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Torsional behavior of polyolefin fiber reinforced concrete Beams of different strength levels

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Abstract

The use of fibers has become widely adopted to enhance the properties of concrete within structural applications, enabling them to withstand various loads. In this research, an experimental study was carried out to examine the impact of incorporating polyolefin fibers (PF) in different ratios on the structural response of reinforced concrete beams to a purely torsional load. The study examined four polyolefin fiber ratios (PFR) (0.0%, 0.5%, 1.0%, 1.5%) for both normal and high strength concrete. A total of 8 reinforced concrete beam specimens were fabricated; four specimens were made of normal concrete and the remaining four were made of high strength concrete. In addition to assessing the torsional behavior of the specimens, the mechanical characteristics of the concrete were investigated. The results demonstrated that the PF had a negligible influence on the concrete compressive strength of both levels. However, the tensile and flexural concrete strengths showed an improvement as the fiber content increased. Specifically, the tensile strength increased by approximately 78% and 41% for normal and high strength concrete, respectively when using a 1.5% PFR (polyolefin fiber ratio). Likewise, the flexural strength increased by approximately 88% and 65% for normal and high strength concrete, respectively, with 1.5% PFR. The experimental torsional test results indicated that torsional performance improved with increasing PFR. The ultimate torsional load demonstrated a 74% and 45% increase for a 1.5% PFR compared to specimens without fibers for normal and high strength concrete, respectively. Additionally, the twist angle of the specimens increased with increasing PFR, reflecting an improvement in their ductility. It is worth noting that the rate of improvement decreased after reaching a PFR of 1.0%.

Keywords: *Torsional Strength, Polyolefin Fiber, High Strength, Normal Strength, Pure Torsion*

1. Introduction

Research conducted in previous years has focused on enhancing the brittle characteristics and low tensile strength of concrete through the incorporation of fibers during production. By introducing fibers into the concrete manufacturing process, several notable advantages have been observed. These encompass the ability to improve concrete ductility, enhance concrete toughness, and promote stress transmission across concrete cracks [1]. Structural concrete can be reinforced using various types of synthetic and metallic fibers. Among these, thermoplastic fibers have garnered considerable interest because of their reduced weight, high tensile strength, and high Young's modulus. Specifically, techniques have been developed for the production of thermoplastic fibers endowed with these desirable attributes. Polypropylene fibers are commonly used in structural concrete, with a typical cross-sectional area ranging between 0.6 and 1.5 mm^2 and a length of approximately 3-6 mm. The elastic modulus of polypropylene fibers falls within the range of 4,000 to 10,000 MPa and a tensile strength between 300 and 600 MPa [2]. Furthermore, it is worth noting that polyolefin fibers have a relatively low density of approximately 0.9 t/m^3, which stands in stark contrast to the density of steel fibers, amounting to 7.8 t/m^3 [3].

