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Research Article

Polypropylene Fibers for 3D Brace-Reinforced Concrete

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Abstract

This study proposes an innovative procedure for incorporating polymer fibers into concrete with the objective of enhancing its structural performance and durability. The integration of polymer fibers into advanced composite materials is driven by two primary objectives: first, to enhance the mechanical properties of the composite, and second, to reduce the carbon footprint associated with the conventional production of concrete. This novel approach, entails not only the development of enhanced mechanical properties but also the pursuit of sustainability, thereby facilitating a reduction in the carbon footprint associated with the production of conventional concrete. The study also explores the potential of fibers, beyond mechanical properties and in acoustic emission thus expanding the areas of benefit for sustainable construction. Through a detailed experimental investigation, this work assesses the performance of polymer fibers under various stress conditions, establishing new thresholds that could inform industry standards.

Keywords: *3D Concrete Reinforcement, Discontinuous Fibres, Fibre Reinforced Concrete, Mechanical Strength, Polypropylene Fibres.*

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1. Introduction

The advent of advanced materials in construction signifies a paradigm shift in addressing long-standing challenges, such as cracking and environmental degradation, which often compromise traditional concrete (Neville, 2003). These materials are engineered to enhance the durability and lifespan of concrete structures by reducing porosity, thereby bolstering resistance to chemical attacks. Additionally, the incorporation of recycled components in these composites contributes to sustainability, thereby reducing the carbon footprint associated with conventional concrete production (Lakshmi et al., 2022; Nandagiri et al., 2022).

Through the integration of advanced polymers and nanotechnology, these materials also minimize lifecycle maintenance costs by offering superior resilience against environmental stressors, including extreme temperatures and chemical exposure. This approach not only reduces the need for frequent repairs but also aligns with modern environmental objectives by lowering emissions linked to concrete manufacturing (Naser et al., 2019; M. Wu et al.,2012). As urbanization accelerates, the demand for durable, sustainable construction materials has become increasingly urgent, highlighting the ongoing necessity for innovation and research in this field (Kakooei et al., 2012; P. Patel et al., 2011).

2. Materials

Two distinct sizes of polypropylene fibers were utilized as reinforcement: Polypropylene fiber braid and standard commercial PP fibers (**Figure 1**). The fibers employed in the present experimental study were selected due to their status as commercial products currently utilized in industry as materials to enhance the adhesion of mortar in construction applications. The fibers were employed at a percentage of 0.9% w/w. These percentages were selected based on the conventional percentages of fibers already employed in reinforced mortars for crack control and elasticity enhancement (Feng et al., 2019; Karimi & Mostofinejad, 2020). The polypropylene fibers were procured by the company DOMYLCO. The characteristics of the fibers are enumerated in **Table 1**.

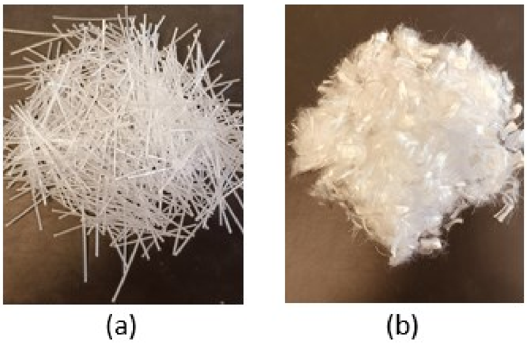

Figure 1. a) Polypropylene Fiber Braid (FB), b) Standard Commercial Polypropylene Fibers (PF).

Table 1. Characteristics of the Fibers Used in Concrete Samples.

Fibers	Length (mm)	Tensile Strength (MPa)	Water Absorption (%)
Polypropylene Fibers Braid (FB)	48.5	600	0.01
Standard Commercial Polypropylene Fibers (PF)	19	400	0.01-0.02

3. Methods

Proportions of the Materials in the Concrete Mix Design

In accordance with the guidelines outlined in ACI 211.2, the concrete mix was meticulously designed using a volumetric approach to achieve a target 28-day compressive strength of 30 MPa. The maximum aggregate size selected for this study was 12.5 mm, with a target slump of 75 to 100 mm. Samples were prepared at the research level, using Portland-type cement to produce C30/37-grade concrete specimens. The constant water-to-cement ratio of 0.54 was maintained in all samples. The primary variable in the mix design was the incorporation of polypropylene fibers with varying lengths and diameters (Wong et al., 2007).

Table 2. Concrete Mix Design.

