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Research Article

Effect of fiber type, shape and volume fraction on mechanical and flexural properties of concrete

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ABSTRACT

An experimental work was herein presented focusing the effect of different type, shape and volume fraction of fibers on the hardened properties of concrete including compressive, splitting tensile and flexural strengths at 7 and 28 curing days. A control concrete mixture including no fiber was prepared and six fiber-reinforced concrete (FRC) mixtures were designed by using two different fiber types and volume fractions. Two types of steel fibers having different shapes (short straight and long hooked end) and polypropylene fiber were used with the volume fraction of 0.4% and 0.8%. The load-deflection curves and toughness of the specimens were analyzed based on ASTM C1609. The results showed that the utilization of short straight steel fibers with 0.8% volume fraction was most efficient at enhancing the compressive strength with 9.98% while the use of 0.8% long hooked end steel fibers provided better splitting tensile and flexural strengths with 33.33% and 30.35%, respectively, compared to specimen with no fiber at 28 curing day. Besides, the long hooked end steel fibers with the volume fraction of 0.8% contributed to an excellent deflection hardening behavior resulting in higher load deflection capacity and higher toughness values at peak load, L/600 and L/150. On the other hand, with incorporation of polypropylene fiber, all strength values decreased regardless of the volume fraction and curing days.

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1. INTRODUCTION

Traditional concrete is a brittle material that performs well in compression but can undergo brittle failure under tensile load. The increase in concrete strength enhances the brittleness of concrete [1]. Therefore, concrete design should be optimized to achieve sufficient energy absorption capacity, ductility, and strength to withstand structural tensile, impact and fatigue loads. In order to improve the engineering properties of concrete in terms of brittle-

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Table 1. Chemical properties of PC

(%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O
PC	19.40	5.36	3.79	64.3	2.25	2.47	0.90	0.06

ness, post-cracking capability and burst failure, short and randomly distributed fibers can be gradually added into concrete [2, 3]. Adding fibers such as basalt, polypropylene (PP), glass, and steel fibers into cement-based composites is so common to upgrade the tensile performance and mechanical properties [4–10]. These advantageous properties of fibers cause an increase in the application of fiber-reinforced concrete throughout the world. For instance, it has been widely used in industrial and infrastructure applications such as overlays, channel lining, airport pavement, etc., due to its positive effect on the durability of concrete.

On the other hand, the influences of fiber types on the hardened properties of concrete differ according to their physical and geometrical properties. Besides, the fiber content of concrete has to be limited depending on the length, shape, and type of fiber because the demanded strength can be achieved by using an adequate amount of fiber. Therefore, their optimum usage of concrete should be determined in a manner that causes the maximum improvement in the mechanical and durability properties of concrete by the minimum decrease in workability [11, 12].

In recent years, many researchers have focused on the influences of adding fibers on the hardened properties of concrete. Most existing studies have been carried out about using fibers, but there are still contradictory results about their effects on concrete. Khaloo et al. [13] used hooked end steel fiber with the volume fraction of 0.5%, 1%, 1.5% and 2% and found that tensile strengths of self-compacting concrete increased by the increase in fiber content while the compressive strength was decreased. Zeyad et al. [14] explained compressive strength reduction due to the effect of the length and shape of hooked end fibers which affect compacting efficiency. On the other hand, Şahin and Köksal [15] used two different hooked end steel fibers with different lengths and a volume fraction of 0.33%, 0.67%, and 1%. They indicated that the steel fiber volume and length do not affect compressive strength, while the steel fiber with high tensile strength improved the tensile strengths of concrete.

Similarly, Olivito and Zuccarello [16] concluded that steel fiber length has little effect on compression behavior. In the study of Yoo et al. [17], 1%, 2%, 3% and 4% volume fractions of straight fiber were used and the specimen obtained the highest load carrying capacity and elastic modulus with fiber volume fraction of 3%. Altun et al. [18] utilized hooked end steel fiber at dosages of 0, 30 and 60 kg/m^3 and found that the use of steel fiber at a dosage of 30 kg/m^3 showed the highest enhancement in

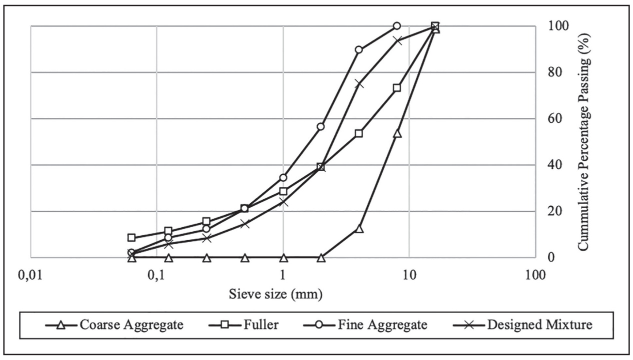


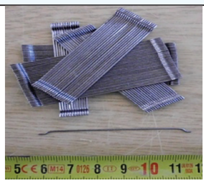
Figure 1. Grain size distribution of aggregates.

terms of flexural toughness and ultimate load. Özkılıç et al. [19] also used hooked end steel fiber with the volume fraction of 0.5%, 1%, 1.5% and 2% and concluded that 2% volume fraction of steel fiber was a limit value because the bending behavior began to dominate at that dosage. This finding was explained by the reduction in workability and bulking caused by high steel fiber content. In the study of Koroglu and Ashour [20] waste steel bead wires were added into concrete between 1% and 5% with an increment of 1%. They also found that the use of fiber ratio more than 2% caused a decrease in both compressive and splitting tensile strength, which was attributed to the reduction in workability.

Nonetheless, Cifuentes et al. [21] and Malek et al. [22] found that using PP fiber enhanced the ductility and flexural toughness compared to plain concrete in regardless of the fiber volume. Besides, some authors [23, 24] reported an increase of up to 10% in flexural strength with the addition of PP fiber. However, Ramesh et al. [25] concluded that the best flexural strength was observed by incorporating 0.6% PP fiber compared to those of 0.3%, 0.9% and 1.2% PP fiber. On the other hand, L. Bei-xing et al. [26] and Mazaheripour et al. [27] indicated that PP fiber changed the compressive strength hardly ever, while some other studies [28–30] found an increase up to 20%, which was attributed to the influence of fiber and aggregate interlocking mechanisms.

This study aimed to assess how different types, shapes and volume fractions of fibers influence the hardened properties, which were compressive, splitting and flexural tensile strengths of concrete. Within this scope, two types of fibers (PP and steel), two different shapes of steel fibers and two fiber volume fractions (0.4% and 0.8%) were considered. The flexural performance also included deflection capacity and toughness values based on ASTM C1609.

