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Experimental investigation of fibrous reinforced concrete beams under torsion loads

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Abstract: This experimental work investigates the effect of hybrid fiber between polypropylene fiber (PPF), and glass fiber (GF) on the torsional behavior of fiber-reinforced concrete (FRC) beams. Five reinforced concrete (RC) beams were subjected to a test of pure torsion and loaded until failure. The tested beams had various fiber contents: Specimen 1 is a control beam (without fiber), specimen 2 contains 1% GF, specimen 3 contains 1% PPF, specimen 4 contains 1% GF and 1% PPF, and specimen 5 contains 1.5% GF and 1.5% PPF in terms of volume. In the experimental tests, the torsional moment, crack pattern, ductility, and energy absorption of specimens were determined. Tests demonstrated that using a hybrid of PPF and GF enhanced the torsional moment, ductility, and energy absorption of RC beams. Consequently, the maximum torsional strength increased by 29.14%, and 39.43% when (1% PPF and 1% GF), and (1.5% PPF and 1.5% GF) were added, respectively.

Keywords: Torsional behavior, hybrid fiber reinforced concrete beams, polypropylene fiber, and glass fiber.

1. Introduction

Torsion is the twisting of elements about their longitudinal axis. Forces that twist the elements are known as torsional loads. Torsion snap problems have been studied since 1784, when Coulomb [1] found that the torsional moment of a circular section was proportional to its twisting angle. Hus [2] investigated the torsion failure mechanism of a rectangular section beam using a high-speed camera. This failure is like the flexure of unreinforced concrete. Therefore, it displays bending failure. This is known as the skew bending theory. Stronger torsion resistance is required for modern, and tall structures made of conventional concrete. After employing the ultimate strength method in the 1960s, the effect of torsion became more significant, particularly for members whose behavior is characterized by torsion. Many structural components, including spandrel beams, inverted L-beams used in sunshades, curved beams, edge beams of the slab, and space frames, must be designed due to torsion. Torsion design was first included in the ACI Building Code in 1971[3].

Numerous researchers are interested in the issue of torsion failure in reinforced concrete (RC) beams. This is because torsion failure reduces the shear capacity of the beam further, leading to the related brittle failure mode. Besides, this failure happens unexpectedly without sufficient warning to residents, so it is usually disastrous. Traditionally, longitudinal rebars, closed stirrups or enlarging the section are used as measures to prevent the torsional failure of concrete beams. Increasing the steel ratio enhances the torsional strength of reinforced concrete beams according to Hsu [2,4]. when the length-height ratio of deep beams decreased and concrete strength increased, the torsional strength and stiffness increased as investigated by Ashour, et al., 1999 [5]. Koutchoukali and Belarbi, 2001 [6] demonstrated that the equilibrium torsional of high strength RC beams cannot be achieved with the minimum amount of reinforcement specified by ACI318-99 [7]. But ACI Code is effective at predicting torsional strength and limiting torsion reinforcement, which results in ductile behavior according to Bernardo and Lopes, 2009 [8].

In the past two decades, researchers have discovered many methods to strengthen the torsional behavior of RC beams. According to Zhou, et al., 2017 [9] using glass fiber-reinforced polymer (GFRP) in concrete beams could effectively stop the spreading of cracks, which would reduce the crack's width and spacing. Hadhood et al., 2020 [10] Recommend using rectangular GFRP spirals of glass fiber-reinforced polymer (GFRP) to reinforce concrete beams as it showed superior tensile resistance providing high ultimate torsional moments after cracking. Kandekar and Talikoti, 2019 [11] found that using aramid fiber to fully wrap RC beams or wrap in 100 mm wide strips significantly enhances the beam torsional strength. Mohammed et al., 2016 [12] found that RC beams that were strengthened by a thin layer of ultra-high-performance fiber-reinforced concrete (UHPFC) showed a significant improvement in torsional behavior. Besides, the UHPFC can be used as an effective external reinforcement for RC beams without stirrups.

