

## INVESTIGATING FLEXURAL PERFORMANCE OF FIBER-REINFORCED CONCRETE WITH DIFFERENT CONTENTS AND TYPES OF MACROSYNTHETIC FIBER

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*Concrete, as one of the most widely used construction materials, has brittle behavior. Adding fiber to concrete affects the latter's ductility behavior as well as some of the mechanical properties. Hence, experimental research was conducted to study the effect of fiber type and content on the flexural performance of fiber-reinforced concrete. In this study, the concrete samples were made and evaluated in accordance with ASTM C1609, ASTM C1399 and ASTM C79 standards, with three different types of polymer fibers, including twisted, barchip and fibrillated, and three contents of 0.2, 0.4 and 0.6 volume percentages. The results showed that by adding fibers to concrete samples, the flexural strength and flexural toughness increased by 19.6–81.69% and 3.98–79.89%, respectively. Furthermore, adding the fibers to the concrete sample increased the postcracking flexural strength by 16.63–30.14%. The concrete containing twisted and broken fibers, despite their different fiber types, had similar flexural performance.*

**Keywords:** fiber-reinforced concrete, flexural strength, average residual strength, flexural toughness.

**Introduction.** Fiber-reinforced concrete is a type of concrete that is mixed with fiber. Various types of fibers are used to produce fiber-reinforced concrete, which include glass, polymer, carbon and steel [1]. In the present research, macrosynthetic polymer fibers were used. Some of the consequences of applying macrosynthetic fibers in concrete include reduced shrinkage of fresh and hardened concrete, increased ductility, vulnerability and hardness of concrete, increased strength against fatigue stresses, increased durability and lifetime of concrete, improved concrete mechanical properties (tensile strength, flexural strength, etc.), control of secondary/thermal cracks of concrete, preventing the in-depth propagation of cracks, postcracking chargeability and reduced permeability against chloride and sulfate ions [2]. To date, numerous studies have been conducted on fiber-reinforced concrete, most of which have been focused on the evaluation of fiber-reinforced concrete using steel and plastic fibers or their combination.

Alberti et al. studied self-compacting fiber-reinforced concrete by combining polyolefin and steel fibers and reported that the combination of polyolefin and steel fibers had higher performance in terms of rupture toughness and flexure than the use of a single type of fiber [3]. Jamshidi, Latifi and Pakravan reviewed the literature on the use of hybrid fibers in concrete and reported that combining various types of fibers would yield better results in terms of concrete toughness and energy absorption [4]. Jadhav et al. conducted research on the flexural performance of hybrid fiber-reinforced concrete beams and reported that such fibers improved the flexural performance of the fiber-reinforced concrete beam [5]. Vibhuti et al. studied the mechanical properties of fiber-reinforced concrete for pavement and evaluated the effect of adding single and hybrid fibers to concrete. Accordingly, they reported that the hybrid fibers improved compressive and flexural strength value as compared to the single fibers [6]. Alternatively,