A group of researchers has directed their efforts towards the development of polymer materials and their beneficial impact on engineering technology. Specifically, they have explored the utilization of polyolefin fibers to enhance the performance of concrete [4,5]. Moreover, previous studies have extensively examined the role of fibers in enhancing the flexural behavior of reinforced concrete beams [6,7]. Recently, there has been growing interest in investigating the torsional response of concrete beams reinforced with fibers in 2006, Altun et al. [8], conducted experimental tests on box beam specimens. These specimens were made with steel fibers of 6 cm length, and the volume ratio of fibers was approximately 0.77. The results indicated that even with a weight reduction of about 44%, the load-bearing capacity of the tested beam specimens decreased by only approximately 29%. Lin et al. [9] conducted a study on cement-based composites containing polyolefin fibers and silica fume. The research aimed to assess the engineered properties of these composites, considering factors such as water-cementitious ratio, silica fume dosage, and polyolefin fiber length and dosage. Multiple tests were conducted, and the results showed that Specimens incorporating silica fume exhibited a higher compressive strength in comparison to specimens with fibers and the control group. The combination of silica fume and polyolefin fibers led to improved tensile strength, ductility, and resistance to chloride penetration. Shorter polyolefin fibers were found to enhance concrete characteristics more effectively. Specimens containing Silica fume exhibited higher resistivity and lower total charge passed. Yousefv et al. [10] in 2019 conducted a study on concrete reinforced with polyolefin fibers tested under varying temperature conditions. Incorporating fibers at a volume fraction of 1.5% led to a 29% boost in tensile strength and a 56% enhancement in the modulus of rupture. However, at temperatures above 400°C, the fibers lost their effectiveness due to oxidation, leading to increased porosity and decreased concrete strength. Arash and Morteza [11]in 2017 conducted a study on the mechanical properties of polyolefin fiber-reinforced lightweight concrete (LWC). The objective was to assess the impact of polyolefin fibers on the characteristics of concrete by modifying the fiber-matrix properties at the interface. The study aimed to determine the compressive, flexural, and splitting tensile strengths of the lightweight concrete samples. Different percentages (ranging from 0% to 2%) of polyolefin fibers were introduced into the reinforced composite. The lightweight concrete was specifically designed to achieve a density of 1.8 t/m³ after 28 days of curing, with a minimum compressive strength of 30 MPa. In 2018, Abdullah [12] examined 12 reinforced concrete beams including both hollow and solid square cross-sectional shapes (160 mm height, 1000 mm length) under pure torsion. The study investigated how varying steel fiber percentages and the composition of the concrete core influenced ultimate torsion, crack capacity, and twist angle. The research findings showed that the introduction of steel fibers, increasing from 0% to 2.5%, resulted in a substantial enhancement of the ultimate torsional capacity, with a 98.2% increase for solid-section beams and a 91.3% increase for hollow-section beams. Additionally, there were significant improvements in crack capacity, with an increase of 178% for solid-section beams and 163% for hollow-section beams, respectively. Concrete core had no impact on ultimate torque or beam elongation. In 2021, Mures et al. [14] Examined the performance of high-strength concrete beams, both solid and hollow, reinforced with steel fibers and exposed to pure torsional forces. The study found an inverse relationship between the width and number of cracks and the ratio of steel fibers incorporated in the concrete beams. Said et al. [15] investigated the impact of using different types of hybrid fibers (carbon fiber, basalt fiber, and steel fiber) on the torsional performance of reinforced concrete beams. The study generated forecasts concerning the ultimate torsional capacity of hybrid fiber-reinforced concrete (HFRC) beams, relying on various theories and code guidelines. They also developed a formula to account for the influence of hybrid fibers on the ultimate torsional strength of these HFRC beams. Abdullah et al. [16] concluded that the type and shape of fiber reinforcement have a substantial impact on the mechanical properties and performance of concrete structures. They showed that the corrugated steel fibers were the most effective in improving concrete strength and torsional behavior, while polyolefin fibers offered enhanced ductility under torsion. Hussain et al. [17] Illustrated that elevating the quantity of steel fibers within high-strength concrete beams enhances their torsional strength. Additionally, higher concrete compressive strength and closer spacing between transverse reinforcements contributed to even greater torsional strength. These findings provided valuable insights into the use of fibers in improving the effectiveness of high-strength concrete beams. Awoyera et al. [18] presented a review paper compiling valuable insights into the influence of reinforcement fibers on the torsional behavior of structural elements. It delineates both advances and areas requiring further exploration to enhance the performance of concrete structures while also contributing to environmentally responsible construction practices.

In this study, a total of 8 rectangular solid-section reinforced concrete beam specimens were employed. Depending on the concrete strength, whether it was normal or high, the specimens were equally divided into two groups, with 4 specimens in each group. Pure torsional load was applied to explore the impact of Polyolefin fibers ratios (PFR) on both normal strength concrete (NC) and High strength concrete (HC) beams. The investigation also considered an examination of the mechanical characteristics of the concrete in the presence of PF.

2. Material and experimental methodology

2.1. Materials properties

Tables 1-3 provide information regarding the physical and chemical the physical and chemical attributes of the cement employed, as well as the mechanical characteristics of the fine and coarse aggregates, as per the ASTM standards [19,20]. The particle size distributions of both the gravel (used as coarse aggregates) and the sand (used as fine aggregates). These aggregates were sourced locally, and their respective particle size distributions are depicted in Figure 1. Figure 2 depicts the polyolefin fibers utilized in this study. Additionally, the mechanical attributes of steel reinforcing bars are presented in Table 4.

Table 1: Physical properties of cement in accordance with ASTM C150-18

Test	Method	Value
Fineness (m^2/kg)	Blaine air permeability	305
Setting time (min.)	Initial	132
	Final	263
Compressive strength (MPa)	3 days	22.5
	7 days	26.8

Table 2: Chemical properties of cement as per ASTM C150-18.

Chemical Components of Cement Weight (%)									Main Components of Cement Weight (%)				
SiO2	Al2O3	Fe2O3	Cao	MgO	Na2O	K2O	SO3	Insoluble Residue	LOI	C3S	C2S	C3A	C4AF
20.2	5.1	3.2	62.2	1.74	0.29	0.64	1.92	20.2	0.45	1.3	50.1	24.1	6.65

Table 3: Physical characteristics of aggregates in compliance with ASTM C33-18.