Concrete that has been reinforced with fibers has a stronger structural bond and is known as fiber-reinforced concrete. It has a uniform distribution of short, distinct fibers that are randomly oriented. Additionally, fibers can be used in concrete to increase its ductility, corrosion resistance, strength, and durability. According to

Karimipour et al., 2022 [13] high-performance reinforced concrete (HPC) rectangular beams with PPF performed better in terms of the torsional moment than steel fibers (SF). On the other hand, SF had a more favorable impact on the torsional stiffness of HPC beams than PPF. Nitesh et al., 2019 [14] found that in terms of ultimate torque, torsional toughness, angle of twist, and torsional stiffness, adding fibers significantly enhances the torsional properties of self-compacting concrete compared to vibrated concrete. Concrete that contains steel fibers has greater torsional strength, crack resistance, and combined torsional-shear-bending strength while having less deflection according to Patil and Sangle, 2016 [15]. Fibers showed great enhancement in concrete's mechanical properties, so researchers tended to add more than one type of fiber to take advantage of their combined properties.

In this paper, an experimental study was performed to show the significant influence of polypropylene fiber, and glass fiber in the mechanical properties of concrete beams and identify the effect of hybrid fiber on their torsional behavior.

2. RAW MATERIAL AND GEOMETRIC OF SPECIMENS

2.1 Raw material

Table.1, presents the properties of polypropylene fiber (PPF), and glass fiber (GF). The average ultimate tensile strength for PPF and GF were 550 MPa, and 1400 MPa, respectively. While the modulus of elasticity for PPF, and GF were 3.6 GPa, and 72 GPa, respectively. The length of PPF and GF were 19mm, and 18mm, as well as unit weights were 0.90 g/cm3, and 2.58 g/cm3, respectively.

In this study, PPF, and GF fibers were added to concrete mixes at 0%, 1%, and 1.50% by volume of concrete, as shown in Table 2. To prepare the specimens, gravel, sand, cement, and fibers were mixed. Then water, and superplasticizers were added. The composition of concrete mixes was presented in Table 3. Besides, the average compressive strength, and tensile strength of concrete were 40 MPa, and 4 MPa, respectively. High tensile steel rebars of 8, 10, and 12 mm diameter with yield strength around 350 MPa and ultimate strength about 500 MPa were utilized.

TABLE 1. Fibers' properties.

Fibers	Unit weight (g/cm3)	Tensile strength (MPa)	Elastic modulus (GPa)	Length (mm)	Elongation (%)
PPF	0.90	550	3.6	19	19
GF	2.58	1400	72	18	4.8

TABLE 2. Fibers' contents in concrete mixes.

Specimens	Percentage of fibers to concrete volume	
	Polypropylene fiber	Glass fiber
S1	--	--
S2	--	1%
S3	1%	--
S4	1%	1%
S5	1.5%	1.5%

TABLE 3. Composition of concrete mixes.

Specimens	Cement (kg)	Coarse Agg. (kg)	Fine Agg. (kg)	Water (Liter)	PPF (kg)	GF (kg)	Superplasticizers (Liter)
		10-20 mm					
S1	53	125	65.70	21.20	-	-	1.50
S2	53	125	65.70	21.20	-	2.70	1.50
S3	53	125	65.70	21.20	0.95	-	1.50
S4	53	125	65.70	21.20	0.95	2.70	1.50
S5	53	125	65.70	21.20	1.4	4.10	1.50

2.2 Geometric of specimens

The geometrical characteristics of specimens and steel reinforcement are shown in Fig. 1, Fig. 2, and Fig. 3.

