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The Role of Fiber-Type Reinforcement in the Torsional Behavior of Solid and Hollow Reinforced Concrete Beams

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Abstract: In order to improve the strength of concrete structures, the fiber reinforcement of concrete has become an essential factor. This study was conducted as an experimental program to gain a better understanding of how the variance of fiber shape and type affect the structural performance of solid and hollow reinforced concrete beams using four types of fiber (hooked-end, straight, corrugated steel fiber, and polyolefin fiber) under torsion. For this purpose, ten fiber-reinforced concrete beam specimens, five solid and five hollow, with square cross sections were fabricated using the adopted types of fiber. The role of fiber type in the improvement of the mechanical properties of hardened concrete was also investigated. The results revealed that the mechanical properties of the hardened concrete mix was enhanced by using the existing fiber in concrete, and the higher improvement was shown in the splitting tensile strength test and modulus of rapture in specimens with corrugated steel fiber. The torsional behavior of solid and hollow beams was improved significantly, and the capacity of torsional strength was especially improved for the beams strengthened with corrugated steel fiber. Straight and polyolefin fiber showed a slight improvement in the concrete mechanical properties and less enhancement in the torsional capacity of the tested beams. However, the tested beams reinforced by polyolefin fiber provide better ductility under torsion compared with the use of other types of fiber.

Keywords: torsional capacity; fiber reinforcement; cracking torque; steel fibers; polyolefin fiber

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1. Introduction

Much of the research in previous years has investigated the improvement of the brittle nature and low tensile strength of concrete by using fibers during the production processes. The ability to enhance the concrete ductility, the increase in concrete toughness, and the stress transfer across the concrete cracks represent the main benefits of using concrete with fibers [1]. Different synthetic and metallic types of fibers can be used with structural concrete, where steel fiber represents the most effective option due to its proven ability at crack bridging and developing a high tensile strength, which may alter the brittle behavior of concrete to become more ductile under the effect of tensile stresses. However, a number of techniques have been adopted to produce thermoplastic fibers with lighter weight, higher tensile strength and a higher young modulus. In general, the cross-sectional area of polypropylene fibers ranges between 0.6 and 1.5 mm^2 with a length of about 3–6 mm, while its elastic modulus and tensile strength are between 4000 and 10,000 MPa and 300 to 600 MPa, respectively [2]. In addition, the density of polyolefin fiber is around 900 kg/m^3, which is very low compared with the density of steel fiber, which equals 7800 kg/m^3 [3].

While most of the previous studies were conducted to investigate the mechanical properties of concrete with steel fiber, there are some researchers that focused on polymer material development and its positive effect on engineering technology by using polyolefin fiber to improve concrete performance [4–10]. However, several previous studies investigated the role of fibers in the improvement of the flexural behavior of reinforced concrete beams [11–15].

The torsional behavior of fiber-reinforced concrete beams has also been an attractive topic to investigate in recent years. In 2006, Altun et al. [16] experimentally tested box beam specimens made with 6 cm length steel fiber and having a volume ratio of about 0.77. The results indicated that with an approximate 44% saving of the weight of tested beam specimens, their load capacity was reduced by only about 29%. Namiq [17], in 2012, studied the torsional behavior of twenty-four reinforced concrete (RC) hollow beams using steel fibers with different ratios. It was found that steel fibers could enhance the ductility and torque capacity of concrete beams. In 2018, Kanekar and Talikoti [18] investigated the torsional capacity of reinforced concrete beams using aramid fiber strips. A total of twenty-one beam specimens were fabricated and tested under pure torsion. Aramid fiber strips of 15 cm in width were used to strengthen the beam specimens with five different spacings, ranging from 100 to 200 cm. It was observed that the torsional capacity of the tested beams was increased significantly compared with the control specimens. In addition, the value of the initial cracking torque was increased for the strengthened beam specimens. Al-Attar et.al. [19], in 2019, carried out an experimental program consisting of cast reinforced self-compacting concrete beams with solid or hollow cross sections to investigate the effect of volume fraction of steel fibers and section geometry on the torsional behavior of such beams. The results showed that the fibers enhanced the torsional capacity for all beams and it was more active in the hollow sections than in the solid ones. Furthermore, in 2019 the behavior of high-strength steel-fiber-reinforced concrete beams was studied by Giridhar and Kumar [20] by testing solid and hollow beam specimens made with different types of steel fibers under the effect of pure torsion. Steel crimped fiber and steel straight fiber with different ratios were used. It was observed that the first cracking torque and ultimate torque were increased with increasing the steel fiber ratio for all tested beams. In 2020, Lijuan Zhang et al. [21] investigated the effect of the volume ratio (0, 0.5%, 1%, 1.5%, and 2%) and shape (hooked-end, straight, and corrugated) of steel fiber on mechanical properties of concrete. It was concluded that the shape of the fiber affected the flexural strength of concrete. The corrugated steel fiber and hooked-end developed a considerable improvement in the flexural strength. Mures et.al. [22] in 2021 investigated the behavior of solid and hollow high-strength concrete beams made with steel fibers under pure torsion. They concluded that the width and number of cracks was inversely proportional to the ratio of steel fibers.