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Eswari conducted experiments on the flexural performance of hybrid fiber-reinforced concrete and evaluated the effect of different contents of polymer and steel fibers on the flexural strength and performance of fiber-reinforced concrete samples. Thus, he reported that adding fibers could improve the evaluated parameters compared to conventional concrete [7]. Kumar et al. studied the effect of adding discrete and fibrillated polypropylene fibers on concrete mixtures with fiber contents of 0.05, 0.1, and 0.15% and measured the parameters of concrete subsidence, compressive strength, dry shrinkage and abrasion strength. Accordingly, they reported that, with equal percentages, the fibrillated fibers had a greater effect on the reduction of subsidence than the multistrand fibers and less effect on the reduction of slump. However, in terms of abrasion strength, the fibrillated and multistrand fibers exhibited similar performance [8]. Singh et al. studied the flexural strength and toughness of fiber-reinforced concrete with different percentages of polypropylene and steel fibers and a total percentage of 1% and reported that combining 75% of the steel fibers and 25% of polypropylene fibers yielded better results in terms of compressive strength, flexural strength and flexural toughness [9]. Bedi et al. investigated the flexural fatigue lifetime of polymer polypropylene concrete at different levels of stress using numerical analyses and obtained the parameters of the probabilistic models. They performed a flexural fatigue test on fiber-reinforced concrete samples with polypropylene fiber contents of 0.5%, 1% and 2%. Accordingly, they reported that the increased fiber content led to the increased fatigue lifetime of the concrete samples [10]. Viragade et al. studied the tensile and compressive behaviors of fibrillated polypropylene fiber-reinforced concrete samples, the results of which indicated increased 7- and 28-day compressive and tensile strengths [11]. Ramujee studied the strength properties of polypropylene fiber-reinforced concrete. In this research, the strength properties of concrete were investigated with different percentages so that the optimal percentage (1.5%) exhibited better results than others [12]. Jiabiao et al. studied the crack control and toughness of fiber-reinforced concrete as well as the advantages and features of adding synthetic fibers to concrete. Adding microfibers by 0.1% of the concrete's volume affected plastic shrinkage. In addition, adding microfibers by 1% of the concrete volume affected the flexural toughness, impact strength and fatigue strength of the hardened concrete. Furthermore, the equivalent flexural strength was measured for the postcracking strength in various samples [13]. Bordelon and Roesler studied fiber reinforced concrete, investigated steel, synthetic and steel fibers, and reported that the use of fibers led to the increased bearing capacity and reduced thickness of the concrete pavement [14]. By reviewing the relevant literature, Rao et al. showed that fiber-reinforced concrete exhibited better performance than conventional concrete [15]. A summary of many recent studies on the effects of different types of fibers on the mechanical properties of concrete is presented in Table 1.

However, in the present research, the effect of the macrosynthetic fiber content and type on the flexural performance of fiber-reinforced concrete was studied. The parameters evaluated in this research included flexural strength (in accordance with ASTM C78 Standard), average residual strength (in accordance with ASTM C1399 Standard) and flexural performance (in accordance with ASTM C1609 Standard). The fibers were added to the concrete mixture in three different types, including twisted, barchip and fibrillated, with contents of 0.2, 0.4 and 0.6 volume percentages. For each parameter, three samples were made, and the results were averaged and then inserted into the relevant tables.

## **1. Laboratory Program.**

**1.1. Test Variables.** To evaluate the postcracking strength and flexural performance, the concrete mixture was designed based on ACI 211 Standard [28]. To evaluate the effect of fibers, all the concrete samples were made with the same mix design and three different types of twisted, barchip and fibrillated fibers with contents of 0.2, 0.4 and 0.6 volume percentages. Different types of fibers are shown in Figure 1, and the concrete mix design is represented in Table 2. Table 3 demonstrates the geometrical and physical properties of the fibers used in the present research [31]. Table 4 shows the designations of concrete samples.

**1.2. Constructing Samples.** To evaluate the average residual strength and flexural performance of the fiber-reinforced concrete, the concrete beam samples were constructed based on ASTM 1399 and ASTM 1609 standards.

The fibers used in the present study were in three twisted, barchip and fibrillated types with contents of 0.2, 0.4 and 0.6 volume percentages. First, cement was mixed with sands, gravel and fibers, and then the water mixed with superplasticizer was added to the mixture so that the fibers were distributed nonuniformly in the mixture.

TABLE 1. The Summary of Fiber’s Effect on Mechanical Properties as Reported in the Literature (Increase↑, Decrease↓, Nonsignificant N.S) [16]