Test	Sand	Gravel
Bulk specific gravity	2.52	2.58
Apparent specific gravity	2.38	2.68
Dense dry density (kg/m3)	1632	1870
Loose dry density (kg/m3)	1461	1718
Sulphate content (%)	0.02	0.22
Absorption (%)	0.83	1.58

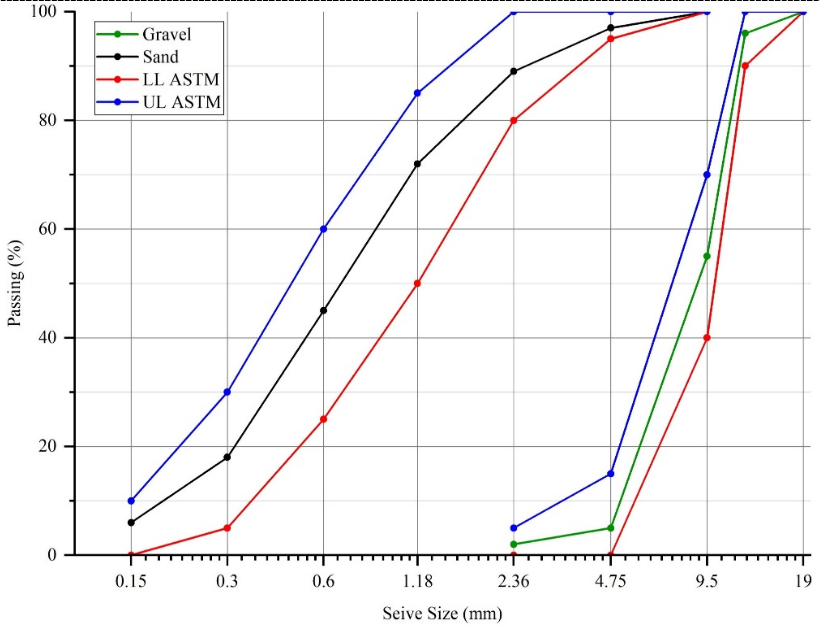


Fig. 1: Sieve analysis of aggregates.

Fig. 2: Polyolefin fiber.

Table 4: Steel's attributes

Steel diameter	Yield strength, *fy* (MPa)	Ultimate strength *fu* (MPa)	Specification
Reinforcement (#8)	395	580	ASTM A615/A615M-18
Reinforcement (#12)	520	640	

Table 5 displays the mechanical properties and geometric specifications of the Polyolefin fibers (PF) used in the study. PF were incorporated into the concrete mixture at varying ratios (0.0%, 0.5%, 1%, and 1.5%) by volume for the specimens under examination. The selected ratios were based on prior research to ensure the desired workability and consistency of the fresh concrete mix [21,22].

Table 5: Properties of polyolefin fiber

Fiber Type	Shape	Length (cm)	Diameter (μmm)	Aspect Ratio	Tensile Strength (MPa)
Polyolefin fiber	——	6	840	71	465

Two types of concrete mixes were prepared to fabricate beam specimens for testing: normal and high strength concrete. PF were added to both mixes in four different ratios (0.0%, 0.5%, 1.0%, 1.5%). Table 6 illustrates the mix proportions of the control concrete mix with 0.0% PFR, which was utilized in the experiment. Sika Visco-Crete (5930) was employed as a superplasticizer, at a concentration of approximately 1% of the total weight of cement. To assess the mechanical characteristics of different concrete mixtures, a total of nine standard test cylinders (300 x 150 mm) and three standard beams (500 x 150 x 150 mm) were meticulously produced for each PFR. Each concrete mix underwent this casting process to evaluate essential characteristics, including compressive strength, splitting tensile strength, and flexural strength, as shown in Figure 3.

Table 6: Control concrete mix ratio.

Parameter	Material quantity (25MPa)	Material quantity (55MPa)
Water/Cement ratio	0.48	0.30
Water (kg/m^3)	172	150
Cement (kg/m^3)	358	460
Fine aggregate (kg/m^3)	782	657
Coarse aggregate (kg/m^3)	1081	1138
Sika Visco Crete (kg/m^3)	3.4	4.6

