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Research Article

Mechanical Properties of Hybrid Fiber Reinforced Concrete at Low Fiber Volume Fraction

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ARTICLEINFO **ABSTRACT**

In the present study concretes containing different types of hybrid fibers at the same volume fraction (0.25%) are compared in terms of mechanical properties. Four types of hybrid composites are constructed using fiber combinations of polypropylene (PP) and carbon, carbon and steel, steel and PP fibers and glass fiber (GF) and steel. 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 four types of hybrids, the carbon–steel combination gives 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; polypropylene; Hybrid composite; glass fiber

1. Introduction

It is a worldwide fact that concrete is a brittle material. However, the toughness of cementitious matrices can be improved by introducing short, random fibers as reinforcement, effectively impeding crack initiation, propagation, and merging [1]. Various types of fibers, such as steel fibers, carbon fibers, and polymer fibers, notably polypropylene (PP) fibers, are commonly utilized for this purpose. PP fibers have gained significant attention due to their remarkable ability to enhance concrete's reinforcement and toughness. Nevertheless, concrete is a complex material consisting of multiple phases, including C-S-H (Calcium-Silicate-Hydrate) gel at the micron scale, sands at the millimeter scale, and coarse aggregates at the centimeter scale. Consequently, while the use of a single fiber type can enhance specific properties of concrete to some extent, it falls short in comprehensively improving all aspects [2]. Recent studies have demonstrated that the hybridization approach, involving the incorporation of two different fiber types into a shared cement matrix, can result in a composite material with more desirable engineering properties. The presence of one fiber type facilitates the efficient utilization of the potential properties offered by the other. However, previous research on hybrid composites has primarily focused on cement paste or mortar, and the mechanical properties of hybrid fiber-reinforced concrete with low fiber volume fractions (0.25%) have not been thoroughly investigated [3].

2. Objective of the present study

The objective of this paper is to systematically determine the fundamental characteristics of four types of hybrid fiber-reinforced concretes: carbon-steel, steel-PP, and PP-carbon fiber and glass fiber and steel combinations, through compressive, splitting tensile, and flexural tests. Composite materials exhibit a combination of properties from two or more constituent materials, which cannot be achieved by either the fiber or matrix alone. Fiber-reinforced composites have been successfully utilized in various engineering applications for several decades. Among them, glass fiber-reinforced polymeric (GFRP) composites have been widely employed in the manufacturing of composite materials. The matrix in these composites consists of organic, polyester, thermostable, vinylester, phenolic, and epoxy resins. Polyester resins are classified as bisphenolic, ortho, or isophthalic.

3. Experimental Program

3.1 Materials

All concrete mixes utilize normal Portland cement, classified as ASTM Type I. The sand employed is locally sourced natural sand with a specific gravity measuring 2.63 [4]. Crushed limestone serves as the coarse aggregate, with a maximum size of 20 mm and a specific gravity of 2.70. The characteristics of the carbon, steel, PP, and glass fibers are presented in table 1. The carbon and PP fibers possess a smooth and straight structure, while the steel fibers are characterized by their hooked ends. Table 2 shows the control concrete mix proportions utilized in the testing program. To ensure the desired slump of approximately 160 mm, the dosage of superplasticizer is appropriately increased for the concretes containing fibers. The mixtures are prepared using a 30-l vertical axis concrete mixer [5]. Initially, the cement, sand, and fibers are dry-mixed for a duration of 30 seconds. Subsequently, coarse aggregate, water, and the superplasticizer are added, and the mixing continued for 5 minutes. After pouring the mixture into oiled molds, a vibrator is employed to reduce the presence of air bubbles. Following a curing period of 1 day, the specimens are demolded and placed in a curing room maintained at 90% relative humidity and 23°C for a total of 27 days [6]. Prior to the tests, the specimens are allowed to air dry in the laboratory for a period of 12 hours.