Reference	Fiber properties			Concrete type	Compressive strength	Splitting tensile strength	Flexural strength	Energy absorption
	Type	Length (mm)	Fiber volume fraction (%)					
[17]	Polypropylene	38	0.2,0.4,0.6	Normal concrete	(4.57-26.32)% ↓	(0.84-34.29)% ↑	(19.6-81.69)% ↑	-
[18]	Polypropylene	39	0.25, 0.75, 1.25	High-strength concrete	8%↑, 3%↑,4%↓	(8, 9, 27)%↑	-	-
[19]	Steel fibers	20, 30, 40	0.25, 0.375, 0.5	Normal concrete	-	-	At least 20.8%↑	↑
[3]	Steel fibers (hooked)	35	0.33	Self-compacting concrete	↓	↑	↑	↑
	Polypropylene	60	0.5	Self-compacting concrete				
[20]	Polypropylene	60	0.10, 0.12	Self-compacting concrete	2%↑, 5% ↓	(19,27)% ↑	(26, 33)%	-
	Steel fibers	50	4% (by cement volume)	Normal concrete	2% ↓	98%↑	-	-
[21]	Polypropylene	50	4% (by cement volume)	Normal concrete	5% ↓	65%↑	-	-
[22]	Hooked-end steel	60	0.25, 0.5, 0.45, 1	High-strength concrete	(12, 14, 15,19)% ↑	(15, 22, 38,57)% ↑	(14, 28, 36, 61)% ↑	-
	Polypropylene (twisted bundle)	54	0.25, 0.375, 0.5	Lightweight concrete	(5, 11, 15)%↑	(8, 24, 33)%↑	(29, 31, 40)%↑	-
[23]		30	0.25, 0.375, 0.5		(3, 10,14)% ↑	(10, 19, 27)%↑	(18, 22, 30)%↑	-
	Polypropylene (straight)	20	0.25, 0.375, 0.5		(4, 10,14)% ↑	(13, 14, 21)%↑	(6, 10, 20)%↑	-
[24]	Steel	50	1.5	Roller-compacted concrete	N.S	-	24%↑	-
	Steel	36	0.5	Pervious concrete	24% ↑	33%↑	19%↑	-
[25]	PPS	54	0.3		28% ↑	37%↑	21%↑	-
	Glass	12	0.2		32% ↑	28%↑	17%↑	-
[26]	Hook end steel	30	0.5, 1, 1.5	Self-compacting concrete	(34, 32, 20)% ↑	-	55%, 151%, 339% ↑	-
	Steel fibers (corrugated)	35	1	Normal concrete	18%↑	-	80%↑	↑
[9]	Polypropylene (fibrillated)	60						
[27]	Wollastonite	20	2,3,5	Geopolymer concrete	-	-	-	80%↑

TABLE 2. Research Mix Design

Materials	Coarse aggregate	Fine aggregate	Cement	Water	Super plasticizer	Fiber
Weight per unit volume (kg/m <sup>3</sup> )	880	789	442	199	2.2	1.8 3.6 5.4

TABLE 3. Physical and Geometrical Properties of Fibers

Material	Shape	Resistance in acidic and alkaline environments	Water absorption	Melting point °C	Flash point, °C	Elastic modulus, GPa	Tensile strength MPa	Diameter, mm	Length, mm	Density g/cm <sup>3</sup>	Color
Polyolefin	Macro*	Excellent	None	≥120	≥590	≥4.2	570-660	≥ 0.3	38	0.91-0.96	Gray

Note: \* a single strand of fine string sticking together.

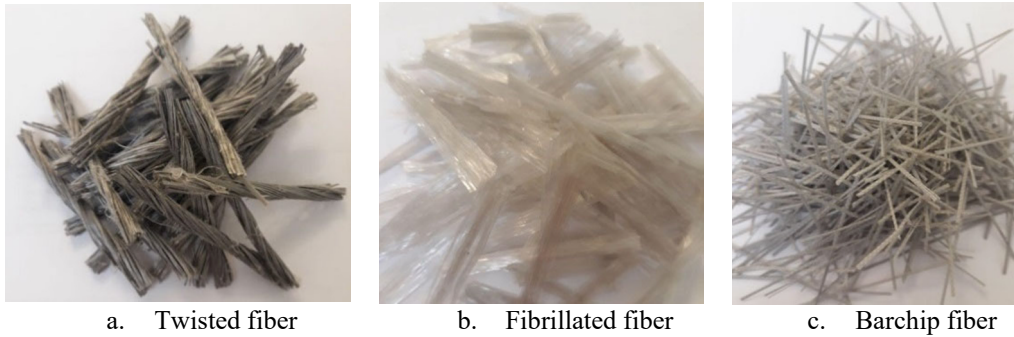


Fig. 1. Different fibers used in research.

TABLE 4. Nominating Samples

Name of the specimens	Shape of fiber	Fiber volume fraction (%)
B2	Barchip	0.2
B4	Barchip	0.4
B6	Barchip	0.6
F2	Fibrillate	0.2
F4	Fibrillate	0.4
F6	Fibrillate	0.6
T2	Twisted	0.2
T4	Twisted	0.4
T6	Twisted	0.6
N	-	0.0

### 1.3. Laboratory Settings and Measurements.

1.3.1. *Flexural Strength.* In accordance with ASTM C78 Standard, the four-point loading and beam dimensions were selected as 350 × 100 × 100 mm. The distance between the two upper and the two lower supports was set as 100 mm and 300 mm, respectively. The vertical load was applied at a loading rate of 0.5 (mm/min) [29].

