_{30}
1	–	–	–	44.3	4.36	5.54	3.16	5.89	9.78
2	0.5	–	–	50.7	5.21	6.02	4.08	7.48	14.82
3	–	0.5	–	47.8	4.80	6.90	4.15	7.90	22.80
4	–	–	0.5	44.5	4.14	5.74	4.04	6.26	16.76
5	0.2	0.3	–	58.2	5.95	7.36	4.23	8.14	29.32
6	0.2	–	0.3	57.8	5.72	7.30	3.89	6.20	15.90
7	–	0.2	0.3	45.3	4.46	5.83	3.40	6.31	18.44

3.1. Compressive strength

From Table 3, it was found that among the three types of fibers, carbon fibers gave the highest compressive strength, PP fibers gave the lowest compressive strength. When the fibers used in a hybrid form, it obviously increased strength in the case of carbon–steel fibers and carbon–PP fibers. In the case of steel–PP fibers, it slightly increased strength compared to simple PP fibers and decreased strength compared to simple steel fibers at the same fiber volume fraction. Among the three hybrids, carbon–steel fibers gave the highest strength and steel–PP fibers gave the lowest strength.

3.2. Splitting tensile strength

Fiber addition increased strength with carbon and steel fibers, but decreased with PP fibers when the fibers used in an individual form. Similar to the case of compressive strength above, carbon fibers gave the highest splitting tensile strength, while PP fibers gave the lowest splitting tensile strength. In hybrid form, carbon–steel fibers gave the highest splitting tensile strength, which was much higher than that of either carbon fiber-reinforced concrete or steel fiber-reinforced concrete. Steel–PP fibers gave the lowest splitting tensile strength, which was lower than that of steel fiber-reinforced concrete but higher than that of PP fiber-reinforced concrete.

3.3. Modulus of rupture (MOR)

Fiber addition increased MOR with all fibers. Among the three types of fibers, steel fibers gave the highest MOR, while PP fibers gave the lowest MOR. When the fibers were used in a hybrid form, it increased MOR in the case of carbon–steel fibers and carbon–PP fibers compared to any of the simple fibers. In the case of steel–PP fibers, it slightly increased MOR when compared to simple PP fibers, but decreased strength when compared to simple steel fibers.

3.4. Flexural toughness

By bridging across macrocrack and reducing its opening, the fibers obviously affect the postpeak flexural softening

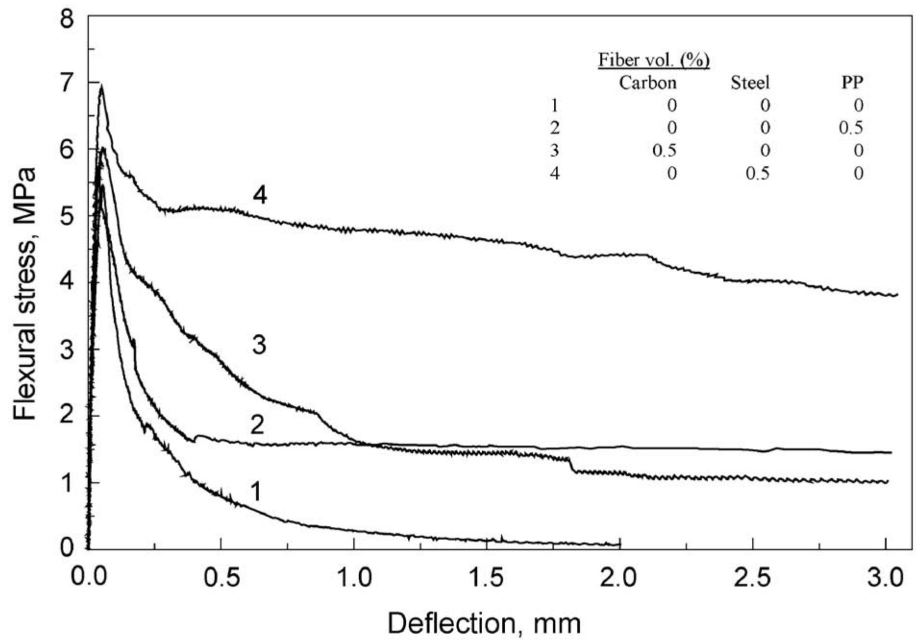

Fig. 1. Plots of flexural stress versus deflection for simple fiber-reinforced concrete beams.