In the present work, ten square reinforced concrete beam specimens, divided equally into solid and hollow sections, were tested under pure torsion to investigate the effect of using fiber reinforcement. This study examined the mechanical properties of concrete as a first stage, followed by the behavior of the tested specimens by considering the effect of the parameter type, size, and shape of the fiber.

2. Materials and Experimental Work

2.1. Material Properties

According to ASTM standards [23–25] the physical and chemical properties of the adopted cement and the mechanical properties of fine and coarse aggregates are listed in Tables 1–3. The particle size distributions of the coarse aggregate (gravel) and fine aggregate (sand), which were provided from local sources, are shown in Figure 1. Three shapes of steel fibers in addition to the polyolefin fibers were used in the present study, as shown in Figure 2. The geometric details and mechanical properties of the adopted types of fibers are shown in Table 4. A constant ratio of approximately 1%, which represents a volume fraction from the total volume of the concrete mix, was used for each type of fiber to prepare the fiber-reinforced concrete for all the tested specimens in this investigation. This was chosen based on previous research, which is the suitable ratio to develop an acceptable workability and consistency for the fresh concrete mixes [26–30].

Table 1. Physical characteristics of cement according to ASTM C150-18.

Standard Test	Test Method	Test Value
Fineness (m^2/kg)	Blaine air permeability	302
Setting time (minutes)	Initial	131
	Final	262
Compressive strength (MPa)	3 days	22.7
	7 days	27.8

Table 2. Chemical characteristics of cement according to ASTM C114-18.

Chemical Components of Cement Weight (%)										Main Components of Cement Weight (%)			
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Insoluble Residue	LOI	C_3S	C_2S	C_3A	C_4AF
20.2	5.1	3.2	62.2	1.74	0.29	0.64	1.92	0.45	1.3	50.1	24.1	6.65	10.2

Table 3. Physical properties of aggregates according to ASTM C33-18.

Property	Coarse Aggregate (Gravel)	Fine Aggregate (Sand)
Bulk specific gravity	2.42	2.63
Apparent specific gravity	2.40	2.72
Dense dry density (kg/m^3)	1632	1870
Loose dry density (kg/m^3)	1452	1720
Sulphate content (%)	0.02	0.23
Absorption (%)	0.85	1.61

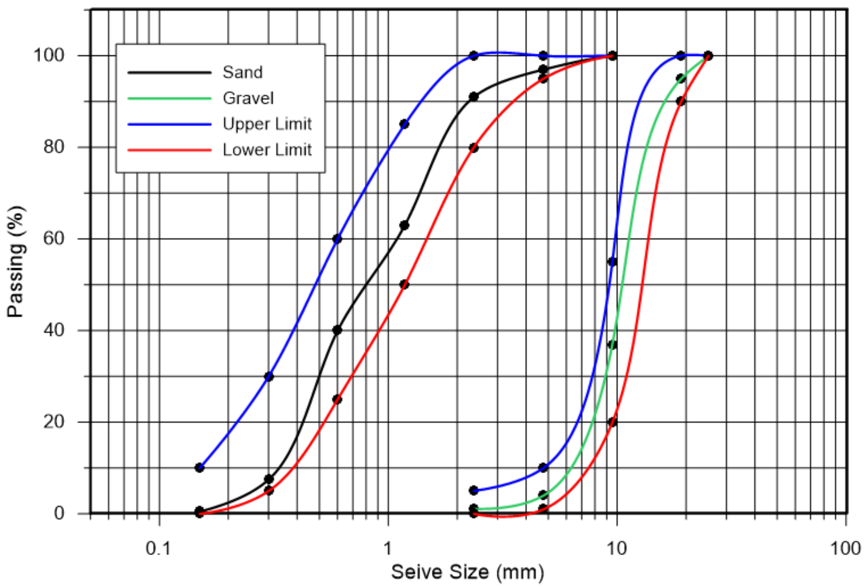

Figure 1. Particle size distribution of aggregates.

Four similar concrete mixes, except in the type of added fiber and one mix without fiber (as a control), were prepared to fabricate the tested beam specimens. The mix proportion of the adopted control concrete mix is shown in Table 5, where Hyperplast (PC200) was used as a superplasticizer with a ratio of about 0.7% of the total weight of cement. Six standard test cylinders (300 × 150 mm) and three standard prisms (500 × 150 × 150 mm) were cast for each one of the five concrete mixes in order to evaluate their mechanical properties, which included the compressive strength, splitting tensile strength, and modulus of rupture. The yield tensile strength of the reinforced steel rebar used in the fabrication of tested beam specimens was about 445 MPa, while its ultimate strength reached approximately 589 MPa.