Table 2. Physical and geometrical properties for fibers

Name	Fiber type	Picture	d (mm)	l (mm)	Aspect ratio	E_f (GPa)	f_t (MPa)	Density (g/cm³)
HL	Long hooked end steel fiber		0.90	60	66	210	Min 1150	7.8
SS	Short straight steel fiber		0.15	6	40	200	3000	7.2
PP	Polypropylene synthetic fiber		–	6	240	–	350	0.91

l=length of fiber, d=diameter of fiber, Aspect ratio=l/d, Ef=modulus of elasticity of fiber, ft=tensile strength of fiber.

Table 3. Mixture proportions of fiber-reinforced concrete specimens

Mix code	Fiber content by volume (%)	Unit weight (kg/m³)						Slump (mm)
		Cement	Water	Fiber	Aggregates		SP	
					0–5 mm	5–15 mm		
Control	–	350	200	0	1007.0	671.3	1.75	150
HL-0.4	0.4	350	200	31.4	1001.1	667.4	1.75	130
HL-0.8	0.8	350	200	62.8	995.2	663.5	1.75	120
SS-0.4	0.4	350	200	28.8	1000.8	667.4	2	150
SS-0.8	0.8	350	200	57.6	995.2	663.5	2	140
PP-0.4	0.4	350	200	3.64	1001.1	667.4	2	160
PP-0.8	0.8	350	200	7.28	995.2	663.5	2.5	170

HL=long hooked end steel fiber, SS=short straight steel fiber, PP=polypropylene fiber.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Mixture Proportions

In this work, CEM I 42.5 Portland Cement (PC) with specific gravity of 3.15 was used as binder and its properties were as shown in Table 1. Fine and coarse aggregates with the maximum aggregate size of 5 mm and 16 mm, respectively, were used. The specific gravity and water absorption of sand was 2.39 and 2.30%, respectively. Gravel had the specific gravity of 2.68 and water absorption of 0.4%. Figure 1 shows the grain size distribution of the aggregates used in this study. Polycarboxylic polymer-based superplasticizer (SP) with a specific gravity of 1.06 was used in all mixtures.

Two different shapes of steel fibers, i.e., long hooked end and short straight fibers, and a polypropylene synthetic fiber were considered to investigate the influence of fiber shape and type on the mechanical and flexural performance of concrete as shown in Table 2. The long hooked end steel fiber, short straight steel fiber and polypropylene fiber were denoted as HL, SS and PP, respectively.

In this study, a control mixture including no fiber and six FRC mixtures were designed as shown in Table 3. In all mixtures, the ratio of water/PC was kept constant as 0.50 while fine and coarse aggregates were added into the mixtures in 60% and 40% of the total aggregate by weight, respectively. Besides, in order to adjust the similar slump val-

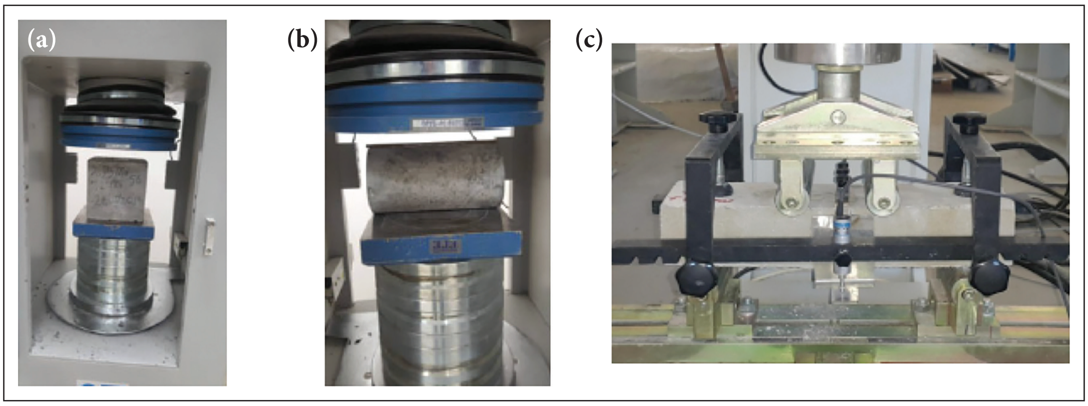


Figure 2. Mechanical tests: **(a)** compressive strength, **(b)** splitting tensile strength and **(c)** flexural tensile strength.

ues, SP were used as variable. Except control mixture, the fiber contents of 0.4% and 0.8% by the volume of concrete were used. In the Mix Code, the percentages of the fiber content of the mixtures were written next to the fiber types. That is, SS-0.4 represented the concrete mixture including 0.4% short straight steel fiber by volume.

2.2. Mix Procedure and Sample Preparation

For the mix procedure, all aggregates and steel fibers used in the designed mixture were mixed with 2/3 of the mixing water during 3 minutes. Then, PC and SP mixed with the rest of the water were mixed for additional 7 minutes. In the PP fiber-reinforced mixtures, at last, PP fiber was added and mixed into the mixture slowly to satisfy uniform distribution when the ingredients were dispersed effectively. To adjust the similar workability, slump flow test was carried out and the slump flow diameters of the fresh mixtures were measured. These values were found in the range of 120 mm–170 mm as shown in Table 3. Then, they were poured into moulds by two layers and vibrated for 60 times. After casting concrete, the specimens were covered with plastic sheets to inhibit the loss of moisture. They were kept in a room temperature and after 24 hours, the specimens were demolded and cured in saturated lime water until 7 and 28 curing days.

2.3. Test Procedure

In order to assess the effects of fiber type, shape and volume fraction on the mechanical and flexural properties of FRC, compressive, splitting tensile and flexural strength tests were conducted as shown in Figure 2. For each designed mixtures, three specimens were tested and mean value of them was reported as test results to obtain the hardened properties.

The compressive strength tests were carried out using 150x150x150 mm^3 cube specimens according to ASTM C39 [31]. The loading rate was 6 kN/sec. The test was continued until it lost its all-load carrying capacity.

The splitting tensile strength test was carried out using cylindrical specimens with a diameter of 100 mm and a height of 200 mm as per ASTM C496 [32]. The loading rate was arranged as 1.7 kN/sec. A thin plywood bearing strip was put along the length of the specimen to distribute the diametrical compressive force uniformly.