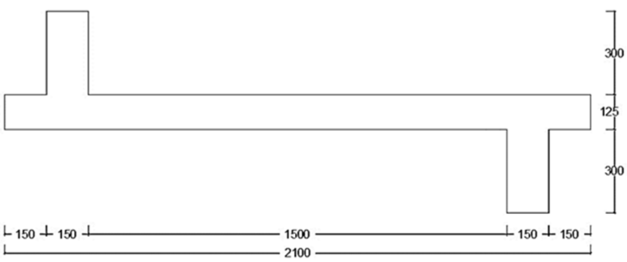


Fig 1. Plane of specimens

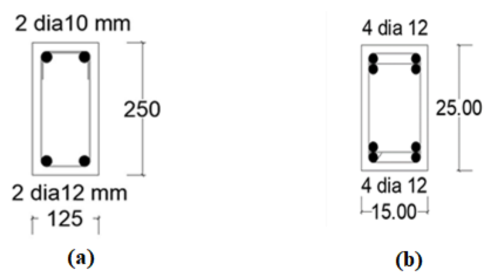
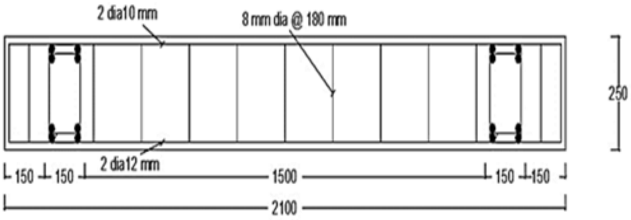
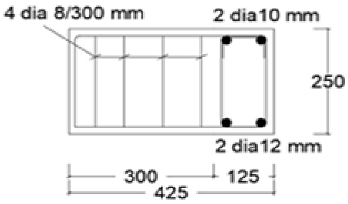


Fig 2. Cross-sectional area and transverse reinforcement details for (a) Beam, and (b) Cantilever.



(a)

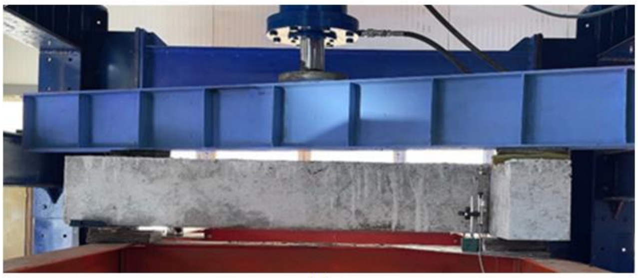


(b)

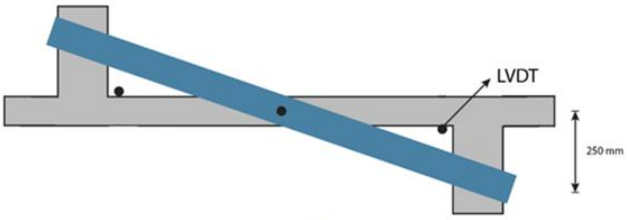
Fig 3. Longitudinal section and transverse reinforcement details for (a) Beam, and (b) Cantilever.

3. EXPERIMENTAL METHODS AND LOADING CONDITIONS

After 28 days of curing, beams were tested under pure torsion until failure. Figure 4 presents the loading condition of the tested specimens. The load was applied by a load cell of a capacity 900 kN. To measure the angle of twist, two LVDTs were installed under the specimens.



(a)



(b)

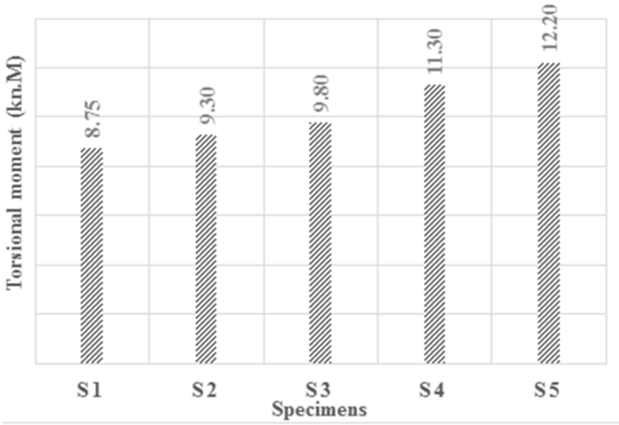
Fig 4. Torsional test setup, (a) Elevation, (b) Plan.

4. RESULTS AND DISCUSSION

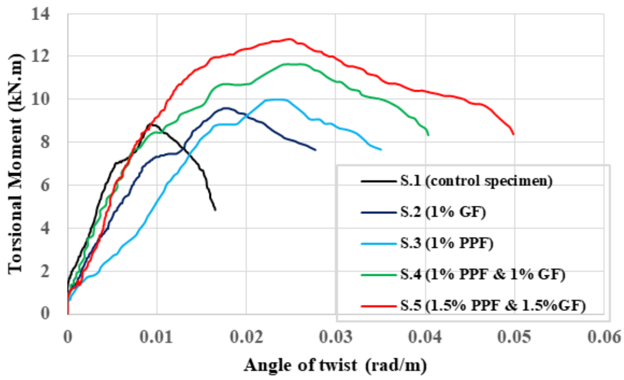
To achieve the objectives of this paper, five hybrid fiber reinforced concrete beams were tested, and the results of torsional strength, crack pattern, first crack, ductility, and energy absorption were measured.