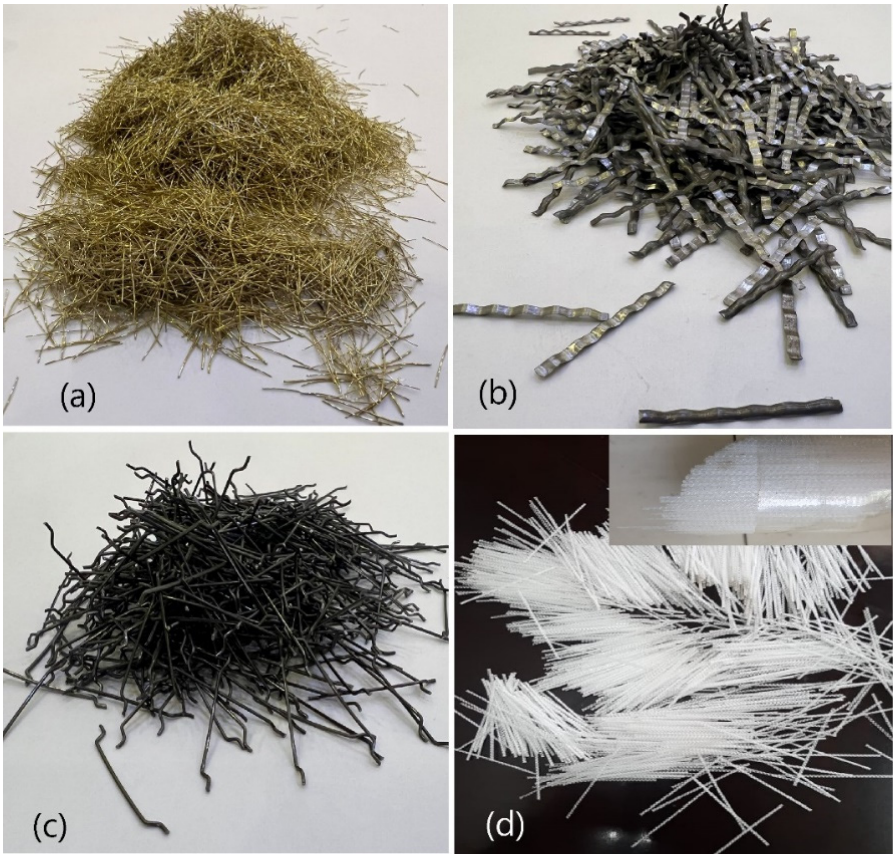

Figure 2. Types of fibers: (**a**) Straight steel fiber; (**b**) Corrugated steel fiber; (**c**) Hooked-end steel fiber; (**d**) Polyolefin fiber.

Table 4. Types and properties of adopted fibers.

Fiber Type	Shape	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength (MPa)
Straight steel fiber	Straight	12	0.25	50	2850
Hooked-end steel fiber	Hooked-end	30	0.5	60	>1000
Corrugated steel fiber	Corrugated	50	0.6	83	>700
Polyolefin fiber	——	60	0.84	71	465

Table 5. Proportion of control concrete mix.

Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Fiber (kg/m^3)		Super Plasticizer PC200 (Liter)
				Steel Fiber	Polyolefin Fiber	
396	755	1125	159	78	9.1	4

2.2. Tested Beam Specimens

Ten reinforced concrete beams were tested under pure torsion. As shown in Table 6, five of them were cast with a solid cross section, while the others had hollow cross sections. One reference beam specimen, concrete with zero fiber, was prepared for each type of beam cross section for comparison. All beams were 1150 mm in length, 250 mm in overall width and 250 overall in depth. The wall thickness of the hollow beams was 50 mm. The geometry and reinforcement details of the beam specimens are shown in Figure 3.

Table 6. Details of tested beam specimens.

Beam Specimen	B1	B2S	B3H	B4C	B5P	H1	H2S	H3H	H4C	H5P
Length (mm)	1150	1150	1150	1150	1150	1150	1150	1150	1150	1150
Overall depth (mm)	250	250	250	250	250	250	250	250	250	250
Overall width	250	250	250	250	250	250	250	250	250	250
Section type	Solid	Solid	Solid	Solid	Solid	Hollow	Hollow	Hollow	Hollow	Hollow
Fiber type	—	Steel	Steel	Steel	Polyolefin	—	Steel	Steel	Steel	Polyolefin
Fiber shape	—	Straight	Hooked-end	Corrugated	—	—	Straight	Hooked-end	Corrugated	—
Longitudinal reinforcement	4 ϕ12 mm top and bottom									
Transverse reinforcement	Φ8 mm @ 175 mm									