Four-point bending test through displacement control was carried out to measure the flexural strength based on ASTM C78 [33]. The beams with a cross-section of 100x100 mm^2 and a length of 400 mm were used and the mid-span deflection was measured using a Linear Variable Differential Transformer (LVDT) placed at the middle of the specimen. The loading rate was arranged as 0.003 mm/sec. The load-deflection curves determined the flexural behavior of the FRC specimens.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1. Compressive Strength

3.1.1. Effects of Fiber Type and Shape on Compressive Strength

Figure 3 illustrates the effect of fiber type and shape on the compressive strength of concrete with/ without fiber at 7 and 28 days. For seven curing days, concrete specimens with no fiber had the highest compressive strength with 37.1 MPa compared to the FRC specimens, regardless of the fiber content. On the other hand, for 28 curing days, the highest compressive strengths were obtained in the short straight steel fiber-reinforced concrete specimens with 43.5 MPa and 45.2 MPa for 0.4% and 0.8% fiber content, respectively, representing increases of 5.84% and 9.98% compared to the control specimen. This may be because at early age, the fibers could not show their effects on the strength due to the immaturity of the matrices. However, by improving the matrix, the SS fibers could inhibit the crack initiation and propagation and contribute an effective bridging mechanism. The effectiveness of SS fiber was so sharp for all fiber contents at 28 days. This could be because the shortest fiber in length could bridge the micro cracks more effectively. In the other studies [10, 34–36], it was also found that short and straight micro fibers

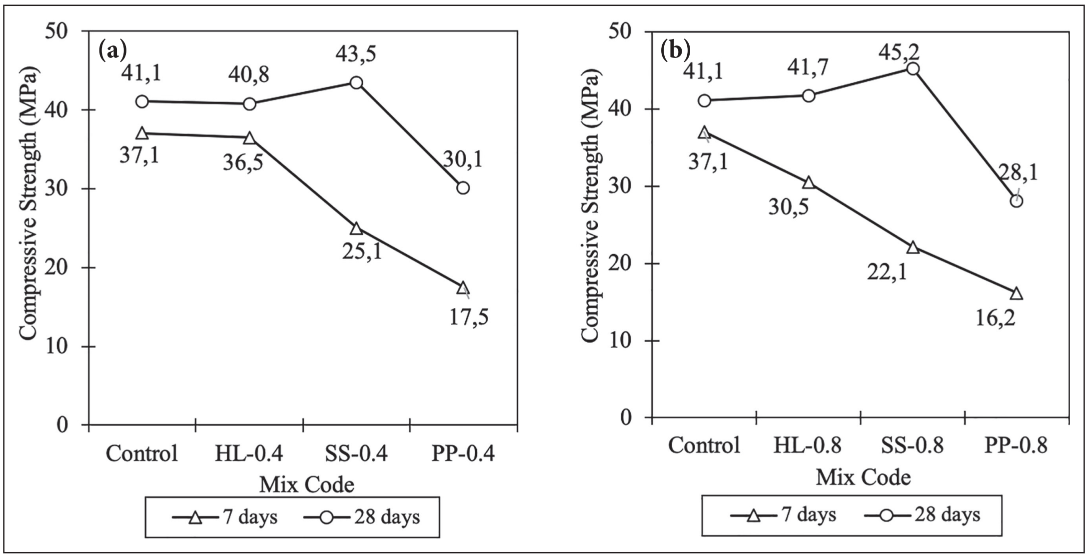


Figure 3. Effect of fiber type and shape on compressive strength for **(a)** 0.4% volume of fiber, **(b)** 0.8% volume of fiber.

played a vital role on the enhancement of the compressive strength of FRC because of inhibiting the micro-crack propagation. However, the compressive strength of PP fiber-reinforced concrete with the fiber volume of 0.4% and 0.8% were the lowest at 7 and 28 curing days. That is, the compressive strength of PP0.4 was lower than that of the control concrete by 52.83% and 26.76%, respectively, at 7 days while for PP0.8, it was 56.33% and 31.63% at the age of 28 days. Some researchers [37, 38] think that PP fiber plays an essential role in bridging cracks when distributed inside the concrete. Because the stress transferred between the crack tip and the concrete surface in the crack areas can be achieved by the great adhesion between the concrete and fiber. Therefore, the stress occurred in the concrete becomes uniform, resulting in alleviating the degree of stress concentration. However, the use of high amount of PP fiber in concrete cause poor dispersion of fibers resulting in weak interfacial transition areas in matrix. In this study, the high degradation in compressive strength of PP fiber-reinforced concrete specimens can be attributed to the inclusion of a high dosage of PP fibers because in the matrix, the average distances between the fibers can shorten by the high fiber content.

As a consequence, the fibers can overlap, thus worsening the bonding between the paste and fibers. According to the study of Zhang [39] about the compressive strength of PP fiber-reinforced concrete having fiber content of 0%, 0.089%, 0.13%, 0.17%, 0.22%, 0.56% volume fraction, it was found that the use of PP fiber at a certain percentage enhanced the compressive strength. However, the compressive strength of PP fiber-reinforced concrete with the fiber volume of 0.22% and 0.56% became lower than that of plain concrete. Moreover, in this study, referring to Table 3, the slump values of PP fiber-reinforced concrete mixtures also proved that PP fibers induced a decrease in flowability, leading to the use of a higher amount of SP. It was observed that PP fibers caused the formation of agglomerations during the mixing process due to their higher resistance to flowability. The decreased flowability of the new matrix could inhibit the dispersion of PP fibers resulting in a reduction in compressive strength. In the aspect of long hooked steel fiber-reinforced concrete, it was found that the inclusion of long hooked steel fiber with a volume fraction of 0.4% provided slightly lower compressive strength than that of control concrete for all curing ages while the specimen of HL0.8 exhibited slight improvement in compressive strength with 1.46% at 28 days. This increase can be due to the confining effect caused by long hooked end steel fibers to FRC.

3.1.2. Effects of Fiber Volume Fraction on Compressive Strength

The changes in compressive strength of FRC having different fiber volume fractions at 7 and 28 curing days were presented in Figure 4. As seen, at 7 days, compressive strength values were reduced with the increase in the fiber content for all fiber types and shapes. On the other hand, for 28 curing days, using short steel fiber with 0.4% and 0.8% volume content improved the compressive strength by 5.84% and 9.98% regarding control specimens, respectively. That could be because the stress between the matrix and fiber may reduce by the use of a higher dosage of short steel fiber content and thus, the crack initiation and propagation can be delayed resulting in an improvement of strength. This result is consistent with the other studies [40, 41]. However, it can be said that the quantity of HL did not have an essential influence on the compressive strength of concrete; that is, the specimen of HL0.4 and HL0.8 had the compressive strength of 40.8 MPa and 41.7 MPa, respectively, at 28 days.