1.3.2. *Average Residual Strength.* In accordance with ASTM C1399 Standard, the four-point loading and beam dimensions were selected as  $350 \times 100 \times 100$  mm. The distances between the two upper and the two lower supports were selected as 100 mm and 300 mm, respectively. The vertical load was applied at a loading rate of 0.6 (mm/min) [30].

In accordance with ASTM C1399 Standard, the cut or cast fiber-reinforced concrete beam was cracked using the four-point loading device by means of a steel plate, which helped maintain the concrete sample in the initial sampling cycle. The steel plate is used to control the displacement rate when the beam is cracked. Once the beam is cracked by a certain method, the steel plate is removed, and the cracked beam is reloaded to obtain the load–displacement curve data. The load values are reaveraged at the specified displacement values in the loading curve and then used to calculate the mean residual strength of the beam.

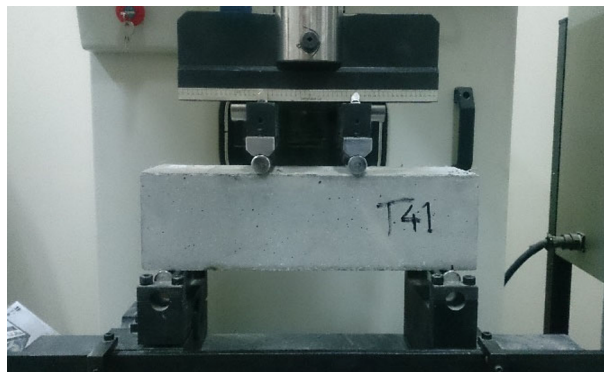


Fig. 2. Setting the device and sample for test.

1.3.3. *Flexural Performance.* Energy absorption or flexural toughness is obtained based on the ASTM C1609 Standard. The sample properties and preparation of the device are similar to those of the ASTM C1399 Standard, except that in this standard, loading is performed in one step at a rate of 0.5 (mm/min). The load–displacement curve of the prismatic beam sample with certain dimensions is depicted using the data obtained from the four-point flexure testing, and finally, the components of energy absorption or toughness are obtained by calculating the area under the curve to a certain displacement [31].

## 2. Experimental Results.

2.1. *Flexural Strength.* To obtain the flexural strength of the fiber-reinforced concrete samples, the samples were made in accordance with ASTM C78 Standard and underwent four-point flexural loading. The load–displacement curve of the span is derived, and the maximum flexural strength is obtained using the maximum flexural force through Eq. (1).

$$R = PL / bd^2 \quad (1)$$

Table 5 and Fig. 3 represent the flexural strength for various fiber-reinforced concrete samples.

2.2. *Average Residual Strength.* The average residual strength is calculated using the certain displacement of the beam that is obtained from a beam cracked in a standard method. The average residual strength for each beam is obtained using the loads determined in reloading and at span displacements of 0.5, 0.75, 1.00 and 1.25 mm via Eq. (2):

$$ARS = ((P_A + P_B + P_C + P_D) / 4) * L / bd^2 \quad (2)$$

The results of the average residual strength are shown in Table (6), and the load–displacement curves of the second phase of loading of the concrete samples are plotted in Figs. 4–7.

TABLE 5. Flexural Strength Results for Concrete Samples

Specimen	P, N	R, MPa	Percent increase, %
N	13399.76	4.02	0.00
B2	16026.67	4.81	19.60
B4	18377.48	5.51	37.15
B6	18797.02	5.64	40.28
T2	16610	4.98	23.88
T4	17906.13	5.37	33.58
T6	20401.7	6.12	52.23
F2	20325.36	6.10	51.68
F4	21974.15	6.59	63.99
F6	24345.86	7.30	81.69

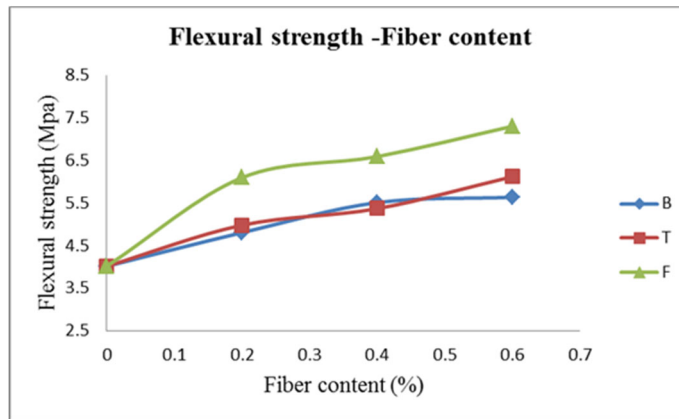


Fig. 3. Flexural strength of fiber-reinforced concrete samples.

