Using Fibers Instead of Stirrups for Enhancing Torsional Strength in Reactive Powder Concrete Beams

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ABSTRACT

This study investigates the torsional behavior of Fiber-Reinforced Concrete (FRC) beams subjected to pure torsion. Six concrete mixtures incorporating different fiber types and dosages were tested, including Basalt Fibers (BF), Steel Fibers (SF), and Glass Fibers (GF), to evaluate their potential as substitutes of traditional transverse reinforcement. The findings show that the fiber type and dosage significantly influence the torsional strength and ductility. Incorporating 1% BF reduced the torsional capacity by 53%, while 1% GF caused a 14% reduction. In contrast, adding 1% SF improved the torsional strength by 106%. The hybrid mixtures further enhanced the performance, with a combination of 0.5% BF and 0.5% GF, increasing the torsional capacity by 29.6% compared to the control beam. Overall, the results indicate that FRC can effectively replace stirrups in torsion-resistant beams, with hybrid fiber systems offering additional structural benefits.

Keywords-basalt fiber; steel fiber; glass fiber; torsional strength; stirrups

I. INTRODUCTION

Concrete is subject to damage due to cracking caused by the shrinkage and expansion, earthquakes, etc. This weakness allows water to infiltrate the structure, leading to the rust expansion of the reinforcing bars and decreased structural integrity. Torsion is important in Reinforced Concrete (RC) beams because it affects their strength and failure mode. The failure due to torsion and sheerness is undesirable as it occurs suddenly without warning. Torsion can represent a significant challenge in concrete structural elements, including eccentrically loaded beams, spandrel beams, and curved girders. These structural parts must withstand torsion, and the torsion design has gained significance in concrete construction [1, 2]. The development and application of new engineering materials serve as an essential driver for the innovation of engineering structures. Reactive Powder Concrete (RPC) is a fiber-reinforced, cement-based composite material with extraordinary strength and durability [3, 4]. Compared to conventional concrete, RPC demonstrates much higher tensile strength [5] and superior post-cracking performance [6]. Its improved ductility is mainly attributed to the fiber bridging effect across cracks, which can reduce the need for conventional reinforcement. However, the research on the torsional behavior of RPC beams remains limited. Authors in [7] investigated how different fiber types and lengths, including synthetic fibers and SF, influence the mechanical and structural performance of FRC. The results showed that fibers enhance the compressive, tensile, flexural, and torsional strengths, while also improving the crack control, ductility, and energy absorption under complex loading conditions, such as bending and torsion. The fiber length and distribution were found to play a critical role in performance. Authors in [8] examined the shear strength and structural behavior of High-Strength Concrete (HSC) beams reinforced with SF. The findings indicated that incorporating 0.75% hooked SF increased the shear capacity by about 13.2% while also improved the ductility, crack control, and energy dissipation. Similarly, authors in [9] focused on Ultra-High-Performance Concrete (UHPC) deep beams reinforced with SF and BF. The results revealed that SF generally enhances the shear strength and ductility, while BF delays the crack initiation and propagation, providing a more sustainable and environmentally friendly reinforcement option.

The research on the torsional performance of UHPC beams remains limited compared to the studies on the flexural and shear behavior [10, 11]. Moreover, most existing studies on RPC beams have primarily focused on the role of SF in the torsional performance [12-14]. Incorporating different fiber types in suitable proportions may further enhance the overall properties of concrete, producing high-performance composites. This approach, known as hybridization [15-17], has gained increasing attention. Several studies have investigated the use of fibers as partial or complete replacements for transverse reinforcement in RC beams. However, only a few have examined the combined effects of the fiber dosage and length on the torsional behavior in beams without transverse reinforcement. For example, authors in [18] studied concrete beams reinforced with hooked SF of varying lengths (13 mm, 35 mm, and 60 mm) and dosages (0%, 0.5%, 1%, and 1.5%). It was demonstrated that adding SF significantly improved the compressive, tensile, flexural, and torsional strengths compared to the control specimens. The beams with 1% and 1.5% fibers exhibited notable gains in the crack resistance, ductility, and energy absorption, effectively replacing the conventional stirrups in torsion-loaded beams. Furthermore, shorter fibers (13 mm) provided better distribution and bonding, leading to improved mechanical performance and more ductile failure modes. Similarly, authors in [19] demonstrated that SF enhance the torsional strength, ductility, and crack control, particularly in beams lacking adequate conventional reinforcement. The findings of [20] further exhibited that UHPC beams without SF fail in a brittle manner under torsion, whereas those with SF fail more gradually, showing clear warning signs, such as spiral and diagonal cracking. Authors in [21] examined large-scale RC beams under pure torsion, comparing different fiber volumes and reinforcement configurations. The results confirmed that even moderate SF amounts can improve the post-cracking torsional capacity, stiffness, and ductility, while also reducing the stiffness degradation after cracking. These improvements indicate that SFRC can effectively substitute for minimum transverse reinforcement, offering both structural and economic advantages.