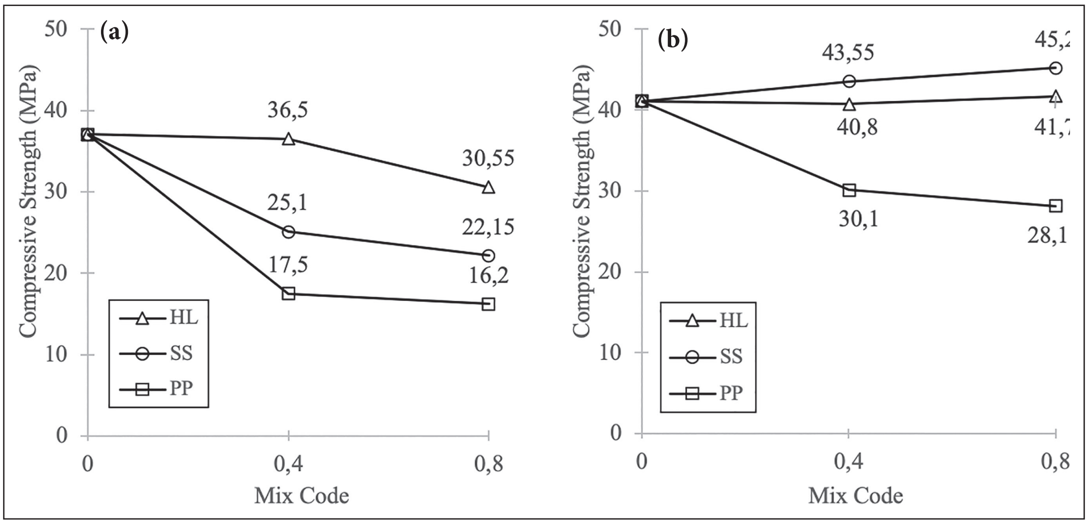


Figure 4. Effect of fiber volume fraction on compressive strength at **(a)** 7 days, **(b)** 28 days.

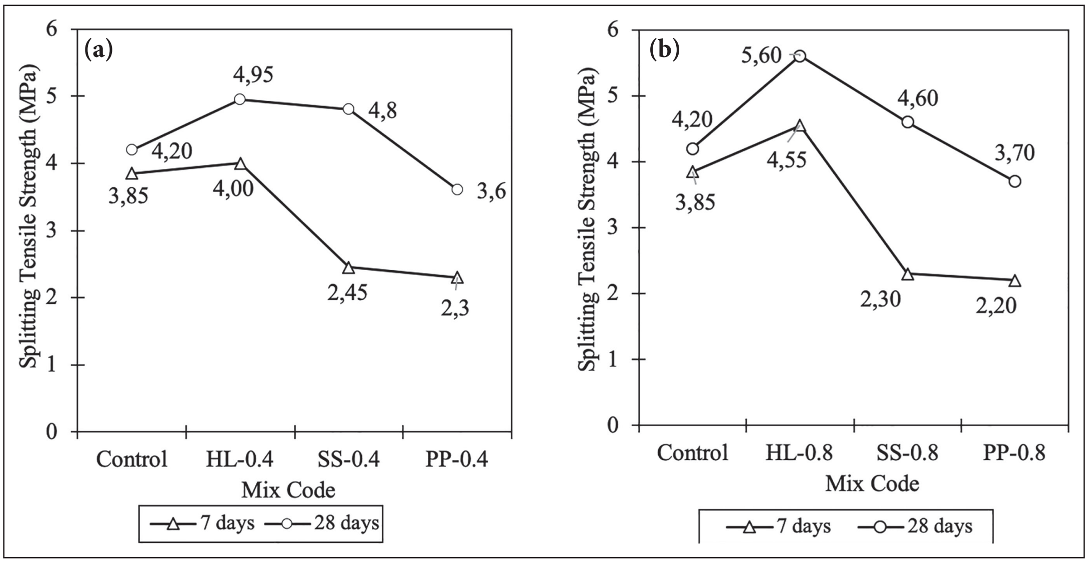


Figure 5. Effect of fiber type and shape on splitting tensile strength for **(a)** 0.4% volume of fiber, **(b)** 0.8% volume of fiber.

In contrast, an increase in PP fiber volume content resulted in a significant reduction in the compressive strength at all curing ages. Using PP with 0.4% and 0.8% by volume fraction decreased the compressive strength by 52.83% and 56.33%, respectively, for seven days and 26.75% and 31.63%, respectively, for 28 days. In general, especially for higher fiber content, a decreasing trend can be observed due to the poor dispersion of fibers and the formation of clumps of fibers during the mixing process, as in the case of this study. According to the research carried out by Ahmed et al. [42], the use of PP fibers at the percentage of 0.18% to 0.40% increased the compressive strength by about 5%, but at high PP fiber volume contents i.e., 0.55% to 0.60%, it decreased nearly 3–5% compared to plain concrete at 28 days. Wang et al. [43] also found that 0.5% PP fiber volume content negatively affected the compressive strength and the reason of this result was explained by the reduction in the elastic modulus of the entire concrete matrix [44]. Besides, the reduction in compressive strength may be explained by having a high water/cement ratio of mixtures. As already known, the lower water/cement ratio affects the microstructure of paste- aggregate interfacial transition zone by reducing the capillary porosity of the hardened paste [45]. The adhesion between aggregates and paste can be influenced by the increase in water content in the bulk paste resulting in a reduction of concrete performance. Therefore, the high w/c ratio could weaken the reinforcement effect of PP fibers. Zhang et al. [39] used the PP fiber contents of 0.8, 1.2, 1.6, 2.0, and 5.0 kg/m^3 for 0.4, 0.5 and 0.6 water/cement ratios and they concluded that the increase in water/cement ratio reduced the compressive strengths of the specimens for all PP fiber content.

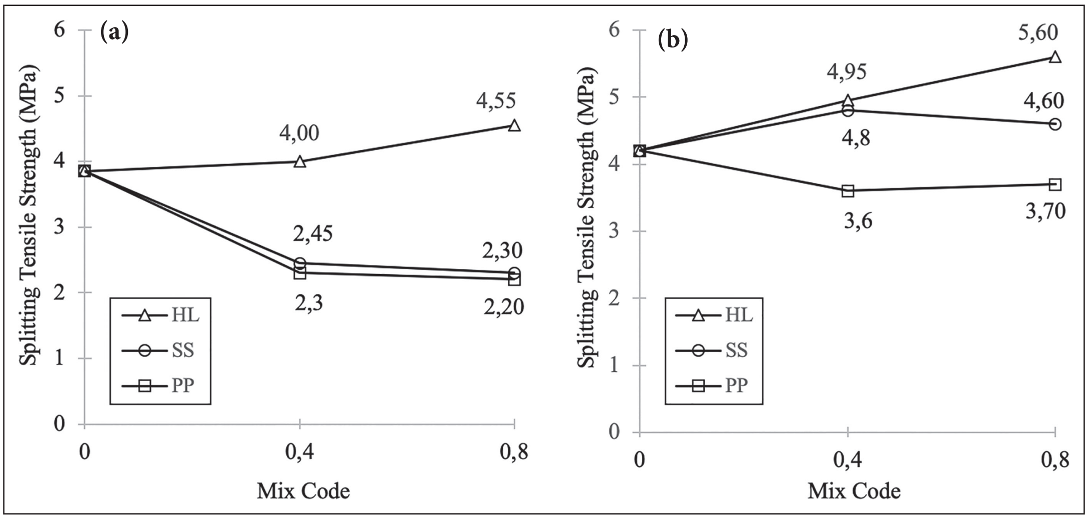


Figure 6. Effect of fiber content on splitting tensile strength at **(a)** 7 days, **(b)** 28 days.