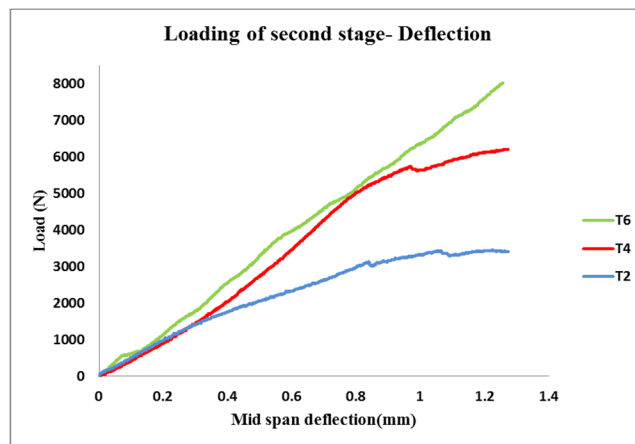


Fig. 4. Load–displacement curve of the second phase of loading of the concrete samples with twisted fibers.

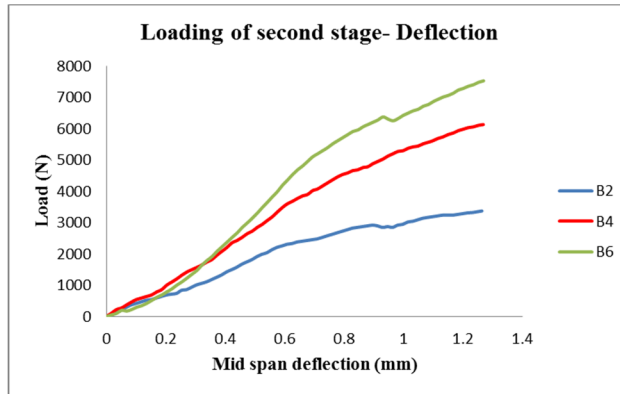


Fig. 5. Load–displacement curve of the second phase of loading of the concrete samples with barchip fibers.

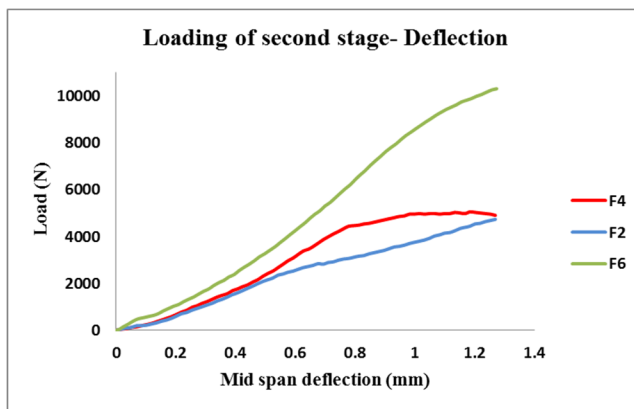


Fig. 6. Load–displacement curve of the second phase of loading of the concrete samples with fibrillated fibers.

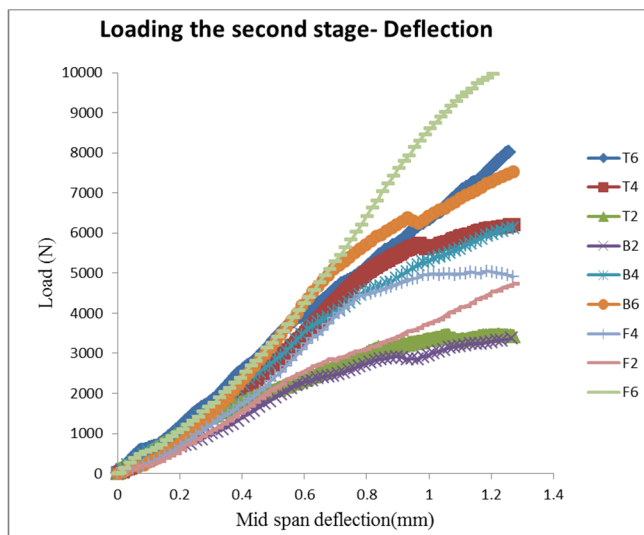


Fig. 7. Comparing load–displacement curves of the second phase of loading for different fiber-reinforced concrete samples.