response of the concrete. Figs. 1 and 2 compare the stress deflection of concrete beams reinforced with carbon, steel, PP fibers, and their three hybrid forms. From the figures, it was found that for the unreinforced concrete, the material demonstrated relative brittle behavior, the stress decreases rapidly with increase of midspan deflection after peak load. However, for the reinforced concretes, the decrease trends were flatter. Moreover, the stress platform or pseudohardening responses appeared generally, which were much dependent on the type of the added fibers and their combinations. A summary of calculated toughness indices is reported in Table 3. The data showed that the toughness was increased with all fibers. Among the three individual fibers, steel fibers gave the highest flexural toughness values for all of indices I_5, I_{10}, and I_{30}, while carbon fibers gave the lowest toughness index of I_{30}, and PP fibers gave the lowest toughness indices of I_5 and I_{10}. However, in hybrid form, the ductility characteristics were dramatically improved in case of carbon–steel fibers. It gave the highest flexural toughness, which was much higher compared to that of simple carbon fibers or steel fibers, especially for the index of I_{30}, as shown in Fig. 2. Steel–PP fibers and carbon–PP fibers demonstrated similar flexural toughness when compared to simple PP fibers or carbon fibers, but show slight decrease when compared to simple steel fibers.

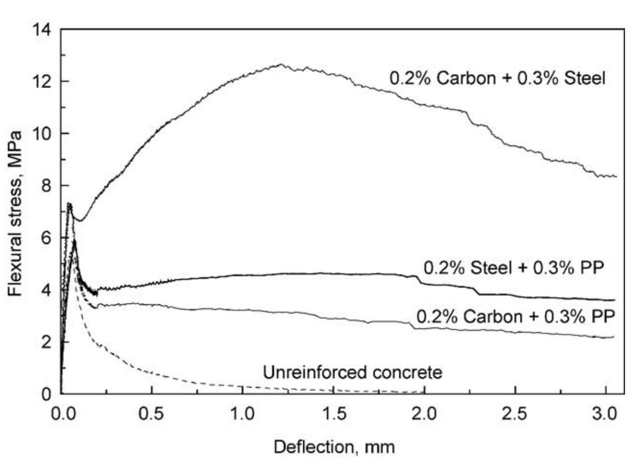

Fig. 2. Plots of flexural stress versus deflection for hybrid fiber-reinforced concrete beams.

4. Discussion and conclusion

In order to strengthen the matrix, the specific fiber spacing must be decreased to reduce the allowable flaw size [10]. This may be achieved by using fine short discrete fibers, such as carbon fibers of approximately a few microns in diameter. These fibers can provide bridging of the microcracks before they reach the critical flaw size. To provide the toughening component, fibers of high ultimate strain capacity are required so that they can bridge the macrocracks in matrix, and PP fibers or steel fibers are used for this purpose. Between these two fibers, PP was a low modulus fiber, the hybrid systems containing PP appeared to be less effective in controlling matrix crack opening. From the test results above, it was found that the main advantage of carbon fiber addition is the resulting high compressive and splitting tensile strengths, while the main advantage of steel fiber addition is the resulting high MOR and flexural toughness. Therefore, the carbon–steel hybrid was the most beneficial for the improvement of strength and flexural toughness. From Table 3, improvement of 31.4% in compressive strength, 36.5% in splitting tensile strength, 32.9% in MOR, and 33.9–199.5% in toughness indices were obtained for carbon–steel hybrid composite compared to unreinforced concrete.

As can be seen in Fig. 2, the load-carrying capacity for the carbon–steel hybrid decreases rapidly in the postpeak region. The brittle response may be attributed to the low carbon fiber volume fraction (only 0.2%) and the short length of chopped fibers being shorter than the average aggregate size that can only affect the prepeak microcracking. However, the decrease in load was recovered as the steel fibers began to pull out from matrix. The toughness of carbon–steel hybrids represented an increase of about 28% and 98% for I_{30} compared to simple steel fibers and carbon fibers, respectively.

Obviously, the presence of the steel fibers had increased the resistance of the composite reinforced with randomly distributed short carbon fibers and vice versa. As a result, the potential strength capacities of the carbon fibers or steel fibers were better utilized and the strength and flexural toughness of the steel–carbon hybrids were hence higher than the all-steel or all-carbon fiber composites.

Various conclusions can be drawn from this experimental study. The test results first indicated that at low fiber volume fraction, it is possible to obtain material with the enhanced strength and improved toughness from hybrid fibers. In the range of this study, it was shown that carbon fibers have high modulus and tensile strength, steel fibers have similar modulus to carbon fibers and with medium elongation and tensile strength, while PP fibers have high elongation, low modulus, and tensile strength. The best composite properties were obtained from the hybrid containing carbon and steel fibers, which had the greatest strength and flexural toughness because of the similar modulus and the synergistic interaction between the two reinforcing fibers.

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