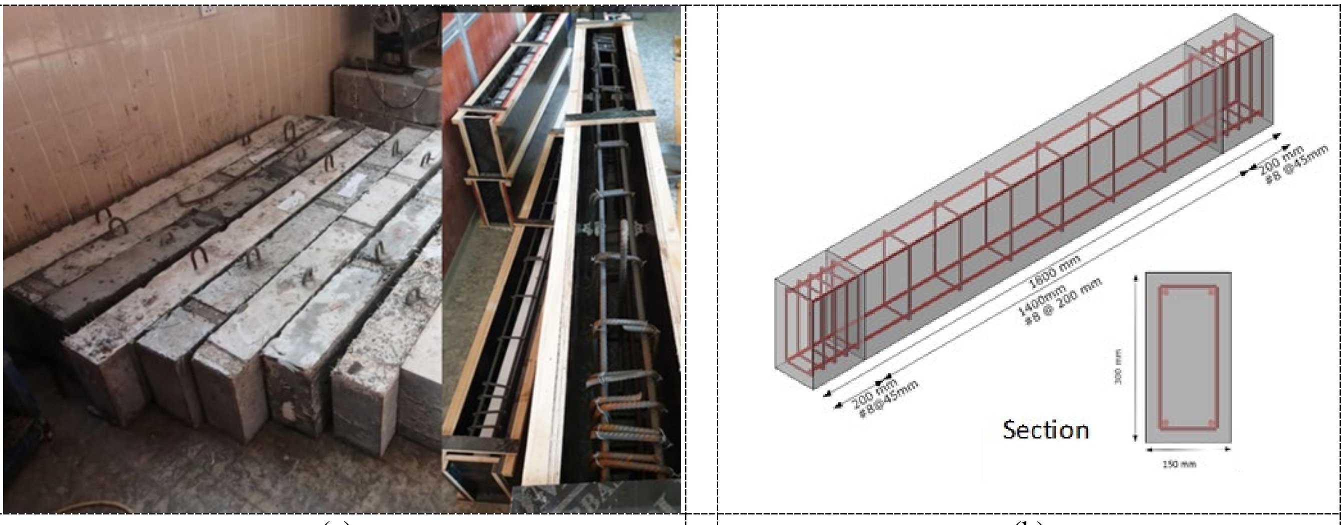
Fig. 3: Compressive, splitting and flexural specimen's test.

2.2. Tested beam specimens

A total of 8 reinforced concrete beams were subjected to pure torsional loading were considered. Table 7 illustrates the beams that were designed with a solid cross section. For the purpose of comparison, a single reference beam specimen was prepared, with no fibers. All beams had the same dimensions, measuring 1400 mm in effective length, 150 mm in overall width, and 300 mm in overall depth. Figure 4 provides a visual representation of the beam specimens, including their geometry and reinforcement details.

Table 7: Details of tested beam specimens.

Specimens	PFR %	Concrete type	Reinforcement	
			Longitudinal	Stirrup
HS00,200,4	0.0	High	4#12	#8@ 200 mm
NS00,200,4	0.0	Normal		
HS0.5,200,4	0.5	High		
NS0.5,200,4	0.5	Normal		
HS1.0,200,4	1.0	High		
NS1.0,200,4	1.0	Normal		
HS1.5,200,4	1.5	High		
NS1.5,200,4	1.5	Normal		

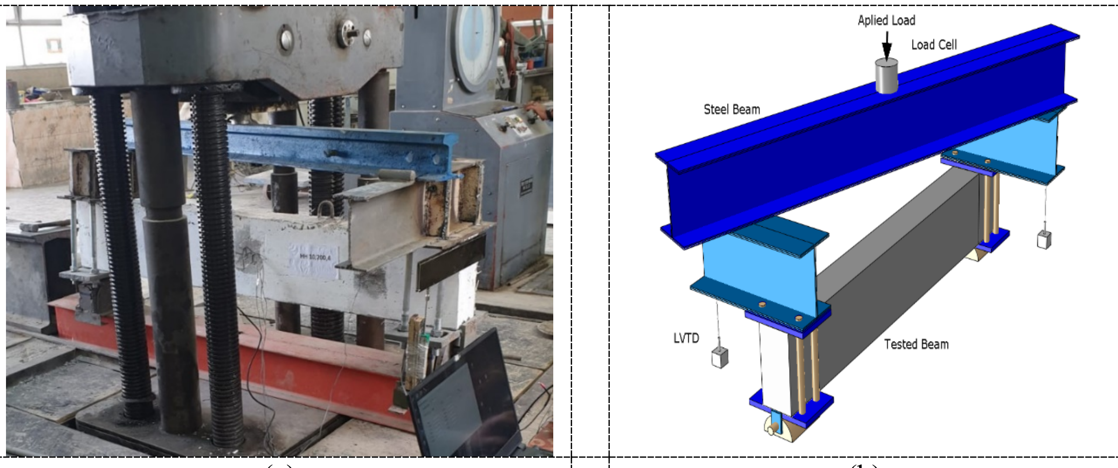


(a) (b)

Fig. 4: Beam specimen's geometry.