TABLE 6. Average Residual Strength Results

No.	Type of fiber concrete	Load, N				Load, N (Ave)	$L/bd^2$	ARS, MPa	R, MPa	ARS/R, %
		Mid span deflection(mm)								
		$P_{A,0.5}$	$P_{B,0.75}$	$P_{C,1}$	$P_{D,1.25}$					
1	F6	3350	5842	8600	10222	7003.5	0.0003	2.1	7.3	28.77
2	B6	3330	5400	6450	7480	5657.5	0.0003	1.7	5.64	30.14
3	T6	3311	4856	6374	7995	5634.5	0.0003	1.7	6.12	27.78
4	F4	3400	4553	5360	6350	4915.45	0.0003	1.5	6.59	22.76
5	B4	2800	4300	5300	6100	4625	0.0003	1.4	5.51	25.40
6	T4	2747	4660	5641	6180	4807	0.0003	1.4	5.37	26.07
7	F2	2100	2980	3750	4650	3370	0.0003	1	6.10	16.39
8	T2	2060	2771	3335	3409	2893.75	0.0003	0.9	4.98	18.07
9	B2	1910	2594	3000	3350	2713.5	0.0003	0.8	4.81	16.63

Figure 8 represents the comparison of the average residual strengths by changing the fiber content. The obtained results indicated that the fibrillated fibers had higher average residual strength than others; however, due to the problems during constructing the samples with fibrillated fibers, it is not recommended to use these fibers at high contents. Despite the different shapes, the twisted and broken fibers yielded different results.

**2.3. Flexural Performance.** To evaluate the flexural performance of the fiber-reinforced concrete samples, the concrete beam samples were constructed in accordance with ASTM C1609 Standard and underwent four-point flexural loading. The load–displacement curve of the span was derived, and the area under the graph up to the span center displacement was measured as the flexural toughness. Figures 9, 10, and 11 represent the span center load–displacement curves for various fiber-reinforced concrete samples.

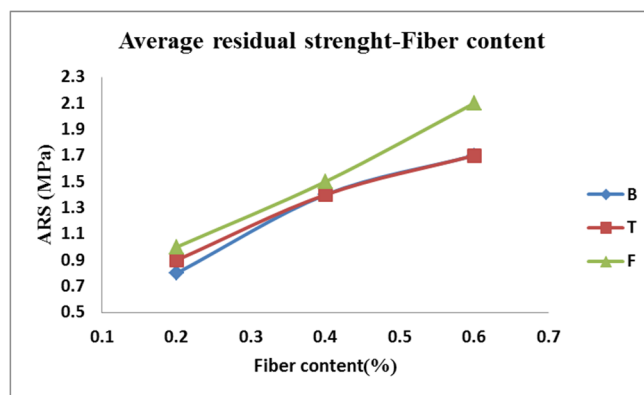


Fig. 8. Comparing average residual strength by changing the fiber content.



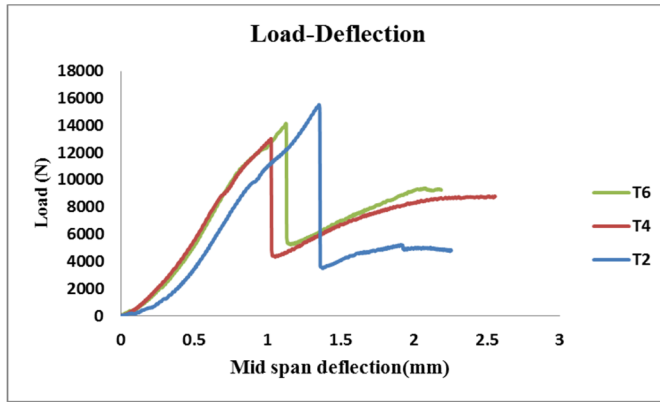


Fig. 9. Load–displacement curve of fiber-reinforced concrete sample with twisted fiber.