II. RESEARCH SIGNIFICANCE

Research on the torsional properties of RPC beams remains limited in literature. This study addresses this gap by examining the structural behavior, cracking patterns, failure modes, cracking torsional strength, and ultimate torsional strength of RPC beams without transverse reinforcement. The investigation focuses on the effectiveness of fibers as substitutes for torsional stirrups, their role in enhancing the torsional performance, and the resulting failure mechanisms. These insights are essential for developing design approaches that incorporate RPC in torsion-resistant structures. To achieve this, six concrete mixtures with different fiber types and dosages were tested under pure torsional loading, with fibers serving as a full replacement for transverse reinforcement.

III. MATERIAL PROPERTIES

The production of RPC involved the use of GF, BF, and SF, as illustrated in Figure 1. The properties of the fibers are detailed in Table I. As shown in Table II, this study incorporated varying quantities and percentages of fibers into the concrete to modify its characteristics. The samples were formulated using ordinary Portland cement, sand, silica fume, and fibers. The concrete composition is presented in Table III. Additionally, the overall water-to-cement ratio for all combinations was maintained at 0.15. Reinforcement bars with a diameter of 6 mm were utilized. The results of the ultimate and yield strengths of the used bars are displayed in Table IV.

(a) (b) (c)

Fig. 1. (a) GF, (b) SF, (c) BF.

TABLE I. PROPERTIES OF DIFFERENT FIBER TYPES

Fibers	Length (mm)	Dimeter (mm)	L/D	Density (kg/m^3)	Tensile strength (GPa)	Modulus of elasticity (GPa)	Elongation (%)
GF	12	0.013	923	2680	1.7	72	2.3
BF	6	0.017	352	2700	2.6	91	3.1
SF	12	0.22	54.54	7850	2.4	200	4

TABLE II. BEAM DESIGNATION ACCORDING TO FIBER TYPE

Specimens	Longitudinal reinforcement		Fiber component (as a proportion of the concrete volume)		
			BF (%)	SF (%)	GF (%)
B1	169	57	–	–	–
B2-1	169	57	1	–	–
B3-1	169	57	–	–	1
B4-1	169	57	–	1	–
B5B-1	169	57	0.5	0.5	–
B6B-1	169	57	0.5	–	0.5

TABLE III. COMPONENTS OF CONCRETE MIXTURES

Beams	Cement (kg)	Water (L)	Fine sand (kg)	Silica fume (kg)		HRWR (L)	BF (kg)	SF (kg)	GF (kg)
B1	24.75	4.5	29.25	6	5.25	1.125	–	–	–
B2-1	24.75	4.5	29.25	6	5.25	1.125	0.85	–	–
B3-1	24.75	4.5	29.25	6	5.25	1.125	–	–	0.63
B4-1	24.75	4.5	29.25	6	5.25	1.125	–	2.36	–
B5B-1	24.75	4.5	29.25	6	5.25	1.125	0.424	1.181	–
B6B-1	24.75	4.5	29.25	6	5.25	1.125	0.424	–	0.318

TABLE IV. STEEL BARS' TENSILE STRENGTH

Bar diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)
6	468.63	481.7

A. Geometric Characteristics of Specimens

The stirrups and longitudinal reinforcement are made from deformed steel bars that have a diameter of 6 mm. The configuration and physical characteristics of the supplement are depicted in Figure 2.

B. The Process of Casting and Curing of Concrete

At the University of Technology Civil Engineering Department Laboratory concrete was produced. Three layers of concrete were poured into the formwork, and each layer was crushed by electric vibration. Before being removed from the formwork, the beams were kept in the lab for 48 h during which the curing process started. The samples in the trays were taken out after 48 h and were allowed to air-dry for around 5 h. After that, the samples were placed in a hot water bath set at 60°C for 28 days. Subsequently, the specimens were taken out of the water and saved at room temperature until the testing date, which was 75 days after casting. Figure 3 shows the procedures for getting the samples ready.