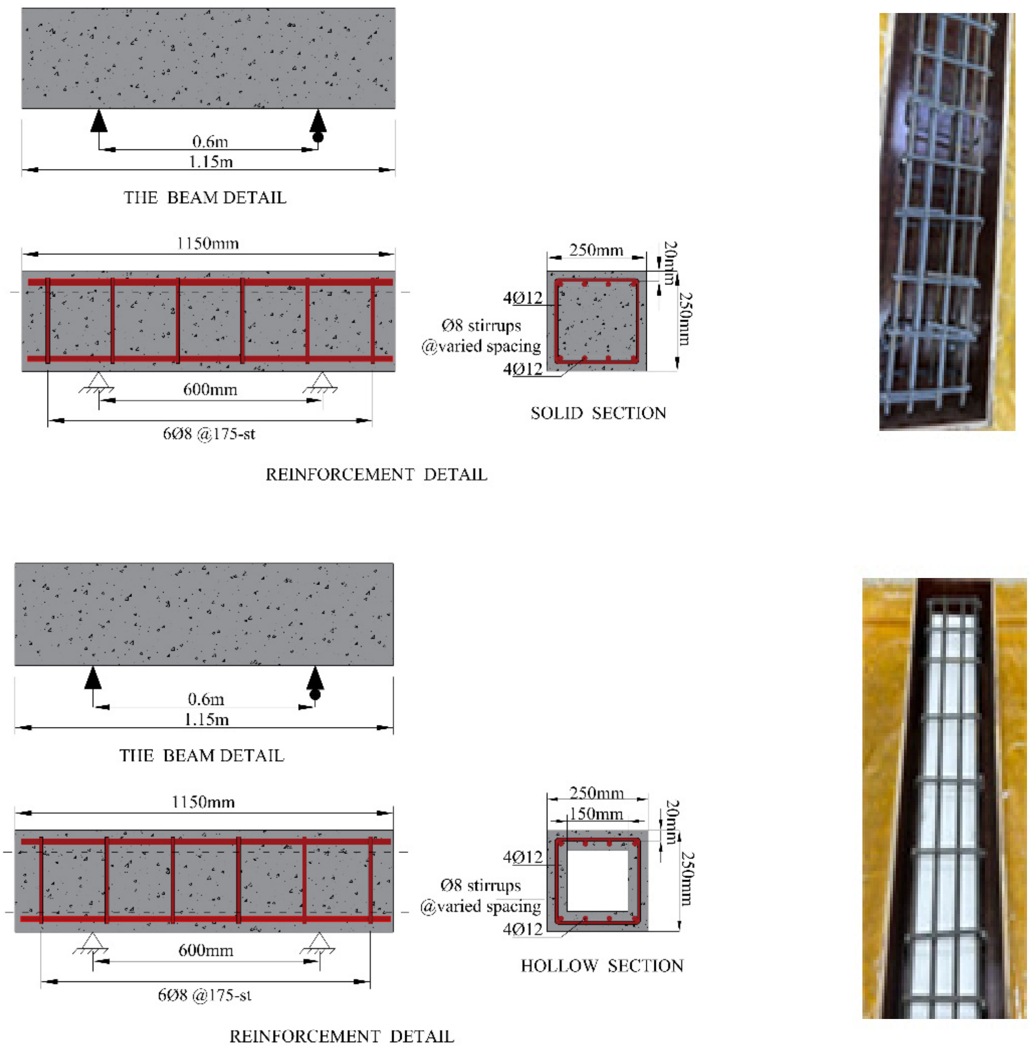

Figure 3. Geometric and reinforcement details of tested beam specimens.

2.3. Test Procedure

All of the beam specimens were tested under the applied loading from a 500 kN capacity universal testing machine. Each beam was supported by two roller supports and the applied load was transferred through a load-spreader beam (I-section steel girder), to the support arms that were fixed together with bolts and fixed to the end roller supports via welding, as shown in Figure 4, in order to allow the beam specimens to twist and elongate/shorten freely. Two LVDTs (a linear variable differential transformer) were fixed on the steel arm to measure the angle of the twist. The axial displacement of the beam was measured by using another two LVDTs attached horizontally to the center of the beam-ends. A monotonic applied torque was increased until the beams failed. The applied torque versus the developed angle of twist were recorded for each load increment in addition to the cracking torque, ultimate torque, and their corresponding angle of twist values.