Table 1: Properties of Carbon, Steel, PP Fiber, and Glass Fibers (GF)

Parameter	Carbon	Steel	PP	Glass
Length (mm)	6	32	16	5
Diameter (mm)	8	550	100	10
Density (g/cm3)	1.8	8.8	0.8	2.53
Modulus (GPa)	240	200	8	58
Elongation at break (%)	1.4	3.2	8.1	5.2
Tensile strength (MPa)	2500	1500	800	4600

Table 2: Concrete Mix Proportion

Material	Quantity
Type I Cement (kg/m3)	490
Sand (kg/m3)	684
Crushed Limestone (kg/m3)	1024
Water (kg/m3)	196
Superplasticizer (kg/m3)	2.5
Slump (mm)	160

3.2 Testing Procedure

For each mixture, fifteen specimens are prepared, consisting of nine 100x100-mm cubes and six 100x100x500-mm beams. The compressive and splitting tensile tests are conducted on the 100x100-mm cube specimens [7]. To meet the specifications of ASTM C 1018, the four-point loading flexural tests were performed on the 100x100x500-mm beams at a loading rate of 0.05 mm/min. Throughout the flexural tests, a computerized data recording system is used to measure and record the load and mid span deflection. Subsequently, a load-displacement curve is generated and printed for further analysis [8]. Table 3 indicate the blending of different types of types of fibers. Based on the blending of fibers six combination and one controlled concrete is considered in the present study for comparison [9]. It is important to note that a total of 83 specimens underwent testing as part of this investigation, further enhancing the robustness of the study.

Table 3: Combination of Fiber-Reinforced Concretes

Batch No	Fiber volume fraction (%)			
	Carbon	Steel	PP	GF
1	-	-	-	-
2	0.25	-	-	0.25
3	-	0.25	-	-
4	-	-	0.25	0.25
5	0.2	0.3	-	0.2
6	0.2	-	0.3	0.2
7	-	0.2	0.3	0.2

4. Results and Discussions

4.1 Compressive Strength

The table 4 and figure 1 shows the compressive strength of OPCC and fiber-reinforced concretes at 28 days. From figure 1, it is observed that carbon fibers exhibited the highest compressive strength among the four types of fibers analyzed [10]. On the other hand, PP GF fibers showed the lowest compressive strength. When the fibers are combined in a hybrid form, there is a noticeable increase in strength for both carbon-steel and carbon-PP fiber combinations. However, in the case of steel-PP fibers, the strength only slightly improved compared to pure PP fibers, while it decreased compared to pure steel fibers, [11] both having the same fiber volume fraction. Among the four hybrid combinations, carbon-steel fibers demonstrated the highest strength, whereas steel-PP and GF fibers exhibited the lowest strength [12].

Table 4: Compressive strength of OPCC and fiber-reinforced concretes at 28 days

Batch No.	**Compressive strength after 28 days (MPa)**			**Average Compressive strength after 28 days (MPa)**
	Sample I	**Sample II**	**Sample III**	
1	43.02	45.43	44.11	44.18
2	50.47	49.88	51.34	50.56
3	47.78	46.89	48.56	47.74
4	44.87	43.98	45.86	44.90
5	58.68	57.80	59.85	58.77
6	57.67	56.43	58.98	57.69
7	45.12	44.97	46.73	45.60

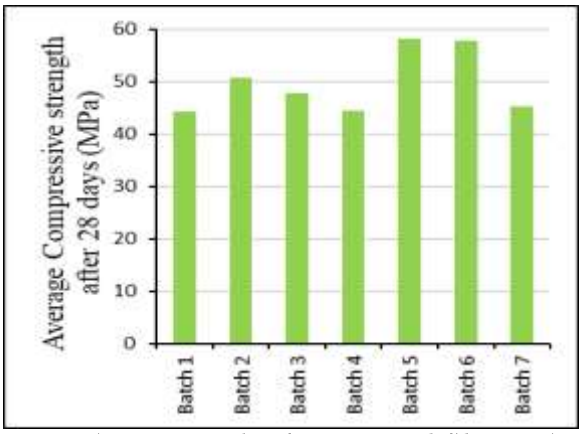

Figure 1: Variation of compressive strength of OPCC and fiber-reinforced concretes after 28 days

4.2 Split tensile strength

The split tensile strength of OPCC and fiber-reinforced concretes at 28 days is shown in table 5 and figure 2[13]. From the figure 2, it is reveals that the inclusion of fibers, such as carbon and steel fibers, increased the strength of the material, but when PP and GF fibers are used individually, the strength decreased. Similar to the compressive strength discussed earlier, carbon fibers exhibited the highest splitting tensile strength, while PP and GF fibers are the lowest [14]. When used in combination, carbon-steel fibers resulted in the highest splitting tensile strength, surpassing both carbon fiber-reinforced concrete and steel fiber-reinforced concrete [15]. On the other hand, steel-PP fibers showed the lowest splitting tensile strength, which was lower than that of steel fiber-reinforced concrete but higher than that of PP and GF fiber-reinforced concrete.