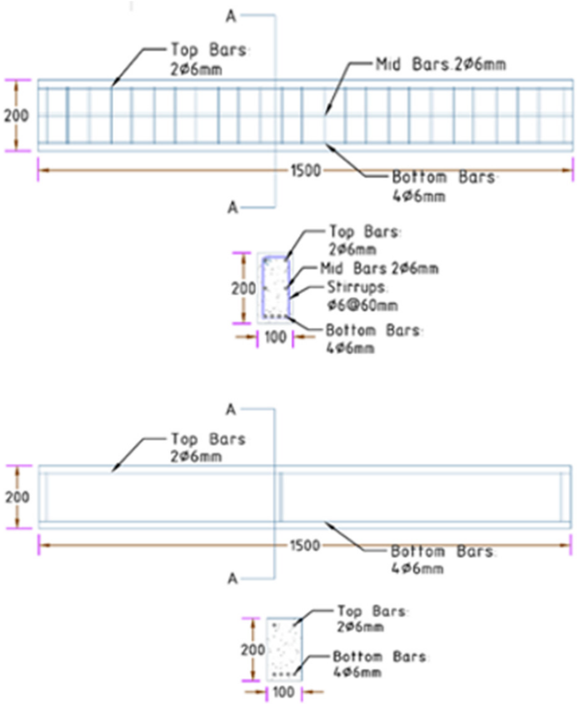

Fig. 2. Geometric properties of specimens.

Fig. 3. Specimen preparation steps.

C. Loading Condition and Test Setup

The University of Technology Laboratory analyzed the torsion of all beams before they failed. The loads were transferred to the test bench via a hydraulic system with a capacity of 2000 kN, as illustrated in Figure 4. Two-point loads were placed at the ends of the beams using a steel beam with a depth of 300 mm and a length of 3.5 m that was inclined at a 45-degree angle, as portrayed in Figure 5. The beam arms had predetermined locations and could withstand a maximum force of 300 kN in the longitudinal axis. To create pure torque, the center of support had to be situated near the middle of the lever's arm. During the experiments, the primary metrics of the structural behavior of the beams were documented at each loading position. In each experiment, the first crack was recognizable to the human eye based on the recorded torsion angle (φ), the capacity for torsion, and the maximum capacity for torsion. The distribution was scheduled over a specific period. The measurements were taken with extreme care every 0.2 kN of extra weight. Additionally, fissures were present at every level. The torsion force increased at a slow rate until the beam was overthrown. The decrease was accompanied by a decrease in the capacity to bear weight as the beam's rotation increased.

Fig. 4. Machine test.

Fig. 5. The arms and IPE section.

IV. RESULTS AND DISCUSSION

This research involved testing six rectangular concrete beams under pure torsion to investigate the efficacy of the fiber dose as a substitute for the absence of transverse reinforcement. The test results are analyzed using many parameters, including cracking patterns, torque rotation diagrams, cracking, ultimate torque capacity, and failure mechanisms.

A. Failure Mode and Crack Pattern

The control beam (B1) exhibited a typical torsional failure mode, as shown in Figure 6. The first crack appeared diagonally, spiraling around the tested section toward mid-span, with an angle of approximately 45°. As loading progressed, significant transverse cracks formed on all sides of the beam and expanded in opposite directions until failure occurred, indicating a ductile failure mechanism. The angle between the primary crack and the beam's longitudinal axis was measured at 52°. In contrast, the FRC beams displayed distinct crack patterns and failure behaviors. The five fiber-reinforced specimens showed broadly similar responses. During the pre-cracking stage, the torsional angle increased gradually and almost linearly with the applied torque. Once the surface stress reached the crack strength of RPC, the fibers began to separate from the matrix, and one or more cracks appeared on the beam's surface. These cracks generally formed at an angle of about 45° to the beam's longitudinal axis, complying with the findings in [15].

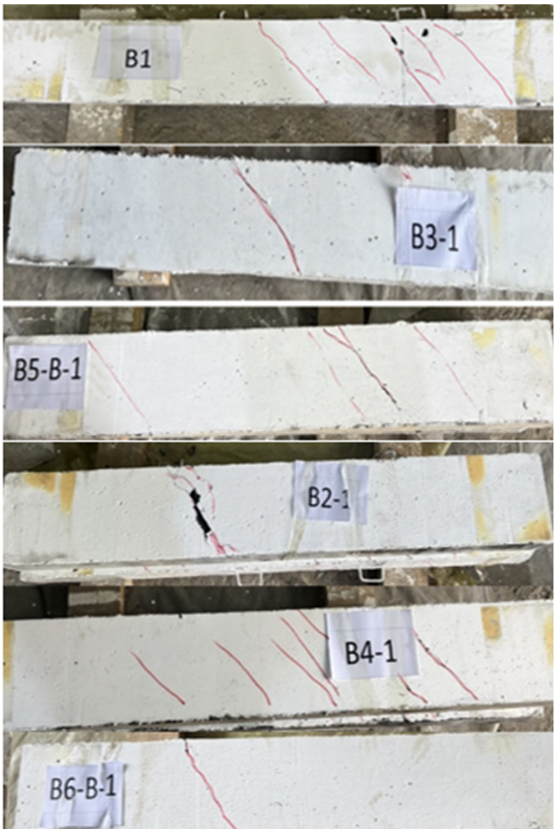

Fig. 6. Specimens that have failed due to torsional loading.