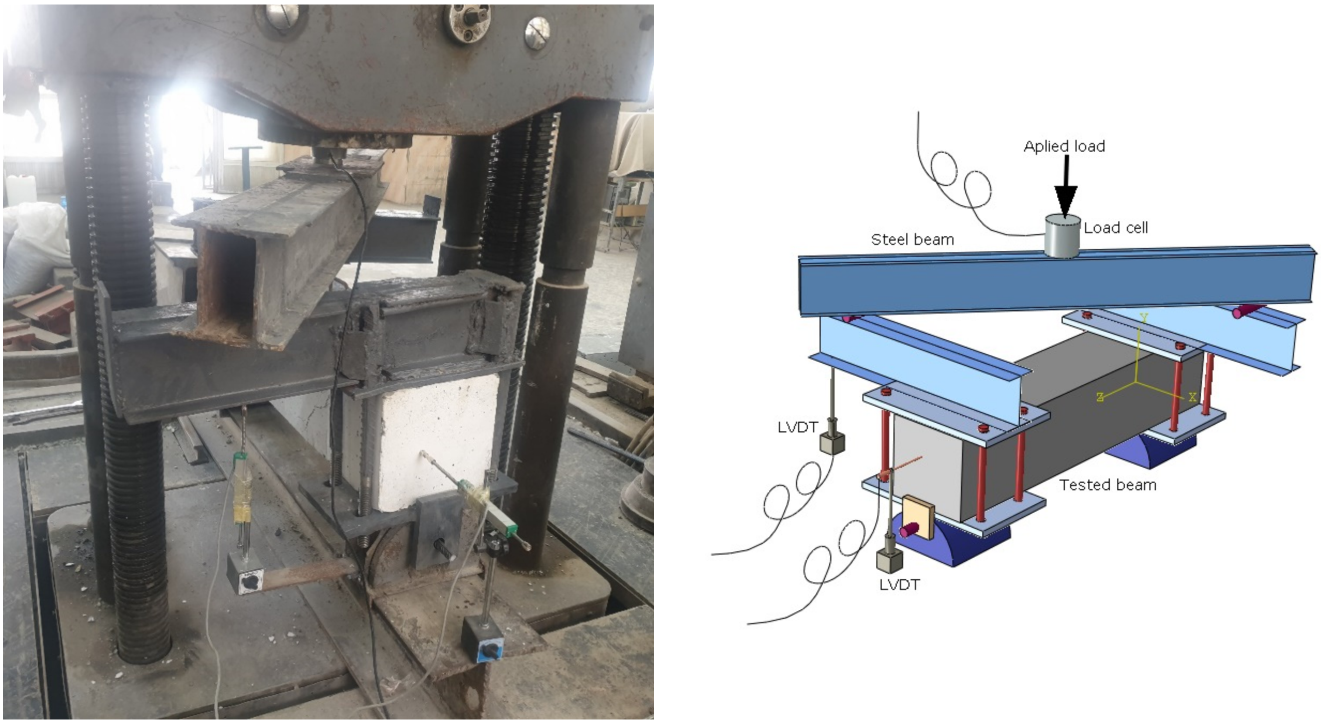

Figure 4. Test setup of beam specimens under pure torsion.

3. Results and Discussion

3.1. Properties of Hardened Concrete

It is well known that the use of fibers in concrete produces a moderate improvement in compressive strength [31]. The test results showed that the compressive strength of the adopted fiber-reinforced concrete was increased by a ratio of around 25%, for steel fiber and 16% for polyolefin fiber, compared with the properties of the concrete control mix, see Table 7. It can be observed that the steel fiber produced a higher compressive strength, because of its ability to produce good bonds with concrete that are stiffer than with polyolefin fiber. The concrete modulus of rupture was greatly improved with the use of fibers compared with the controls. The increasing ratio was approximately 114%, 94%, 50%, and 47% for corrugated steel fiber, hooked-end steel fiber, straight steel fiber, and polyolefin fiber, respectively. This significant increase in the values of the modulus of rupture with the use of fibers may be related to the strong bond between the fiber and concrete matrix, which led to the improved flexural strength of the concrete. In addition, the concrete splitting tensile strength was significantly increased with the presence of fibers due to the developed strong interlock that occurred between the fibers and concrete matrix. Referring to Table 7, it can be observed that the concrete splitting tensile strength was increased in a ratio ranging from 94% with the use of corrugated steel fiber, to 44% with the use of straight steel fibers, compared with the control plain concrete. It can be observed from Figure 5 that the presence of all types of fibers greatly enhanced the splitting tensile strength and modulus of rupture of the concrete mixes with an increasing ratio reaching approximately 100%, while the improvement of the compressive strength only reached 27%. These results may lead to the conclusion that the use of fiber-reinforced concrete represents a suitable solution for the structural members that are subjected mainly to shear or torsion. It must be noted that the mechanical properties of each concrete mix in Figure 5 were normalized by dividing them by the corresponding properties of the control mix.

Table 7. Mechanical characteristics of the designed concrete mixes.

Concrete Mix	Fiber Type	Symbols	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Modulus of Rupture (MPa)
Mix 1	Control (free of fibers)	CO	35.7	4.18	3.21
Mix 2	Straight steel fiber 12 mm	CS	44.1	6.27	4.63
Mix 3	Hooked-end steel fiber 30 mm	CH	43	8.12	5.32
Mix 4	Corrugated steel fiber 30 mm	CC	45.4	8.95	6.24
Mix 5	Polyolefin fiber 60 mm	CP	41.3	6.18	4.73