Table 5: Split tensile strength of OPCC and fiber-reinforced concretes at 28 days

Batch No.	Split tensile strength after 28 days (MPa)			Average Split tensile strength after 28 days (MPa)
	Sample I	Sample II	Sample III	
1	4.34	3.98	5.34	4.55
2	5.32	4.78	6.11	5.40
3	4.56	3.94	5.56	4.68
4	4.23	3.67	5.76	4.55
5	5.87	4.80	6.46	5.71
6	5.31	4.91	6.84	5.68
7	4.75	3.09	5.92	4.58

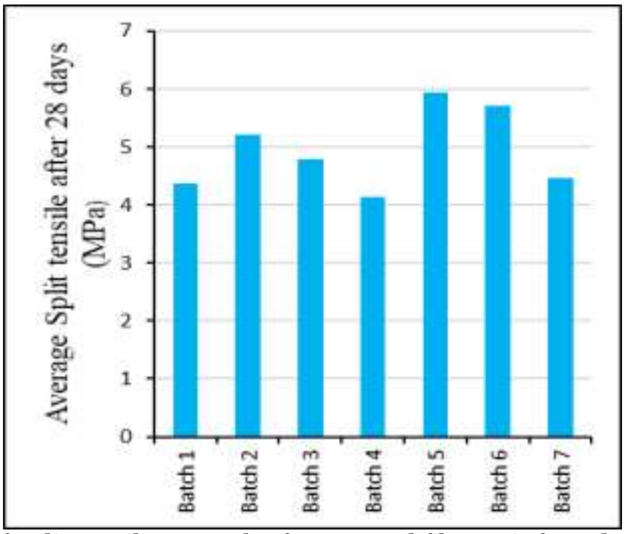

Figure 2: Variation of Split tensile strength of OPCC and fiber-reinforced concretes after 28 days

4.3 Flexural strength

At 28 days, the flexural strength of OPCC and fiber-reinforced concretes is shown in table 6 and figure 3. The introduction of fibers led to an increase in the Flexural strength across all four types [16]. Notably, steel fibers exhibited the highest Flexural strength, whereas PP and GF fibers demonstrated the lowest Flexural strength. The utilization of hybrid fibers resulted in an enhanced Flexural strength for both carbon-steel and carbon-PP combinations, surpassing the Flexural strength values achieved by any single fiber type [17]. However, when steel-PP fibers are combined, the MOR showed a slight improvement compared to using PP and GF fibers alone but exhibited reduced strength in comparison to employing steel fibers alone.

Table 6: Flexural strength of OPCC and fiber-reinforced concretes at 28 days

Batch No.	Flexural strength after 28 days (MPa)			Average Flexural strength after 28 days (MPa)
	Sample I	Sample II	Sample III	
1	4.12	3.89	5.32	4.44
2	5.32	4.78	6.45	5.51
3	4.61	3.81	5.18	4.53
4	4.56	3.80	5.69	4.68
5	5.78	4.77	6.66	5.73
6	5.10	4.53	6.63	5.42
7	4.89	3.41	5.44	4.58

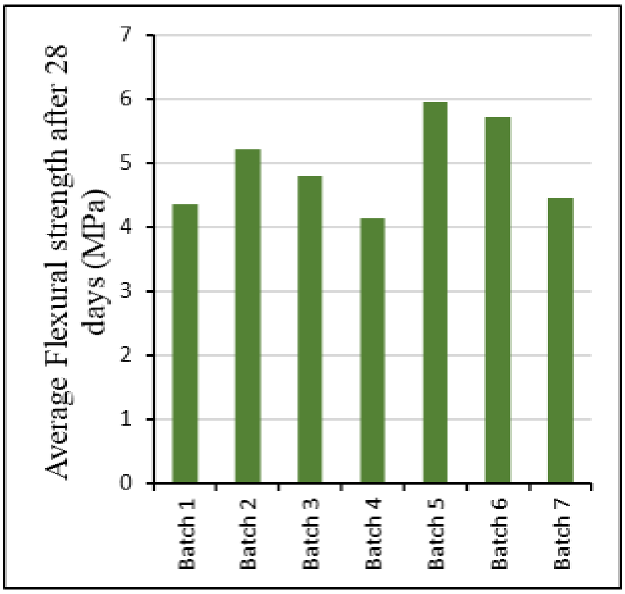

Figure 3: Variation of flexural strength of OPCC and fiber-reinforced concretes after 28 days