3.2. Splitting Tensile Strength

3.2.1. Effects of Fiber Type and Shape on Splitting Tensile Strength

The effect of fiber type and shape on the splitting tensile strength of concrete with and without fiber at 7 and 28 days was presented in Figure 5. Unlike the compressive strength test results, more pronounced enhancement in the splitting tensile strength values were found for HL reinforced concrete specimens compared to plain concrete. That is, the improvement in splitting tensile strength of HL-0.4 and HL-0.8 were about 3.90% and 17.86% at 7 days and 18.18% and 33.33% at 28 days, respectively. It can be explained by the prevention of macro cracks caused by the presence of HL. This is because, long steel fibers with hooked end were more effective in the transfer of tensile stress and they had higher elastic modulus with regards to short steel fibers. Tabatabaeian et al. [46] and Haddadou et al. [47] also proved the effectiveness of HL on the bridging of cracks. On the other hand, adding SS into concrete led to a reduction in splitting tensile strength values for all fiber volume fractions for 7 curing days while for 28 curing days, the splitting tensile strength of SS-0.4 and SS-0.8 increased with 14.28% and 9.52%, respectively, with regards to that of control specimen. At 7 days, the reduction could be due to the immaturity of matrix. However, it was found that, the increase rate of splitting tensile strength of concrete with SS with regards to plain concrete was less than those of the concrete with HL. This result also prove that short fibers can control the opening of the cracks at a certain level but long fibers play a vital role to prevent the propagation of localized cracks and macrocracks. As for PP fibers, the lowest splitting tensile strength values were obtained among all concrete specimens regardless of the fiber content and curing days. This may be because, in this study, the use of PP fibers decreased the workability of concrete resulting in the formation of agglomerations during mixing process. The insufficient dispersion of PP fiber could cause the reduction in splitting tensile strength.

3.2.2. Effects of Fiber Volume Fraction on Splitting Tensile Strength

The effects of fiber volume fraction on splitting tensile strength of concrete at 7 and 28 curing days were shown in Figure 6. It was clear that the use of 0.4% SS and 0.4% PP caused a sharp decrease in splitting strength while a slight improvement in splitting strength was observed as HL volume fraction increased at the curing age of 7. On the other hand, with the incorporation of 0.4% and 0.8% HL and SS fiber, the improvements in the splitting tensile strength were more pronounced at 28 days. The reason is that the steel fiber is tightly gripped by the concrete matrix along the crack resulting in a solid binding capacity between the matrix and steel fiber [48]. However, the increase in splitting tensile strength with increased steel fiber content was more evident for HL reinforced concrete specimens at 28 days. That is, the splitting tensile strength of HL-0.4 and HL-0.8 increased by 17.88% and 33.33%, respectively. It may be attributed to the fact that the stress caused by the external load could be transferred more effectively between the concrete matrix and steel fiber due to the addition of a higher amount of HL, resulting in the use of full tensile strength of steel fiber. In the study of Turk et al. [49], the short steel fiber content was changed as 0%, 0.25%, 0.50%, 0.75% and 1% instead of long, double hooked end steel fiber. They found that concrete specimens with 1% long, double hooked end steel fiber had the highest splitting tensile strength and it reduced as the content of long, double hooked end steel fiber decreased.

Splitting tensile strength is reduced with increased PP fiber volume fraction at all curing ages. It decreased by 40.26% and 42.86% for 7 days and 14.29% and 11.90% for 28 days when 0.4% and 0.8% PP by volume fraction was

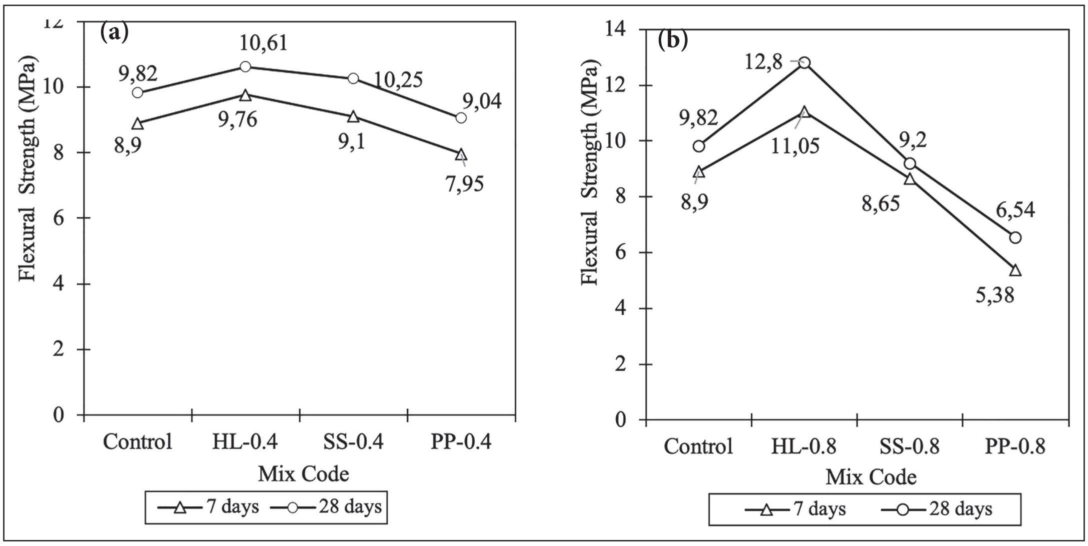


Figure 7. Effect of fiber type and shape on flexural strength for **(a)** 0.4% volume of fiber, **(b)** 0.8% volume of fiber.