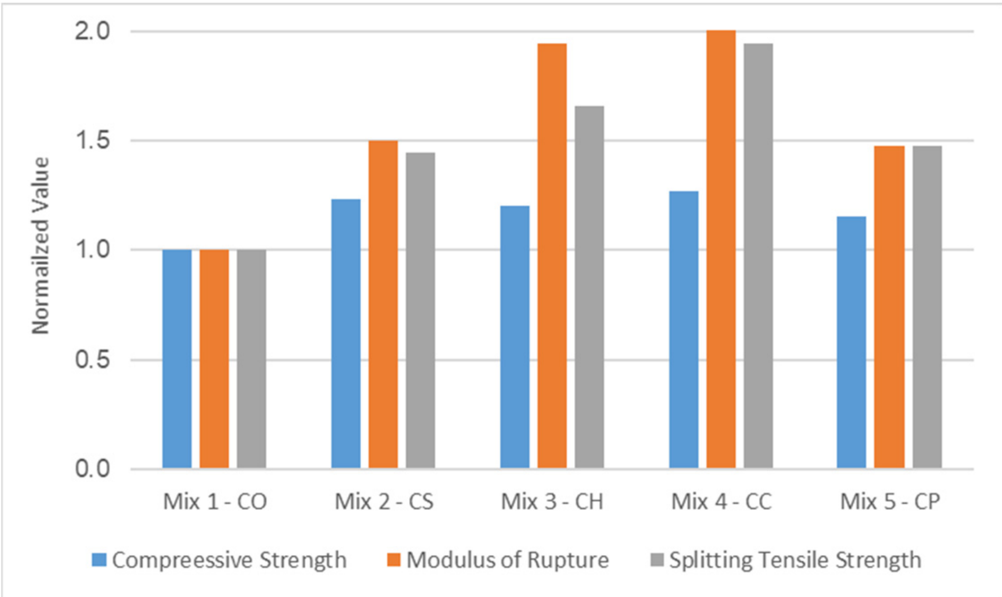

Figure 5. Mechanical characteristics of fiber-reinforced concrete mixes.

3.2. Modes of Failure and Torsional Capacity

Figure 6 shows the modes of failure for the experimentally tested specimens. In general, members under torsion load have shearing stresses, which develop as inclined rings. As shown in Figure 6, the reference solid and hollow beams failed due to major cracks developing from the bottom of the side facing upward, to and along the top face, and then from the top of the back face downward, to and along the bottom face. These cracks were increased in length and width with the increase in the applied torque. Most of these cracks were inclined by an angle of approximately 42°. This mode of failure has been observed in several previous studies [17,19,20]. On the other hand, many smeared inclined cracks developed, which were distributed on the beam sides with the increase in applied torque in the specimens made from fiber-reinforced concrete. In addition, the presence of fibers plays a role in resisting the post-cracking torque and reducing the width of major cracks by separating them to higher density minor cracks, compared with the reference beams. There was no apparent effect of the type of fiber on the tested specimens' modes of failure. It was observed that the crack density in the beams with hollow sections were slightly larger than in the solid beams. In actual fact, all of the tested beam specimens failed in shear, which is a typical mode of failure for beams under pure torsion.

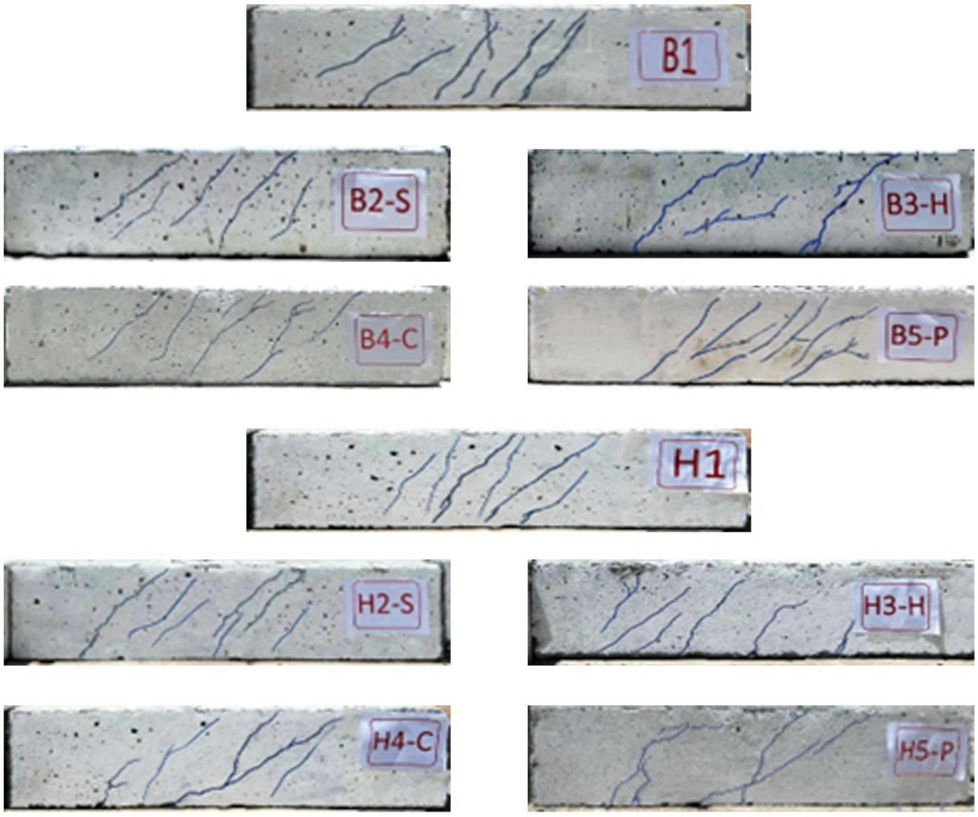

Figure 6. Modes of failure of tested beams.