Constituent	Mass (kg/m^3)
Cement	346
Water	186
Sand	818
Aggregates	1030
Visco 6000	1.400
Polypropylene Commercial Fibers (PF)	2.160
Polypropylene Fibers Braid (FB)	2.160

The specimens were prepared with prismatic samples measuring 40x10x10 cm for mechanical strength testing, specifically designed for four-point bending tests, as well as 15x15 cm cubic specimens suited for compressive strength testing. All specimens were hydrated for 28 days at a controlled ambient temperature in hydration baths filled with potable water. The objective of this study is to evaluate the potential of polymer fibers to enhance structural durability, particularly in seismic regions where increased durability can significantly mitigate damage. A subsequent phase involved testing hybrid fiber blends consisting of standard commercial polypropylene fibers and polypropylene fibers braid to investigate whether a combination of polypropylene fibers could yield a balance in strength that single-fiber types could not achieve. Durability tests were also conducted to quantify the longevity and maintenance requirements of fiber-reinforced concrete.

Following the hydration period, a series of standardized tests were conducted on each specimen to assess its compressive, tensile, and flexural strength. This assessment was undertaken to ascertain the impact of fiber inclusion on the concrete's mechanical properties (Hosseinzadeh et al., 2023). The results obtained from these tests indicated enhancements in durability for specimens that incorporated polypropylene fibers. This finding underscores the potential for incorporating various types of recycled fibers in construction materials, thereby contributing to the development of safer, more durable structures that maintain structural integrity (Latifi et al., 2022).

Four-Point Bending Tests

The four-point bending test, which utilizes a bending needle to accurately measure flexural strength and fracture toughness, is a crucial method in material research. This test involves the application of a controlled force, enabling researchers to observe the material's behavior under stress, a critical aspect for understanding durability and assessing practical applications. A significant advantage of this method is its ability to mitigate the influence, of shear forces, thereby enabling more precise characterization of the sample's intrinsic properties. The data obtained from this test offer valuable insights that guide the development of material formulations with enhanced real-life performance (Chen et al., 2015; Shanbara et al., 2020). For the four-point bending mechanical strength test, an INSTRON 5967 device equipped with a 30 kN load cell and steel rollers positioned at four points was used. The displacement speed of the applied force was maintained at a constant rate of 0.08 mm/min. To measure the bending radius, an exoskeleton adapted to accommodate an extensometer was employed.

The preparation of the samples was conducted over the course of three days. During the initial 24 hour period, the samples were removed from the hydration bath to eliminate excess moisture, thereby enabling the precise attachment of the metal component that would interface with the extensometer sensor. The following day, each sample was meticulously cleaned, and all sides were measured to precisely locate the center point, where the metal piece was affixed using resin adhesive. Following a 24 hour period, the samples were prepared for the integration of the exoskeleton, and the four-point bending test was initiated.

Compression Tests

In order to estimate the maximum stress that a specimen can withstand, compression tests were conducted. These tests utilized a straightforward yet highly reliable method for evaluating concrete samples. Cubic specimens with dimensions of 15 × 15 × 15 cm were prepared. These specimens required minimal treatment beyond removal from the soaking bath a day prior and the recording of their dimensions before testing. Compression tests were conducted on three samples per specimen category to ensure statistical reliability.

This method provides a high level of accuracy by simulating in situ stress scenarios, yielding valuable insights into the structural integrity of materials under varying conditions (Thirumurugan & Sivakumar, 2013). Furthermore, the use of compression testing supports the development of advanced composite materials by enabling researchers to refine material properties effectively before transitioning to large-scale production.

4. Results and Discussion

Four-Point Bending Test Results

The four-point bending tests demonstrated a notable increase in strength for specimens reinforced with randomly oriented polypropylene fibers. The bending-elongation results indicated that samples incorporating fibers with diameters of 12 mm and 19 mm achieved double the strength compared to those without fibers. This substantial improvement can be attributed to the polypropylene fibers' capacity to distribute mechanical loads more effectively, absorbing stress and dispersing it across the composite. The variation in fiber diameter, particularly between 12 mm and 19 mm, underscores the substantial impact of fiber size on performance enhancement. The random orientation of the fibers augments the isotropic nature of the material, enabling it to withstand stress from multiple directions.

The four-point bending test gauged the deflection, demonstrating a two-fold enhancement in strength for samples incorporating randomly oriented polypropylene fibers. The results are presented in **Figure 3**, with the unreinforced sample strength indicated in black at 10,929 N; the commercial polypropylene fibers, marked in red, achieving a maximum strength of 20,159 N; and the polypropylene fiber yield, in blue, reaching a strength of 13,989 N.

The collected data indicate that fiber yield contributed to a relative increase in flexural strength compared to the unreinforced specimen, though the increase was not substantial. Additionally, the figure shows that fiber-reinforced concrete containing polypropylene fibers exhibited an overall enhancement in flexural strength. The study further investigated fiber-reinforced concrete using a combination of these fibers. The findings suggest that fiber yield significantly reduced the flexural strength of polypropylene fiber-reinforced concrete, likely due to weak adhesion between the fiber types.