2.3. Test procedure

The beam samples underwent analysis employing a universal testing machine capable of bearing up to 500 KN. In the experiment, the beams being tested were supported at both ends by rollers, and the load was administered through a steel girder spreader beam. At the beam's extremity, it was positioned between two plates connected by bolts to encase and secure the ends of the beam. The upper plates at the ends of the beam were connected with wing beams to support the spreader beam, while the lower plates were connected to roller supports. All connections were securely fastened using bolts and welding to enable the beam specimens to twist and change in length freely, as shown in Figure 5. To measure the twist angle, LVDTs which stands for Linear Variable Differential Transformers were attached to the bottom of the wing steel arms at each end of the beam. The applied load on the spreader steel beam produced a gradually increasing torque load, this load was incrementally increased until the beams reached their failure point, during this process, the applied torque and the corresponding twist angle were documented at every load increment. Additionally, the ultimate torque, cracking torque, and their respective twist angle values were documented. The experimental program flow chart for this work is shown in Figure 6.



(a) (b)

Fig. 5: Beam specimens under pure torsion.

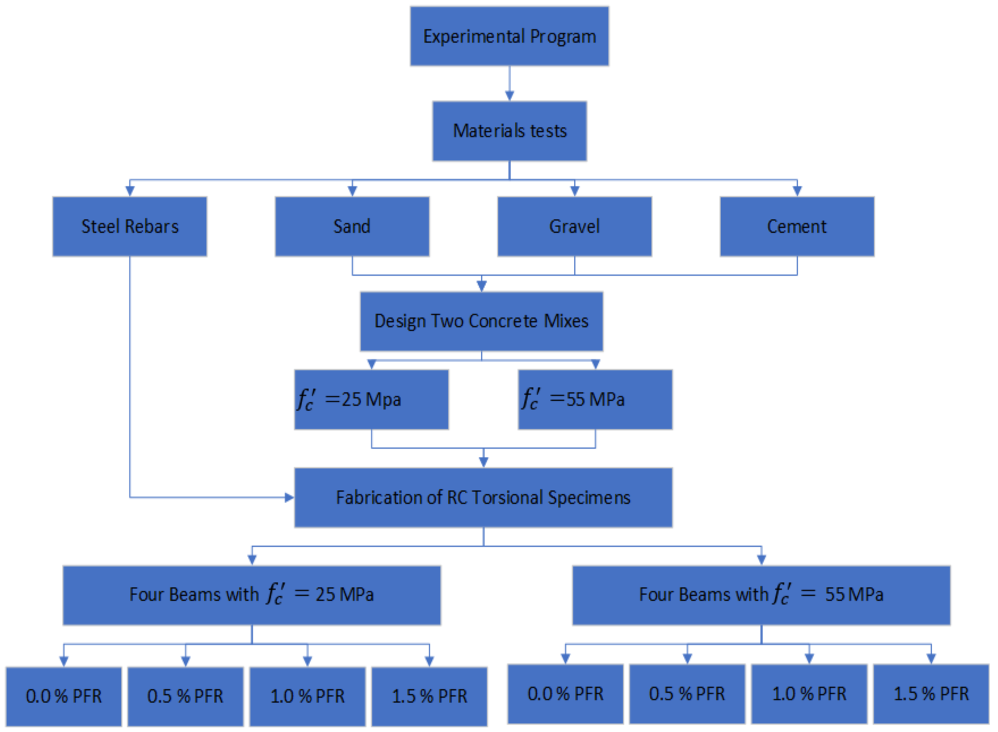


Fig. 6: Experimental program flow chart.

3. Results and discussion

3.1. Properties of hardened concrete

The findings indicated that the presence of fiber had a negligible impact on the compressive strength for both concrete strength levels. However, there was a noticeable Enhancements in tensile and flexural strength were observed as the fiber content increased for both types of concrete. Specifically, when using 1.5% PFR, the increase in tensile strength was 78% and 41% for NC and HC, respectively. Moreover, the increase in flexural strength showed a significant rise of 88% and 65% for a 1.5% fiber content in normal and high-strength concrete, respectively. These results are further illustrated in Table 8 and Figures 7 to 9.