4.1 Torsional strength

Adding PPF and GF improved significantly the maximum torsional strength and angle of twist, as shown in Fig. 5. PPF improves the maximum torsional strength and angle of twist of the tested specimen (S3) more than specimen with GF (S2) as shown in Fig. 5a. Adding a hybrid of 1% PPF, and 1% GF (S4) improved the maximum torsional moment by 29.14% compared to control specimen (S1). In the same line, increasing the content of hybrid fibers to 1.50% PPF, and 1.50% GF (S5) improved the maximum torsional moment by 39.43% compared to control specimen (S1). This could be attributed to the high elastic modulus of GF, and high deformability of PPF which play together an important role to enhance torsional strength of the tested specimens as shown in Fig. 5b.



(a)



(b)

Fig 5. (a) Maximum torsional moment vs specimens, (b) Torsional moment against the angle of twist for various fiber content additions.

4.2 Crack pattern

Increasing the hybrid content plays an important role in increasing first crack load as shown in Fig. 6. Thus, adding 1% GF, and 1% PPF (S4) enhances the first crack torsional moment by 14.34% compared to control specimen (S1). Besides, S5 which contains 1.5% GF, and 1.5% PPF increases the first crack torsional moment by 33.68% compared to control specimen (S1).

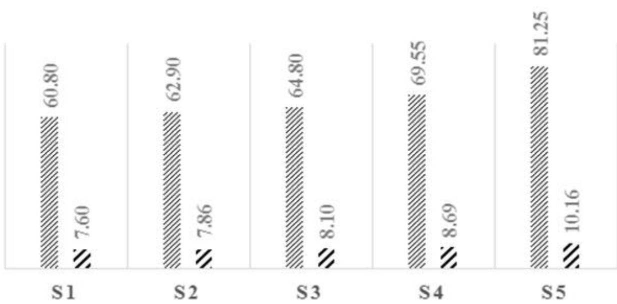


Fig 6. Load and torsional moment of the first crack for various fiber content additions.

Figure 7 depicts the beams after failure with different fiber contents when subjected to a torsional moment. There, beams have a distribution of diagonal cracks along their length. Fibers also reduced the crack width and enhanced the torsional behavior of the beams. This might be illustrated by how fibers function to bond particles together in concrete mixtures and increase matrix strength. The cracks' ability to spread along the specimens' length increased as the fiber content rose, while the width of the cracks reduced. Thus, specimen 5 that contained the highest hybrid fiber content of 1.5% GF, and 1.5% PPF has the best crack distribution.

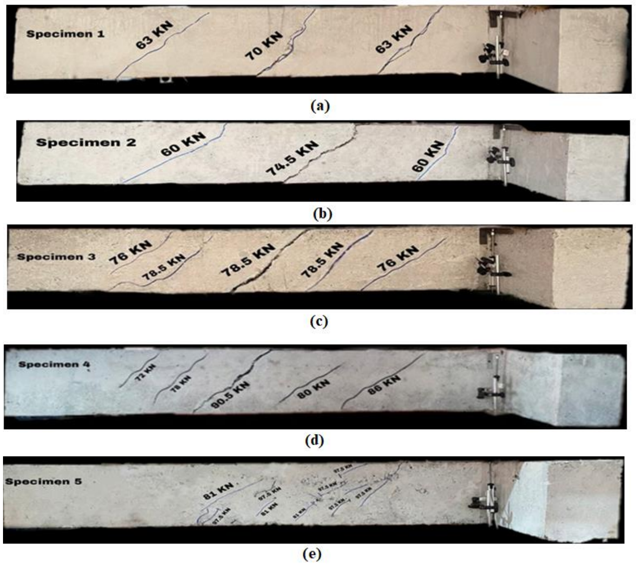


Fig 7. Represents crack propagation after failure, (a) Specimen 1, (b) Specimen 2, (c) Specimen 3, (d) Specimen 4, and (e) Specimen 5.