B. Torsional Moment -Angle of Twist

This study exposed six RC beams to pure torsion and loaded them until deformation occurred. Figure 7 illustrates the relationship between the torque and the twisted angle of the beams. A comparative analysis of the torsional behavior of the FRC beams with that of the control beam is shown in Table V. The relationship between the ultimate torsional moment (Torque kN·m) and the angle of twist (rad per length) is also demonstrated. Figure 8 displays the torsional response of the control beam, which has transverse reinforcement but no fibers, along with the respective FRC beams, which lack transverse reinforcement but incorporate fiber dosages.

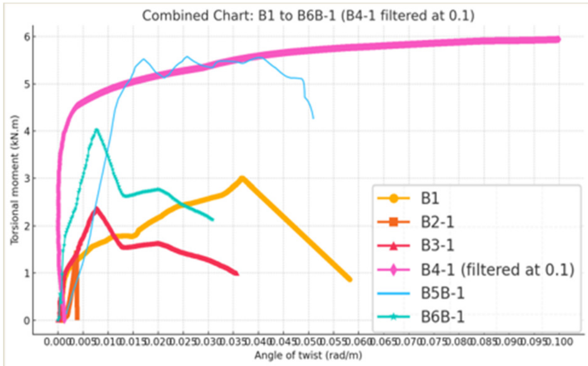

Fig. 7. Torsional moment-angle of twist relationship of specimens.

Adding 1% of BF and GF reduced the torsional moment by 53% and 14%, respectively. This is because of the limited toughness, poor bonding of BF, and a lack of stiffness of GF, but when 1% of SF was added, the torsional moment improved by 106%. Using HF content significantly enhanced the maximum torsional moment of the specimens. Incorporating the fiber of the (B5B-1) and (B6B-1) enhanced the torsional moment strength by 83.2% and 29.6%, respectively, compared to specimen B1. Utilizing more than one type of fiber will increase the durability and improve the concrete strength and stiffness [22]. Despite the limited experimental data portrayed in Figure 8, which presents just five tested beams, these comparisons suggest that the fibers could potentially serve as a substitute of the stirrups in torsional beams. The experimental curves in Figure 8 indicate that this substitution can be achieved under certain conditions, provided that an adequate number of fibers are used. To fully replace traditional shear reinforcement with fibers, the fibrous concrete beams must perform at least as well in terms of strength and ductility as their conventionally reinforced counterparts. Regarding strength, it is feasible to attain equivalent values by incorporating the appropriate percentage of fibers. However, the ductility characteristics differ when using fibers compared to traditional steel reinforcement. Fibers tend to exhibit a slow pull-out behavior, which is less effective when significant shear crack widths occur. In contrast, traditional steel reinforcement can accommodate more plastic deformation.

TABLE V. SUMMARY OF THE EXPERIMENTAL RESULTS

Beams	Tcr (kN.m)	Θcr (rad/m)	Tu (kN.m)	Θu (rad/m)
B1	0.89	0.00113	3.1	0.035
B2-1	1.16	0.055	1.44	0.003
B3-1	1.87	0.048	2.66	0.007
B4-1	3.26	0.036	6.39	0.07
B5B-1	1.7	0.049	5.68	0.039
B6B-1	2.5	0.027	4.02	0.007

V. CONCLUSIONS

The results of this study present the torsional behavior of six RPC beams tested experimentally. The investigation evaluates the effect of replacing transverse reinforcement with fibers, and the following conclusions are drawn:

- The cracking and ultimate torques of the Ultra-High-Performance Concrete (UHPC) beams with hybrid fibers from Basalt Fibers (BF) and Glass Fibers (GF) exceeded those of the beams with a single type of fiber, showing useful hybrid effects. The hybrid use of fibers significantly enhanced the torsional performance of UHPC beams.
- Steel Fibers (SF) enhance the post-cracking rigidity and provide a more uniform progression of cracking compared to a traditional Reinforced Concrete (RC) beam. This effect enhances the performance at serviceability limit states.
- B2-1 and B3-1, using single fibers, showed a minimal enhancement or even a decrease in contrast to B1.
- The control beam (B1) exhibited a typical torsional failure mechanism, with diagonal fractures propagating in a spiral pattern. In contrast, the fiber-reinforced beams developed distinct crack patterns, generally characterized by a dominant major crack.

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