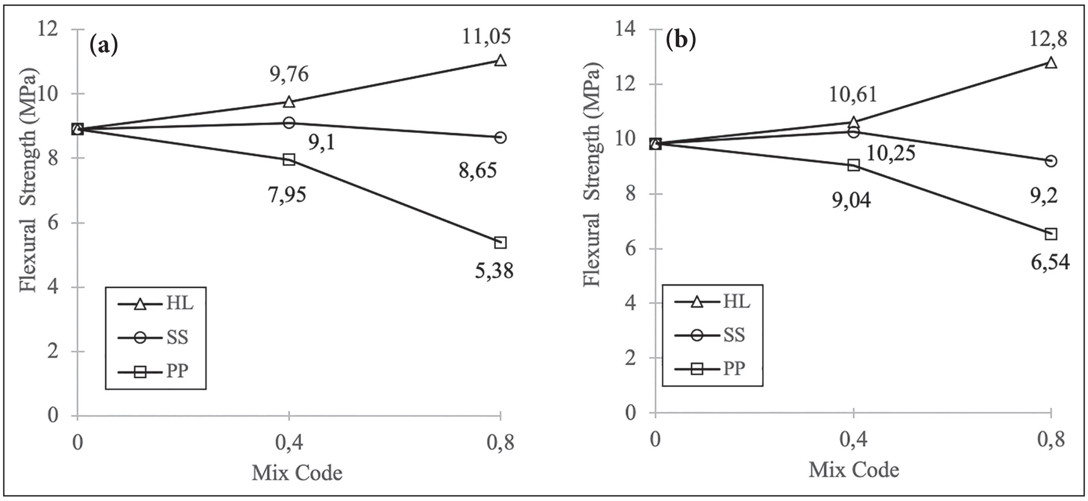


Figure 8. Effect of fiber content on flexural strength at **(a)** 7 days, **(b)** 28 days.

added, respectively. It could be due to having a higher aspect ratio of PP with regards to steel fibers which causes a reduction in workability of the fresh mixture resulting in lower tensile strength [50]. The higher PP fiber volume fraction can worsen the dispersion of fibers during the mixing process, as in the case of this study.

3.3. Flexural Performance

3.3.1. Flexural Strength

3.3.1.1. Effects of Fiber Type and Shape on Flexural Strength

Figure 7 shows the effect of fiber type and shape on the flexural strength of concrete with and without fiber at 7 and 28 days. The concrete reinforced with HL fiber had the highest flexural strength, that is, the use of 0.4% and 0.8% long hooked steel fiber by volume enhanced the flexural strength by 9.66% and 24.16%, respectively, at 7 days while these values were 8.04% and 30.35% at 28 days. It may be attributed to the fact that HL can hold more stress than SS due to its fiber-end, which provides a better mechanical interlock and anchoring effect. Researchers also proved similar findings [49, 51–53]. On the other hand, 0.8% volume of SS caused a reduction in flexural strength by 2.81% and 6.31% at 7 and 28 days, respectively, while 0.4% volume of SS increased the flexural strength by 2.25% and 4.38% at 7 and 28 days, respectively. As for PP fiber-reinforced concrete, PP fiber caused the lowest flexural strength regardless of the fiber content and curing days. This result could be due to the poor bonding between the cement paste and PP because PP fiber has a hydrophobic nature with a relatively smooth surface [54]. Besides, the reduction in fresh properties caused by PP and its lower elastic modulus could lead to limited flexural strength values. Therefore, as seen in the load-deflection curve (Fig. 9 and 10) of PP fiber-reinforced

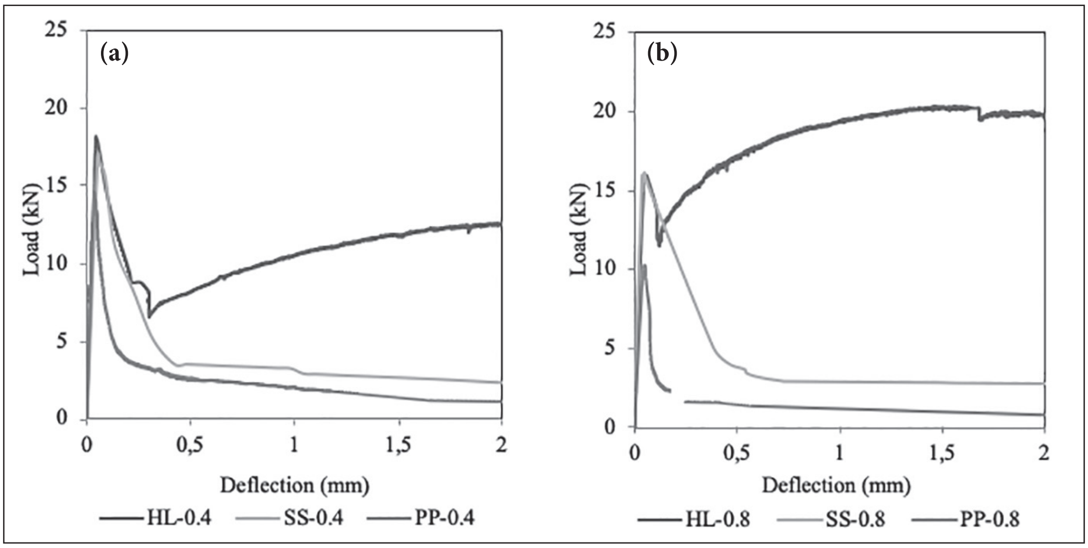


Figure 9. Effect of fiber type and shape on load-deflection curves for **(a)** 0.4% volume of fiber, **(b)** 0.8% volume of fiber at 7 days.

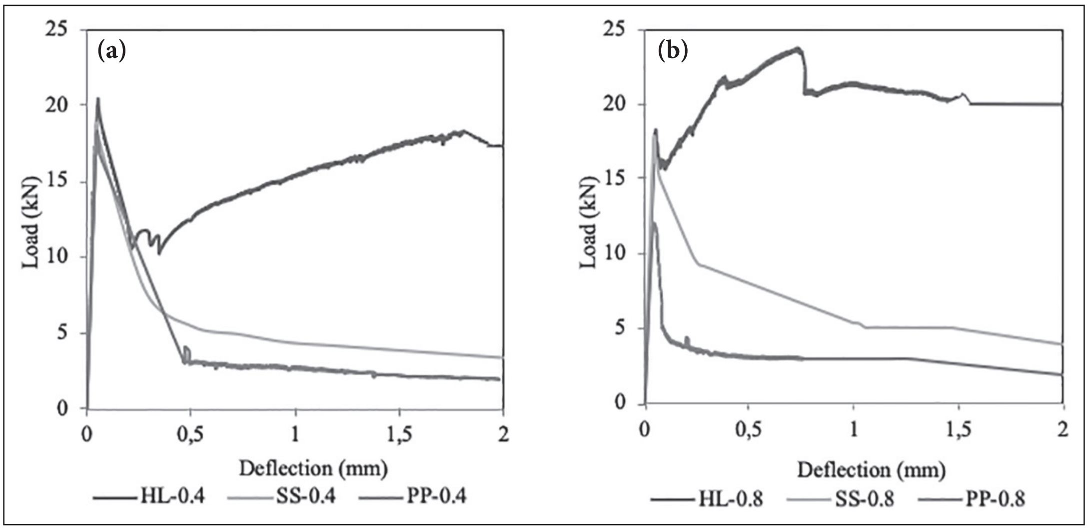


Figure 10. Effect of fiber type and shape on load-deflection curves for **(a)** 0.4% volume of fiber, **(b)** 0.8% volume of fiber at 28 days.

concrete, the peak load was taken as the ultimate failure force and after that point, the specimens lost all load carrying capacity regardless of the curing day and fiber content.