4.3 Ductility and energy absorption

The deformability of reinforced concrete beams under a torsional moment is determined by the ductility factor, which is a crucial parameter. It can be defined as the ratio of the angle of twist (at 80% of the peak torsional moment on the descending part of torsional moment-angle of twist curve) to the angle of twist (at 80% of the peak torsional moment on the ascending part of torsional moment-angle of twist curve) [16,17].

Figure 8 shows that the specimens' ductility was improved by raising the hybrid fiber content. Thus, PPF improved the ductility of the tested specimen more than GF. This could be explained by the higher deformation of PPF more than GF. The ductility factor increased by 8.78%, 12.21%, 21.37%, and 61.45% in specimens S2, S3, S4, and S5, respectively compared to S1 that contains no fiber. This could be clarified by adding additional hybrid fibers to the concrete, which are crucial for bridging small and large cracks and enhancing the concrete's ductility.

The area underneath the torsional moment- angle of twist curve up to the peak torsional moment is known as energy absorption [16,17]. Figure 9 shows that employing hybrid fiber significantly increases the amount of energy absorbed by rotation. The energy absorbed for Specimens S2, S3, S4, and S5 increased by 109.09%, 172.73%, 321.82%, and 329.09%, respectively.

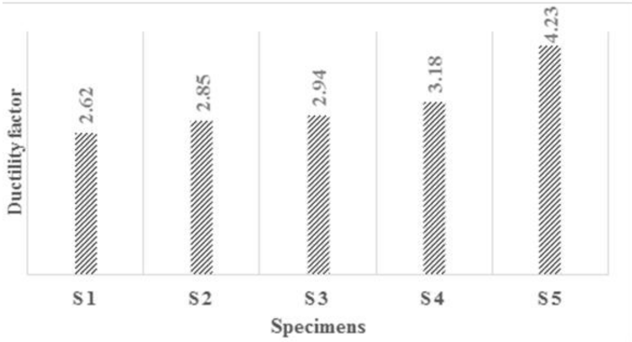


Fig 8. Ductility factor of the tested specimens

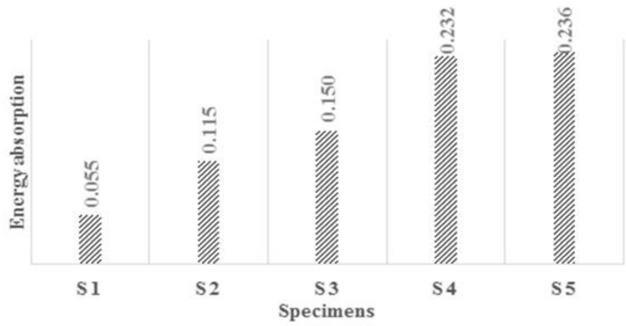


Fig 9. Energy absorption of the tested specimens.

5. CONCLUSION

This paper investigates the influence of hybrid fiber between PPF, and GF on the torsional behavior of reinforced concrete beams. The investigation involved tests on five RC beams: Specimen 1 is control beam (without fiber), specimen 2 contains 1% GF, specimen 3 contains 1% PPF, specimen 4 contains 1% GF and 1% PPF, and specimen 5 contains 1.5% GF and 1.5% PPF in terms of volume. In the experimental tests, the torsional moment, crack pattern, ductility, and energy absorption of specimens were determined.

The main conclusions derived from the experimental work performed on hybrid fiber reinforced concrete specimens are:

1. The torsional behavior of reinforced concrete beams is improved by using hybrid fiber. Therefore, the maximum torsional strength increased by 29.14%, and 39.43% when (1% PPF and 1% GF), and (1.5% PPF and 1.5% GF) added, respectively.

2. Using a hybrid fiber of (1.5% PPF and 1.5% GF) is effective in reducing crack width and increasing crack propagation along the specimens' length.

3. Raising the hybrid fiber content helps bridge micro and macro cracks, making the concrete more ductile. As a result, we observed an increase in ductility of 21.37%, and 61.45% when (1% PPF and 1% GF), and (1.5% PPF and 1.5% GF) added, respectively.

4. The energy absorption of the hybrid fiber specimens is noticeably better than specimens with one fiber only. The energy absorption increased by 321.82%, and 329.09% when (1% PPF and 1% GF), and (1.5% PPF and 1.5% GF) added, respectively.

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