Table 8: Influence of PFR on Concrete Characteristics in Normal and High-Strength Mixes

PFR (%)	Normal strength						High strength					
	Compressive		Tensile		Flexural		Compressive		Tensile		Flexural	
	f'_c (MPa)	$\frac{f'_{c\,Fiber}}{f'_c}$	f_t (MPa)	$\frac{f_{t\,Fiber}}{f_t}$	f_{cr} (MPa)	$\frac{f_{cr\,Fiber}}{f_{cr}}$	f'_c (MPa)	$\frac{f'_{c\,Fiber}}{f'_c}$	f_t (MPa)	$\frac{f_{t\,Fiber}}{f_t}$	f_{cr} (MPa)	$\frac{f_{cr\,Fiber}}{f_{cr}}$
0.0	26.3	------	3.45	------	4.13	------	56.3	------	6.3	------	6.88	------
0.5	25.1	0.95	4.11	1.191	6.15	1.49	57.1	1.014	6.91	1.09	9.34	1.36
1.0	26.8	1.02	5.82	1.686	6.41	1.55	56.9	1.011	8.53	1.35	10.51	1.53
1.5	25.3	0.96	6.15	1.783	7.78	1.88	55.8	0.991	8.92	1.41	11.34	1.65

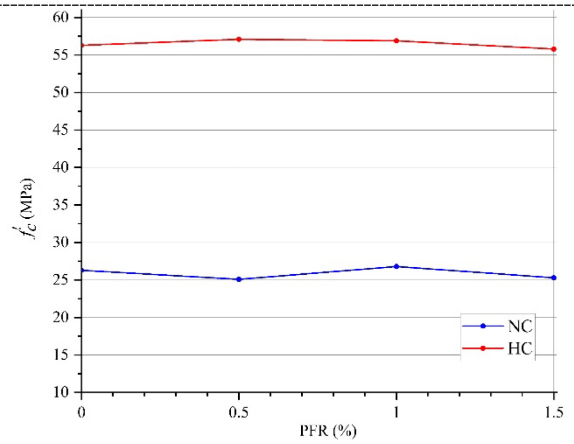


Fig. 7: Effect of PFR on compressive strength of concrete.

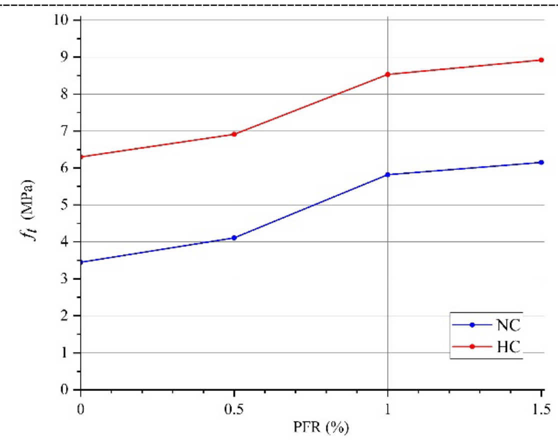


Fig. 8: Effect of PFR on tensile strength of concrete.

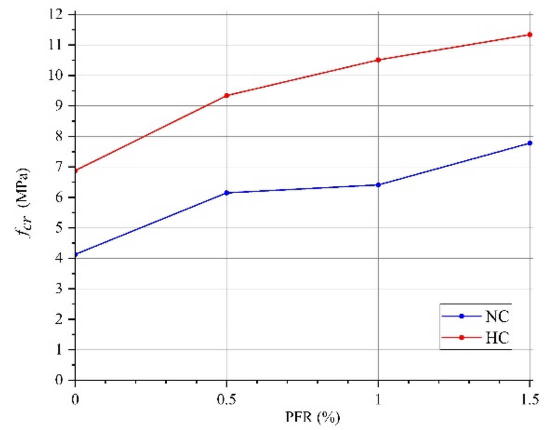


Fig. 9: Effect of PFR on flexural strength of concrete.

3.2. Torsion capacity

According to the experimental results presented in Table 9, the first cracking torque (Tcr) for specimens with PFR of (0.5%, 1.0%, 1.5%) exhibited significant increases of approximately 13%, 34%, and 53%, respectively, for normal concrete beams. Similarly, for high strength specimens, the first cracking torques increased by 4%, 8%, and 28%, respectively, when compared to the cracking torque of the reference specimen with 0.0% PFR. Furthermore, the ultimate torsional capacity (Tu) displayed a proportional relationship with the PFR, ranging from 31% to 74% for normal strength beams and from 13% to 45% for high strength beams when compared to the reference beams. The same trend was observed in the angle of twist of the specimens at first cracking (θcr) and at ultimate torsion (θu). The increases in cracking and ultimate torque, as well as the twist angle, contributed significantly to the enhancement of the specimens' torsional ductility (μθ) as shown in Figures 10 and 11. In fact, the increase reached approximately 58% for normal strength beams and 133% for high strength beams. These improvements can likely be attributed to the enhanced splitting and flexural tensile strength of the concrete beams owing to the inclusion of PF.