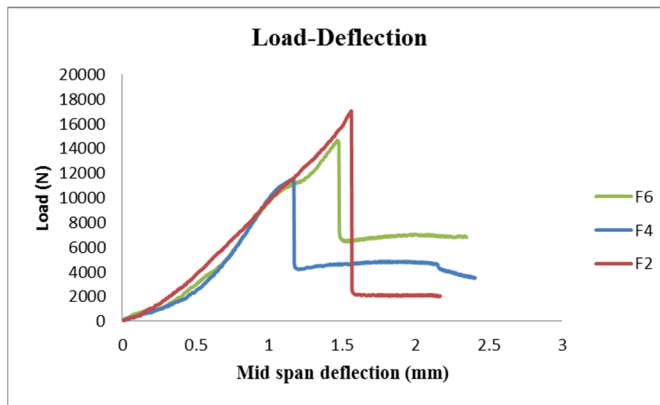


Fig. 10. Load–displacement curve of fiber-reinforced concrete sample with fibrillated fiber.

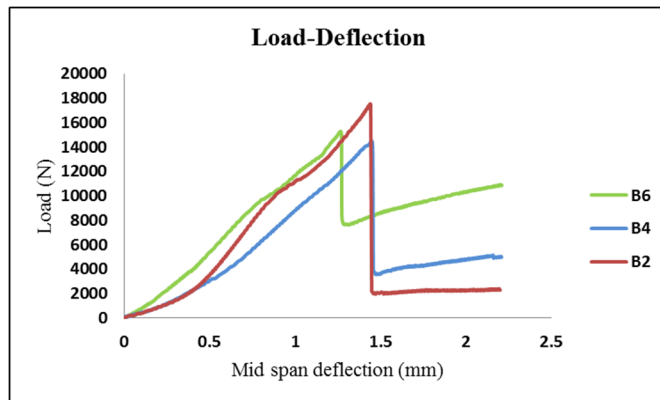


Fig. 11. Load–displacement curve of fiber-reinforced concrete sample with barchip fiber.

Table 7 shows the flexural toughness for various fiber-reinforced concrete samples.

The obtained results showed that increasing the fiber content led to increased flexural performance and flexural toughness. The twisted and barchip fibers led to higher flexural toughness than the fibrillated fibers. The twisted and barchip fibers, despite having different shapes, yielded similar results. Due to the problems during constructing the samples containing fibrillated fibers, it is not recommended to use this fiber at high content.

TABLE 7. Results on Flexural Toughness

No.	Specimen	Flexural toughness, Jul	Percent increase, %
1	B6	15.83	79.89
2	T6	13.78	56.59
3	F6	12.82	45.68
4	T4	12.76	45.00
5	F4	12.43	41.25
8	B4	11.94	35.68
7	T2	11.94	35.68
6	B2	11.13	26.48
9	F2	9.15	3.98
10	N	8.8	0.00

**2.4. Assessment of Ruptured Cross Sections and Fibers.** After the tests, the cross-sectional area of the sample was broken, and the tip of the fiber was examined. Figure 12 shows the number of broken sections of the specimen and tip of the fibers. A cross-sectional analysis of the broken samples showed that most of the sample failure was from aggregates and that the mixture design was suitable. Additionally, according to the figure above, the tip of fibers shows that the fibers have not been ruptured due to elongation and have not been pulled out, which indicates good performance of the fibers.