4.4 Flexural toughness

Table 7 summarizes the calculated toughness indices, which indicated an overall increase in toughness with the addition of all fiber types [8]. Among the individual fibers, steel fibers provided the highest flexural toughness values for indices I_5, I_{10}, and I_{30}, while carbon fibers exhibited the lowest toughness index for I_{30}, PP and GF fibers had the lowest toughness indices for I_5 and I_{10}. However, when combined in hybrid form, carbon-steel fibers significantly improved ductility characteristics [18], resulting in the highest flexural toughness compared to using carbon or steel fibers alone, particularly for the I_{30} index [11], as depicted in Figure 2. Steel-PP fibers and carbon-PP fibers demonstrated similar flexural toughness compared to using PP and GF fibers or carbon fibers separately, with a slight decrease compared to using steel fibers alone.

Table 7: Flexural Toughness Index of OPCC and Fiber-Reinforced Concretes at 28 Days

Batch No.	Toughness Index		
	I_5	I_{10}	I_{30}
1	3.16	5.89	9.78
2	4.08	7.48	14.82
3	4.15	7.90	22.80
4	4.04	6.26	16.78
5	4.23	8.14	29.80
6	3.80	6.20	15.90
7	3.43	6.31	18.44

To enhance the matrix strength, it is necessary to decrease the specific fiber spacing, thereby reducing the allowable flaw size [10]. This objective can be achieved by incorporating fine short discrete fibers, such as carbon fibers with a diameter of a few microns. These fibers effectively bridge the micro-cracks before they reach the critical flaw size [19]. To impart toughness, fibers with high ultimate strain capacity are required to bridge the macro-cracks in the matrix. For this purpose, either PP and GF fibers or steel fibers are utilized. However, the hybrid systems containing PP and GF fibers are found to be less effective in controlling matrix crack opening due to their low modulus [20]. Carbon fibers offer the advantage of increased compressive and splitting tensile strengths, while steel fibers contribute to higher flexural strength and flexural toughness. Therefore, the combination of carbon and steel fibers in a hybrid composite yields the most significant improvements in strength and flexural toughness [21]. According to table 4, the carbon-steel hybrid composite exhibited a 35.4% increase in compressive strength, a 38.5% increase in splitting tensile strength as per table 5, 32.9% increase in flexural strength as per table 6, and toughness indices ranging from 36.9% to 205.5% compared to unreinforced concrete as per table 7 [22].

As depicted in Figure 2, the load-carrying capacity of the carbon-steel hybrid decreases rapidly in the post-peak region, exhibiting a brittle response. This brittleness can be attributed to the low volume fraction of carbon fibers (only 0.3%) and the short length of chopped fibers, which only affect pre-peak micro cracking [23]. However, the load capacity recovers as the steel fibers start to pull out from the matrix. The toughness of carbon-steel hybrids demonstrated an approximately 30% and 98% increase for I30 when compared to pure steel fibers and carbon fibers, respectively [24].

Evidently, the presence of steel fibers enhances the resistance of the composite reinforced with randomly distributed short carbon fibers, and vice versa [25]. This synergistic effect optimizes the strength capacities of both carbon fibers and steel fibers, resulting in superior strength and flexural toughness compared to composites reinforced solely with steel or carbon fibers [26].

5. Conclusions

From the present study the following conclusions can be drawn:

i. At low fiber volume fractions, hybrid fibers can be employed to obtain materials with enhanced strength and improved toughness.
ii. Within the scope of this study, carbon fibers demonstrated high modulus and tensile strength, steel fibers exhibited similar modulus to carbon fibers with moderate elongation and tensile strength, while PP and GF fibers displayed high elongation, low modulus, and tensile strength.
iii. The composite with the highest properties is achieved by combining carbon and steel fibers, benefiting from their similar modulus and the synergistic interaction between the two reinforcing fibers.

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