Table 9. Experimental Results for torsional test specimens

Specimen	TCr (kN.m)	θCr (rad)	TU (kN.m)	θU (rad)	TCr / TU (%)	θCr / θU (%)	Ductility μθ	TCr fiber / Tcr	θCr fiber / θCr	TU fiber / TU	θU fiber / θU
NS,00,200,4	4.46	0.0025	6.97	0.040	63.91	6.25	11.4	1.00	1.00	1.00	1.00
NS,0.5,200,4	5.04	0.0025	9.19	0.058	54.79	4.31	14.1	1.13	1.00	1.32	1.45
NS,1.0,200,4	5.97	0.0045	11.03	0.074	54.13	6.08	18.0	1.34	1.80	1.58	1.85
NS,1.5,200,4	6.82	0.0059	12.15	0.085	56.11	6.95	14.4	1.53	2.36	1.74	2.13
HS,00,200,4	7.87	0.0012	10.66	0.009	73.79	13.33	7.5	1.00	1.00	1.00	1.00
HS,0.5,200,4	8.17	0.0014	12.07	0.016	67.65	8.75	11.4	1.04	1.17	1.13	1.78
HS,1.0,200,4	8.48	0.0019	15.03	0.037	56.40	5.14	17.5	1.08	1.58	1.41	4.11
HS,1.5,200,4	10.08	0.0025	15.53	0.034	64.91	7.35	13.6	1.28	2.08	1.46	3.78

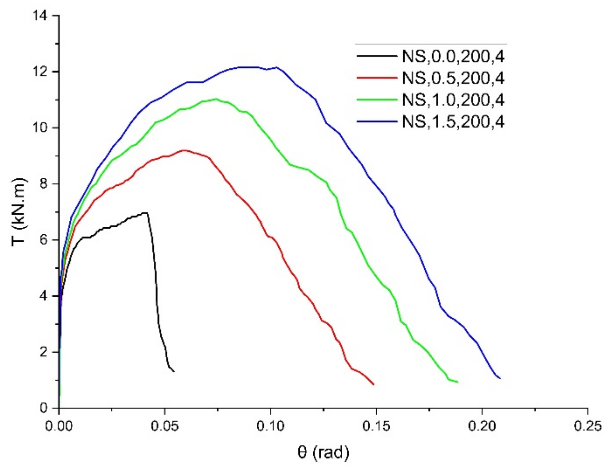


Fig. 10: Torque and twist angle for NC specimens.

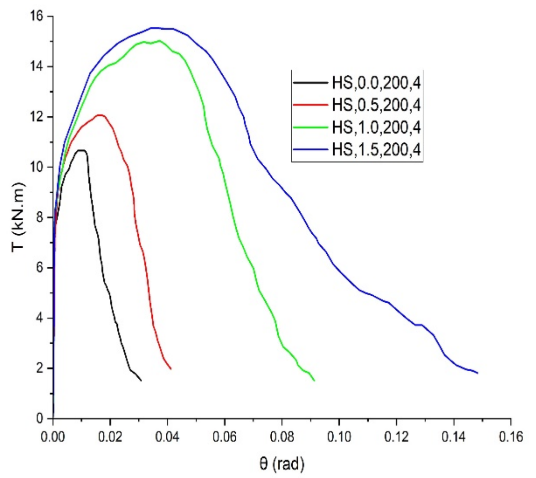


Fig. 11: Torque and twist angle for HC specimens.

3.3. Failure modes

Figure 12 depicts the failure modes observed during the experimental testing of specimens. When members are subjected to torsional loads, they undergo shearing stresses that manifest as inclined rings. In Figure 12, it can be observed that the reference beams with 0.0% PFR and both strength levels of concrete experienced failure characterized by the formation of significant cracks. The cracks first appeared at the bottom surface facing upward, spreaded to the top surface, and then moved towards the top of the rear surface and down to the bottom surface. With increasing applied torque, these cracks extended in both length and width, and most of them exhibited an inclination of roughly 43 degrees. It is noteworthy that this failure mode has been consistently documented in many studies [23,24]. In contrast, the specimens composed of PF concrete displayed a distinct response as the applied torque intensified. Notably, along the sides of the beams, a number of inclined smeared cracks began to manifest. This behavior sharply contrasted with the performance exhibited by the reference beams. The presence of PF proved to be indispensable in countering post-cracking torque and minimizing the width of primary cracks by guiding them towards denser, narrower fissures.