As listed in Table 8, the experimental results showed that the first cracking torque for beams with steel straight, steel hooked-end, steel corrugated and polyolefin fiber was increased to about 25.7%, 42.5%, 50.3%, and 31.7%, respectively, for solid beams, and 112.2%, 132.3%, 131.8%, and 101.1% respectively, for hollow specimens compared with that cracking torques for reference specimens. These increases in the cracking torsional capacity of the fiber-reinforced specimens developed together with a significant increase in their torsional rigidity, which reached approximately 67% for solid beams and 143% for hollow beams. The increase in the cracking torque and torsional rigidity of the tested fiber-reinforced beams may be related to the improvement in the splitting tensile strength of the beams' concrete due to the presence of fibers. In addition, the ultimate torsional capacity for all the tested specimens was increased with the use of fiber reinforcement to a ratio ranging from 21% to 39% for solid beams and from 76% to 116% for hollow beams, compared with the ultimate torsional capacity of the reference beams. These observations were matched with those previously concluded by other researchers [21,22,32,33]. It can be concluded from the previous experimental results that the use of fiber reinforcement in reinforced concrete beams produced a significant improvement in their cracking and ultimate torsional capacities, especially in the case of the hollow beam specimens. Moreover, it can be seen that the use of corrugated steel fibers gave better results compared with the use of other types of fibers for both solid and hollow beam specimens, which have high cohesion and more interaction with the concrete matrix than the other types of fibers due to their shape. This may lead to the conclusion that the fiber shape and its cohesive ability with the concrete paste plays a major role in the enhancement of the concrete beam's torsional capacity.

Table 8. Experimental results of tested beam specimens.

Item	B1	B2S	B3H	B4C	B5P	H1	H2S	H3H	H4C	H5P
Cracking torque, T_{CR} (kN.m)	6.56	8.25	9.35	9.86	8.64	3.62	7.68	8.41	8.39	7.28
Cracking angle of twist, ψ_{cr} (deg.)	0.98	1.18	1.36	1.44	1.43	0.83	1.25	1.38	1.40	1.39
Torsional rigidity (kN.m/rad)	550.3	810.5	739.5	917.2	693.6	317.2	682.2	663.3	772.2	612.1
Ultimate torque, T_{CR} (kN.m)	9.50	11.5	12.8	13.2	11.7	5.5	10.6	11.7	11.9	9.7
Ultimate angle of twist, ψ_u (deg.)	2.19	2.37	2.25	2.20	2.41	2.24	2.60	2.40	2.46	2.96

3.3. Torsional Ductility Index

The applied torques versus the developed angles of twist of the tested beam specimens throughout the experimental tests until failure are shown in Figure 7. It can be noted that all the tested beam specimens behaved linearly under applied torque until yield, but with different inclination angles that related to the presence and type of fiber reinforcement. However, the hollow beam specimens developed a shorter linear behavior stage than the solid ones. It can be noted that the tested beams with fiber reinforcement were subjected to higher values of twisting angle with the increase in applied torque compared with the control beam. In spite of this, the hollow beam specimens had a torsional capacity that was lower than the solid ones but they produced higher torsional ductility. The presence of fiber reinforcement significantly increased the tested beams' torsional ductility. In the present study, the torsional ductility index, defined as the ratio of angle of twist at ultimate torque to the angle of twist at yield, was considered to evaluate the effect of use and type of fiber reinforcement on the torsional ductility of the tested beams. Figure 8 shows that the use of polyolefin fiber resulted in a higher torsional ductility compared with the control beams for both solid and hollow beams. The lesser effect on the torsional ductility of the tested beams was developed by using the corrugated steel fiber and the hooked-end steel fiber for solid and hollow beams, respectively.