3.3.1.2. Effects of Fiber Volume Fraction on Flexural Strength

Figure 8 shows the effects of fiber volume fraction on flexural strength of concrete at 7 and 28 curing days. As observed, the flexural strength increased gradually with HL fiber dosage at 7 and 28 curing days. 0.4% and 0.8% volume of HL improved the flexural strengths by 9.66% and 24.16%, respectively, at 7 days, while these values were 8.04% and 30.35%, respectively, at 28 days. Besides, the use of 0.4% SS caused a slight improvement in flexural strength but 0.8% SS fiber significantly decreased the flexural strength of specimens, especially at 28 days. As mentioned before, long hooked steel fiber positively affected flexural strength due to having a better anchoring effect. The increased long hooked steel fiber volume fraction could reduce the average space between the fibers and thus, more amounts of fibers could sustain the load resulting in a decrease in the stress between the matrix and fiber. Therefore, the initiation and propagation of cracks could be delayed and it could cause an improvement in flexural strength [40].

On the other hand, the increase in PP fiber volume fraction reduced the flexural strength for both 7 and 28 curing days. It decreased by 10.61% and 39.50% for seven days and 7.94% and 33.40% for 28 days when 0.4% and 0.8% PP by volume fraction were added, respectively. It could be

Table 4. Flexural performance of concrete specimens at **(a)** 7 curing day and **(b)** 28 curing day based on ASTM C1609

	a					
	HL0.4	**HL0.8**	**SS0.4**	**SS0.8**	**PP0.4**	**PP0.8**
δ_M (mm)	0.056	1.280	0.045	0.048	0.037	0.049
f_M (MPa)	9.76	11.05	9.10	8.65	7.95	5.38
T_M (N.mm)	0.50	1.03	0.46	0.68	0.29	0.31
$\delta_{L/600}$ (mm)	0.50	0.50	0.50	0.50	0.50	0.50
$f_{L/600}$ (MPa)	4.37	9.10	1.88	1.96	1.41	0.78
$T_{L/600}$ (N.mm)	4.93	7.33	4.03	4.73	2.31	1.38
$\delta_{L/150}$ (mm)	2.00	2.00	2.00	2.00	2.00	2.00
$f_{L/150}$ (MPa)	6.68	10.57	1.24	1.48	0.61	0.42
$T_{L/150}$ (N.mm)	24.25	36.50	8.35	9.03	4.93	3.03
	b					
	HL0.4	**HL0.8**	**SS0.4**	**SS0.8**	**PP0.4**	**PP0.8**
δ_M (mm)	0.053	0.606	0.046	0.048	0.050	0.045
f_M (MPa)	10.61	12.80	10.25	9.20	9.04	6.50
T_M (N.mm)	0.59	11.55	0.44	0.50	0.50	0.32
$\delta_{L/600}$ (mm)	0.50	0.50	0.50	0.50	0.50	0.50
$f_{L/600}$ (MPa)	6.67	11.73	0.63	0.13	1.66	1.69
$T_{L/600}$ (N.mm)	6.37	9.17	6.16	5.39	4.86	2.20
$\delta_{L/150}$ (mm)	2.00	2.00	2.00	2.00	2.00	2.00
$f_{L/150}$ (MPa)	9.24	10.67	1.75	2.14	1.04	0.98
$T_{L/150}$ (N.mm)	31.13	41.78	15.03	13.37	8.54	8.33

because adding a higher dosage of PP fiber led to further harm and defects in terms of mechanical strengths.

3.3.2. Load Deflection Curves and Flexural Toughness Based on ASTM C1609

ASTM C1609 [55] ensures flexural strength and toughness values corresponding to L/600 and L/150 in load-deflection curves. L symbolizes the length of span of the specimen and due to the reason that L is 300 mm in this study, $\delta_{L/150}$ and $\delta_{L/600}$ are the deflection points at 0.5 mm and 2 mm, respectively. $f_{L/600}$ and $f_{L/150}$ are the flexural strength of concrete specimen at the small flexural deformation (L/600) and at the large flexural deformation (L/150), respectively. $T_{L/150}$ and $T_{L/600}$ are the toughness values at L/150 and L/600, respectively, i.e., the area under the load-deflection curve until L/150 and L/600. Besides, δ_m, f_m and T_m are the deflection, flexural strength and toughness values corresponding to peak load.

3.3.2.1. Effects of Fiber Type and Shape on Load-Deflection Curves and Toughness

The effects of fiber type and shape on load-deflection curves of FRC specimens at 7 and 28 days were shown in Figure 9 and 10, respectively. As seen in figures, the linear elastic region of all load-deflection curves were similar, but the FRC specimens' flexural behavior was observed as deflection hardening and deflection softening according to the type and shape of the fibers. For example, concrete with HL exhibited deflection hardening behavior, resulting in higher load bearing capacity after matrix cracking. HL eliminated sudden failure through crack bridging and thus, increased the energy absorption capacity and the post-crack resistance. In other words, including long hooked steel fiber to concrete caused more ductile behavior instead of brittle. Besides, HL reinforced concrete specimens had the highest peak load for all curing days and fiber content. As seen in Table 4, the peak deflections were also obviously enhanced, especially by the use of 0.8% volume of HK fiber, i.e., the peak deflections were found as 1.28 mm and 0.606 mm at 7 and 28 curing days, respectively. It can be due to the strong anchoring influence of long hooked steel fiber associated with fiber geometry. Besides, it could be because longer fibers could handle the greater load in cracks which could delay the crack formation and propagation [56]. On the other hand, referring Figure 8 and 9, deflection softening behavior was observed for both SS and PP fiber-reinforced concrete specimens, i.e., after reaching the peak load, they exhibited a sudden drop and lost their load carrying capacity, regardless of the curing age and fiber content. Abu-Lebdeh [57] also found that hooked end fibers caused 95% and 115% increase in pull-out energy and peak load regarding straight fiber.