It was discerned that the crack density within the beams exhibited a direct correlation with the increase in PF content. PFs functioned as secondary reinforcement, effectively curbing crack widths, enhancing load distribution, and augmenting the beam's capacity for dissipating energy. They accomplished this by bridging across cracks and redistributing stress, thus effectively preventing cracks from widening and advancing. Furthermore, it is important to highlight that the density of cracks in normal strength specimens exceeded that in high-strength specimens, potentially attributed to an increase in the ductility capacity of the PF specimens. It is worth mentioning that all tested beams ultimately failed in shear, which is a typical mode of failure for beams subjected to pure torsion.

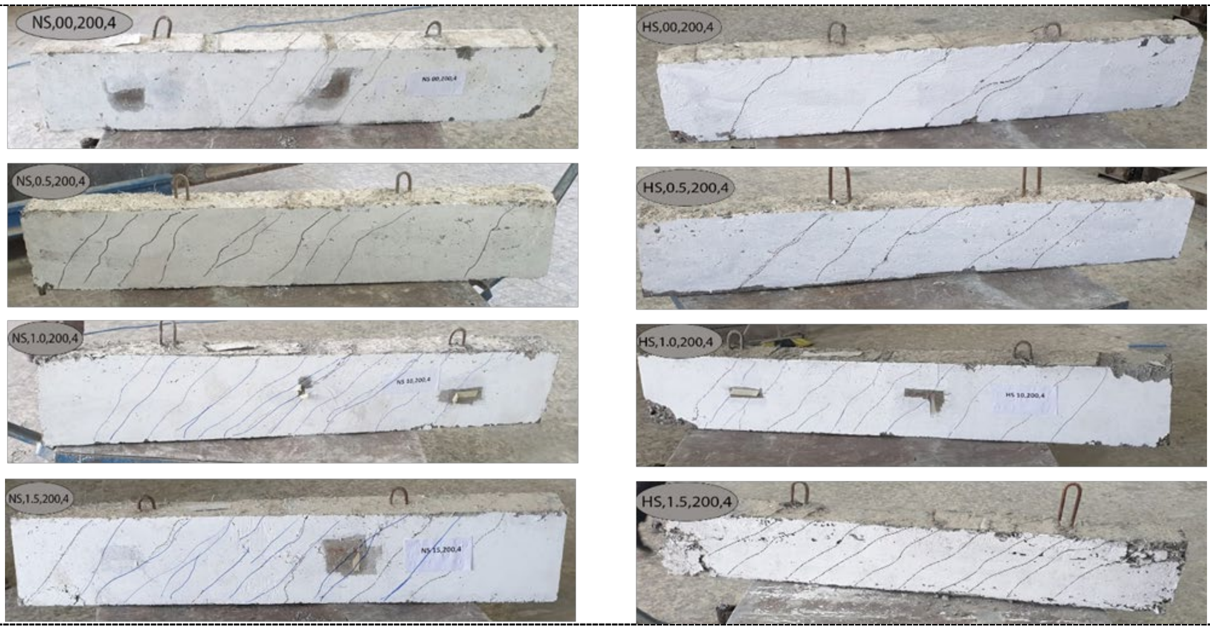


Fig. 12: Modes of failure of tested beams.

4. Conclusion

In this study, a comprehensive examination of PF reinforcement effects on concrete, encompassing its compressive, tensile, and flexural strength characteristics was undertaken. Concurrently, the evaluation of the torsional behavior and capacity of reinforced concrete specimens is studied carefully, considering both normal and high strength concrete compositions. Summarizing our key findings:

1. The inclusion of PF exhibits minimal impact on compressive strength but significantly augments the splitting tensile and flexural strength of PF reinforced concrete. Notably, these enhancements are most prominent in high strength concrete. It was observed that when the PFR of 1.5% is used, an impressive increase in tensile and flexural strength of approximately 41% and 65%, respectively for high strength concrete and an improvement of around 78% and 88%, respectively for normal strength concrete.
2. Furthermore, the incorporation of PF contributes to an amplified torsional capacity, with a more substantial rise observed at PFR of 1.5% for both high and normal strength concrete. It is worth noting that when PF is integrated into high strength concrete beams, the enhancement in torsional strength is comparatively less pronounced than that observed in normal strength concrete beams with PF reinforcement.

3. In comparing the improvement in high strength concrete to normal concrete behavior, it is evident that the addition of PF significantly enhances the behavior of high strength concrete; however, the rate of improvement tends to decrease after a 1% PFR.
4. Moreover, all tested beams exhibit a uniform failure mode, marked by the emergence of primary cracks originating from the lower face and propagating towards the upper face of the specimens. These cracks progressively extend in both length and width as the applied torque intensifies, ultimately leading to failure. It is noteworthy that the increasing PFR has a noticeable impact on this process. Typically, the application of PFR is favored for augmenting the torsional behavior of concrete structures due to its effective enhancement of the bond within the concrete matrix.

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