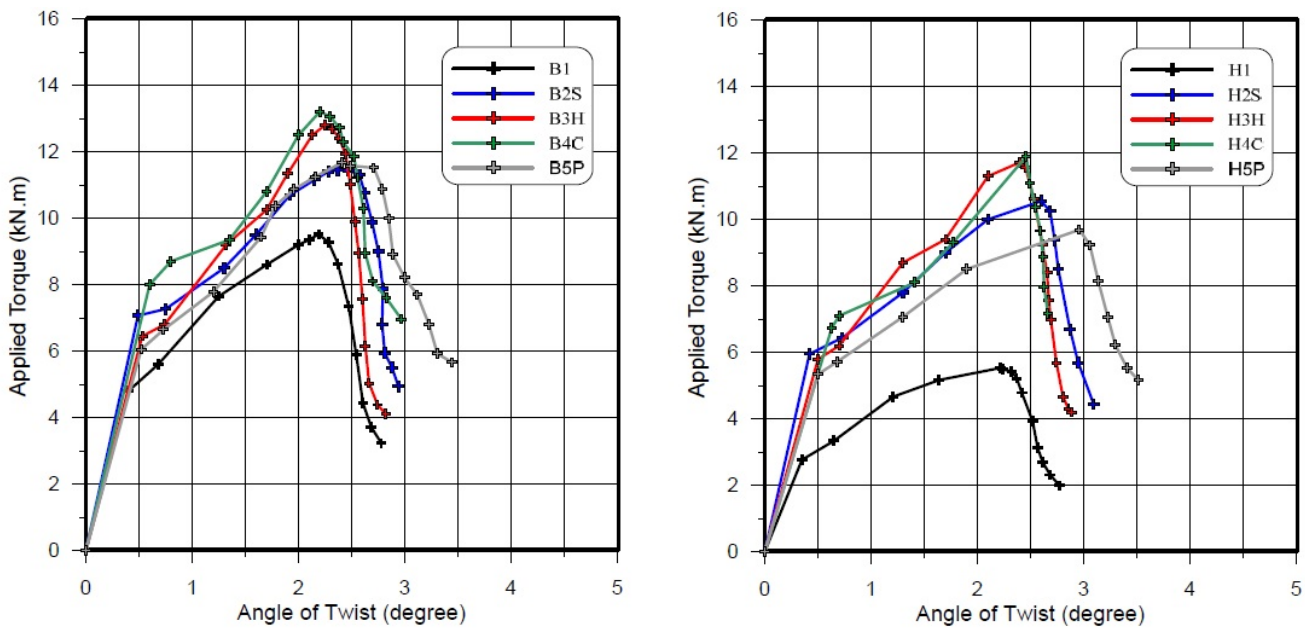

Figure 7. Torque angle of twist relationship of tested beams.

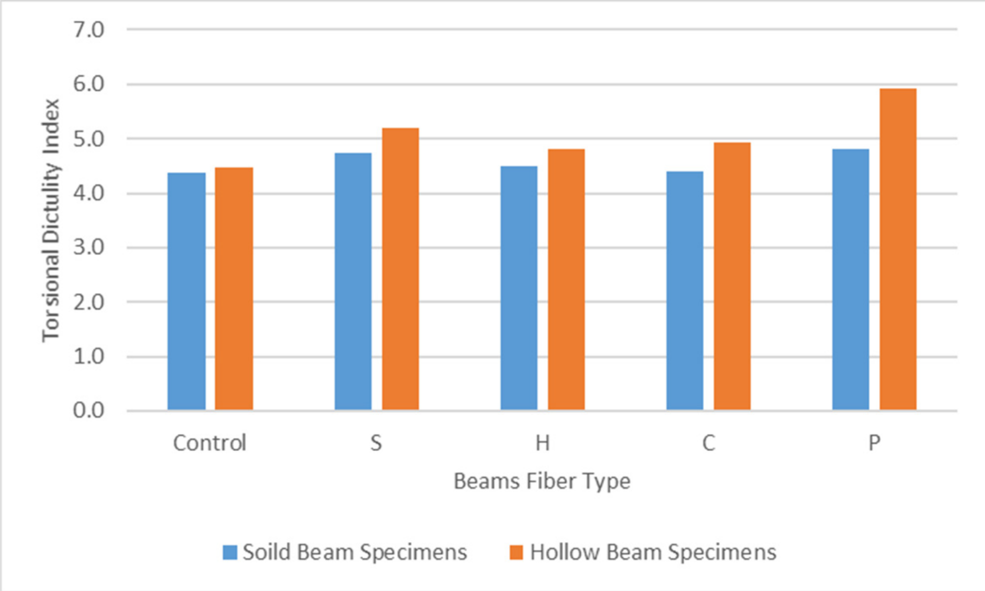

Figure 8. Effect of fiber type on the torsional ductility of tested beams.

4. Conclusions

In this study the role of fiber type in reinforcement on the mechanical characteristics of concrete, and the torsional capacity and ductility of reinforced concrete beams (solid and hollow sections) have been investigated. In summary, the results are as follows:

- The compressive strength, splitting tensile strength, and modulus of rapture of fiber-reinforced concrete were higher than those of plain concrete, where the increasing ratio reached approximately 25%, 94%, and 114%, respectively.
- Among the adopted types of fiber, corrugated steel fiber was the most effective at improving the mechanical properties of concrete, followed by hooked-end steel fiber, straight steel fiber, and polyolefin fiber.
- All of the tested beams failed via the same mode of failure, through the development of some major cracks from the bottom face upward, to the top face of the specimens, which increased in length and width with the increase in the applied torque until failure, without any significant effect of the fiber type.
- The effect of fiber shape on the torsional behavior of the tested beam specimens showed that the corrugated steel fiber produced the highest improvement, whereas the cracking torque was increased to approximately 50% and 132% for solid and hollow tested beams, respectively. However, the use of polyolefin fiber provided the better improvement in the torsional ductility of the tested beams, compared with the other types of fiber.
- Generally, it is preferable to use corrugated and hooked-end steel fibers to improve the torsional behavior of concrete because the bond between the concrete matrix is efficiently increased.

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