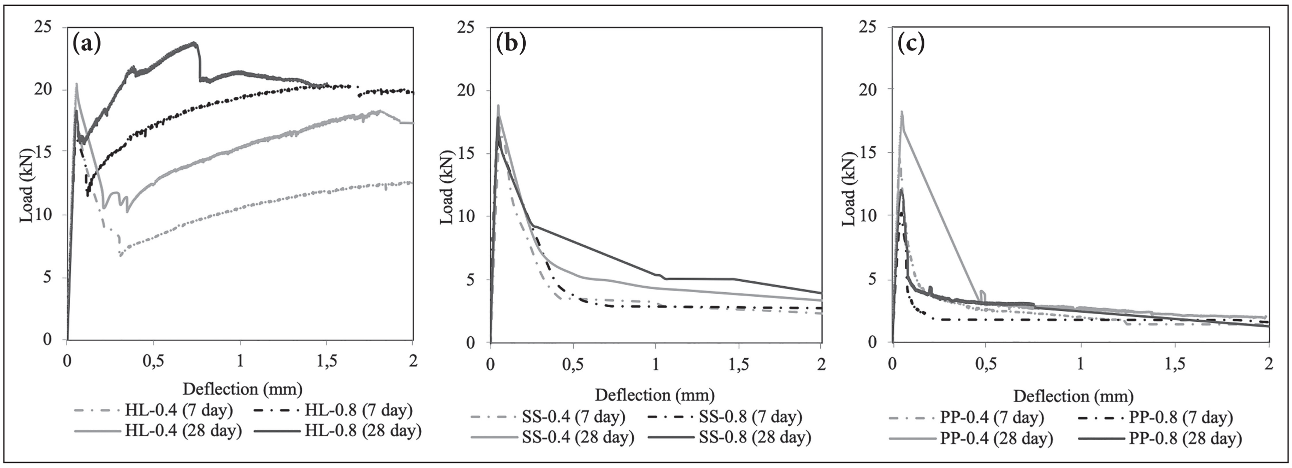


Figure 11. Effect of fiber content of **(a)** HL, **(b)** SS, and **(c)** PP on load-deflection curves.

At deflection point L/600, HL fiber-reinforced concrete specimens were in the strain hardening region regardless of the curing age and fiber content while SS and PP fiber-reinforced concrete specimens were in the softening range. This situation provided higher toughness at deflection L/600, that is 0.4% HL increased TL/600 by 3.34% and 31.19% with regards to 0.4%SS and 0.4%PP, respectively, at 28 days and these values were 70.18% and 316.28% when 0.8% fiber volumes were incorporated.

As expected, the flexural strength and toughness of HL reinforced concrete specimens at L/150 were higher than the others for all curing ages and fiber contents. However, the outcomes of the load-deflection curves also showed that SS and PP fiber-reinforced concrete specimens lost almost all load carrying capacity at deflection L/150. For example, fL/150 of SS fiber-reinforced concrete specimens were 1.36 MPa and 1.94 MPa, in average, at 7 and 28 days, respectively, while these values were 0.51 MPa and 1.0 MPa in average for PP fiber-reinforced concrete specimens.

3.3.2.2. Effects of Fiber Volume Fraction on Load-Deflection Curves and Toughness

The effects of fiber volume fraction on load-deflection curves of FRC specimens at 7 and 28 days were shown in Figure 11. The load-deflection curves became voluminous with higher peak load as HL content increased for all curing days. This deflection hardening behavior demonstrates the more effective reinforcing effect of HL. The deflection capacity and flexural strength at the peak were also increased with the increased HL volume fraction. The quantity of HL had an important influence on the pre-peak portion of the curve, which improved the flexural performance. Namely, FRC specimens having 0.8% volume of HL were in the range of pre-peak response at the deflection point L/600 at 7 and 28 days, while the concrete specimens with 0.4% HL were in the post-peak portion of the curve. Besides, the use of 0.8% volume of HL caused the highest toughness at peak load, L/600 and L/150 for all curing ages, and it shows that they absorbed more energy, which indicates higher ductility in the hardening portion. This may be due to providing effective crack bridging caused by the higher content of HL. This finding is consistent with the studies of Turk et al. [10] and [8].

On the other hand, because of the insufficiency of SS in the bridging of crack and having a lower aspect ratio than HL, SS reinforced concrete specimens exhibited less post-peak load carrying capacity and showed similar flexural performance for all fiber volume fractions. However, using a higher volume fraction of PP fiber in concrete caused a slightly negative effect on deflection capacity and toughness at 7 and 28 days. For example, 0.8% volume of PP decreased the toughness at peak load and L/600 by 35.74% and 54.62%, respectively, compared to the concrete specimens with 0.4% PP at 28 days. As mentioned before, PP fiber decreased the efficiency of the fresh mixture and using a higher volume of PP fiber could increase this negative effect more apparent, resulting in a reduction in flexural performance.

4. CONCLUSION AND SUMMARY

This study designed seven concrete mixtures with a constant water/cement ratio. A control mixture had no fiber and the other six mixtures included fibers with different types, shapes and volume fractions. Within this scope, two types of steel fibers having different shapes and PP fiber were used with the volume fraction of 0.4% and 0.8%. The following conclusions can be listed according to the test results;

1. The highest compressive strength was achieved at the control specimen with no fiber at 7 curing day while for 28-day, the use of short straight steel fibers enhanced the compressive strength. The increase in fiber volume fraction led to a decrease in the compressive strength at 7 days, possibly due to the cement matrix's immaturity. On the other hand, adding 0.8% volume fraction of short straight steel fiber enhanced the compressive strength while long hooked end steel fiber did not show any effect at 28 curing days. Besides, as the PP fiber vol-

ume fraction increased, the compressive strength reduced significantly at all curing ages.

2. The long hooked end steel fiber was the most effective fiber at improving splitting tensile and flexural strength of concrete at all volume fractions and curing days. The highest enhancement was observed at the volume fraction of 0.8% long hooked end steel fiber at 28 curing days. The splitting tensile strength was reduced by adding short straight steel fiber for all fiber volume fractions at 7 days, while for 28 curing days, the use of 0.4% short straight steel fiber enhanced the splitting tensile and flexural strengths more. PP fibers reduced the splitting tensile and flexural strength values regardless of the fiber volume fractions and curing days.
3. Load-deflection curves showed that adding long hooked end steel fiber caused deflection hardening behavior, resulting in higher load bearing capacity after matrix cracking, while the reinforced concrete specimens with short straight steel fibers and PP exhibited deflection softening. The highest enhancement in flexural performance in terms of toughness, peak load and pre-peak response at the deflection point L/600 was observed by the utilization of 0.8% volume fraction of long hooked end steel fiber.

In summary, 0.8% volume fraction of short straight steel fibers showed the best compressive strength reinforcement while long hooked steel fiber did not cause a significant effect regardless of fiber volume. On the other hand, the highest enhancement in splitting tensile and flexural strengths were achieved by utilizing 0.8% volume fraction of long hooked end steel fiber and using 0.4% volume fraction of short straight steel fibers also enhanced the splitting tensile and flexural strength compared to plain concrete. However, PP fibers reduced the compressive, splitting tensile and flexural strength values regardless of the fiber content and curing days. In addition to these, as future work, the effect of hybrid use of different volume fractions of long hooked end steel fiber, short straight steel fibers and PP fiber on mechanical properties of concrete specimens can be investigated to reveal the interaction of these fibers into the matrix.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

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PEER-REVIEW

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