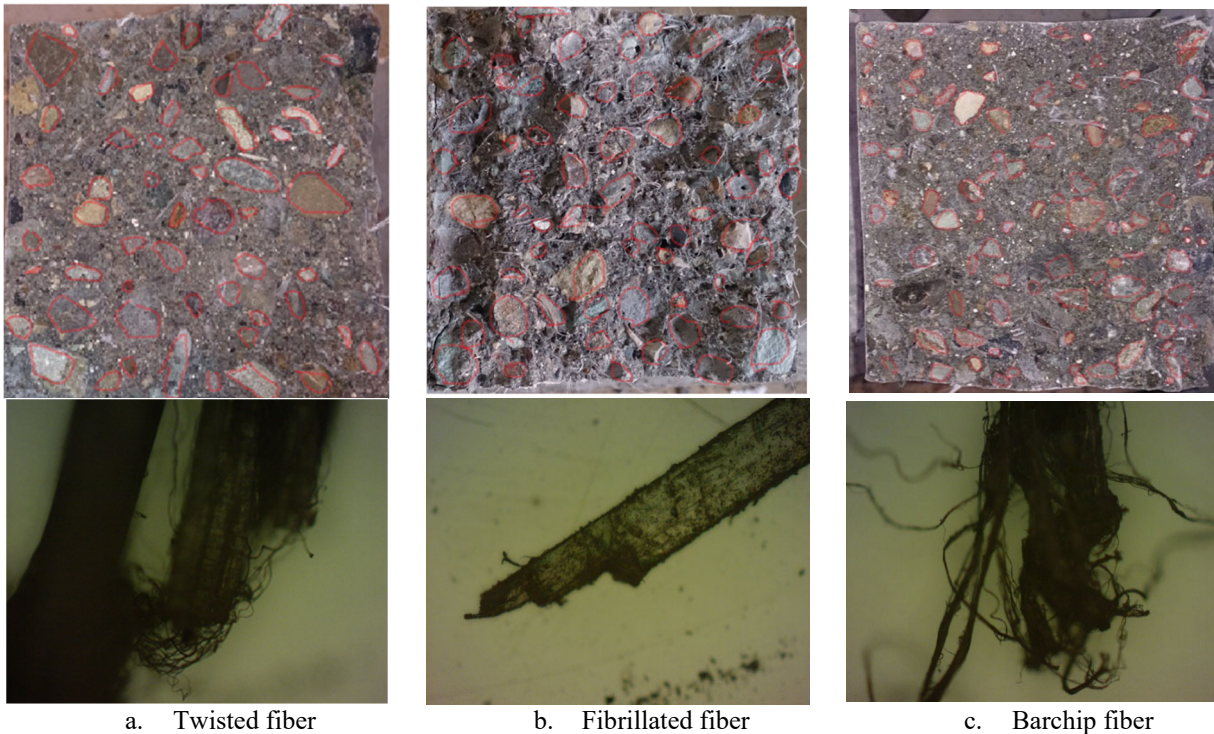


Fig. 12. Fracture face of macro synthetic fiber and beam.

**Conclusions.** In the present research, the flexural strength and postcracking strength of fiber-reinforced concrete, as well as the flexural toughness and equivalent flexural strength ratio, were measured for fiber-reinforced concrete examples with the same mix design and three different fiber types and contents; then, the effect of the fibers on these parameters was investigated.

The main results of the present research are as follows:

1. The results in Table 5 show that adding the fibers by 0.2–0.6 of the volume fraction increased the flexural strength of the samples with barchip, twisted and fibrillated fibers by 19.6–40.28%, 23.88–52.23% and 51.68–81.69%, respectively.

2. The results in Table 6 demonstrate that adding the fibers to the concrete mixture by 0.2–0.6% of the volume fraction resulted in average residual strengths of 16.39–28.77%, 16.63–30.14% and 18.07–27.78% for the fiber-reinforced concrete samples with fibrillated, barchip and twisted fibers, respectively.

3. The results in Table 7 show that adding the fibers to the concrete mixture by 0.2–0.6 of the volume fraction increased the flexural toughness of the samples with barchip, twisted and fibrillated fibers by 26–79%, 35–56% and 4–45%, respectively.

4. According to Table 5, the fibrillated fibers yielded the highest flexural strength compared to the other fibers.

5. According to Table 6, the fibrillated fibers yielded the highest average residual strength compared to the other fibers.

6. Based on Table 7, the highest flexural toughness and performance were obtained for the samples with barchip and twisted fibers with higher fiber content.

7. Based on the obtained results, it could be very practical and applicable to use fibers for structures in which flexure and tension are of great importance, such as concrete pavement designed based on flexural strength. Furthermore, considering the effect of fibers on the design of concrete structures could increase the durability, bearing capacity and longevity of the structure and facilitate achieving a design with a high cost–benefit ratio.

The following recommendations are made:

(1) Due to the problems in constructing the samples with fibrillated fibers, it is recommended to use this fiber in combination with other types of fibers and with contents lower than 0.4%.

(2) Since increasing the fiber content exposes the sample mixing to problems, it is recommended to use the fiber content in the range of 0.2–0.6%.

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