These findings reveal the critical role of fiber diameter in material strength and encourage further exploration of fiber orientation and distribution for performance tuning. Adjusting fiber arrangements systematically could enable the design of composites tailored to specific applications, suggesting the potential for customized solutions in projects with unique structural demands. A comprehensive understanding of the interplay between fiber size and orientation paves the way for innovation in material science, supporting the development of next-generation composites with unique properties (Hsie et al., 2008; Jusoh et al., 2015).

The synergistic effects of fiber diameter and orientation offer significant opportunities for optimizing tensile strength, flexibility, and other mechanical properties, depending on the application requirements. Incorporating polypropylene fibers necessitates an evaluation of their environmental impact, especially in the context of the global transition toward sustainable materials (Yin et al., 2019). Research into the recyclability and lifecycle of these composites is essential to assess their long-term viability and sustainability. Comparative studies with alternative fiber materials would also provide valuable insights, guiding material selection in future engineering projects.

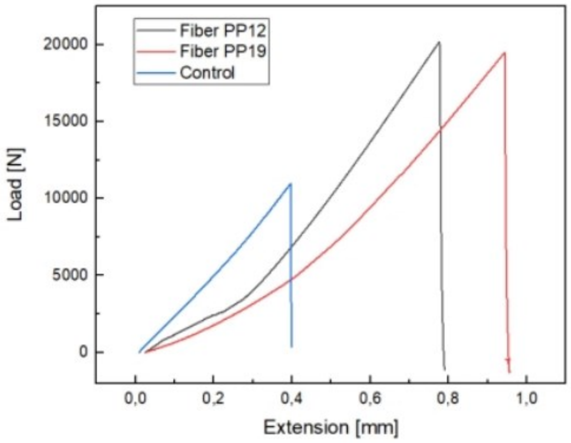

Figure 2. Diagram of the Four-Point Bending Test and Comparative Analysis of Control and Fiber-Reinforced Specimens.

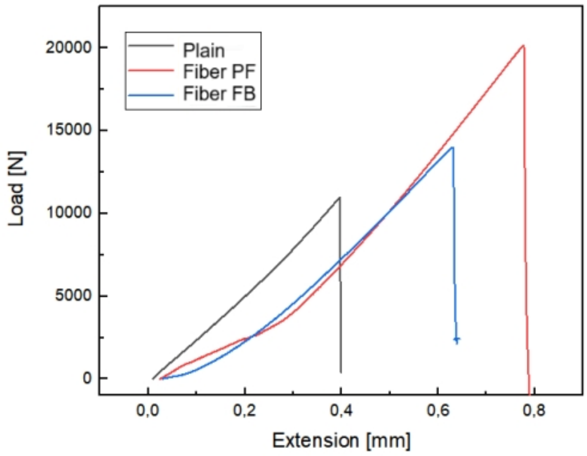

Figure 3. Diagram of the Four-Point Bending Test and Comparative Analysis of Control and Fiber-Reinforced Specimens.

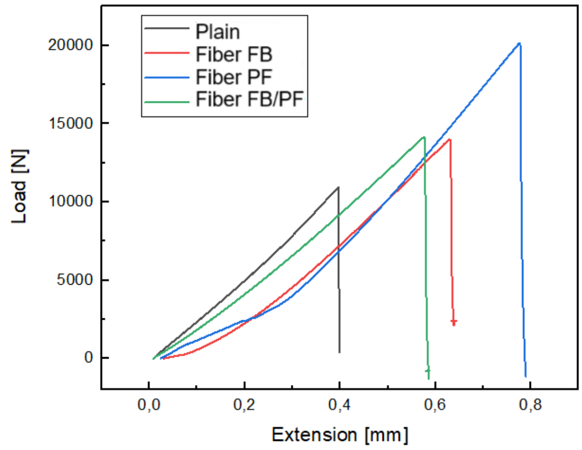

Figure 4. Diagram of the Four-Point Bending Test and Comparative Analysis of Control and Fiber-Reinforced Specimens.

Compression results

The findings from the compression tests demonstrate that the incorporation of polypropylene fibers into concrete specimens does not exert a substantial influence on compressive strength when compared to the control of concrete specimens. The outcomes of these tests are delineated in **Table 3**. The results of the compression tests suggest the feasibility of utilizing a combination of polypropylene fibers in concrete, as it results in a substantial enhancement in compressive strength. This indicates that not only is reinforcement provided but also the overall performance of the concrete is improved. The findings suggest that the synergy between polypropylene fibers within the concrete matrix is responsible for the enhanced performance observed. Consequently, it can be posited that while polypropylene fibers alone do not contribute meaningfully to compressive strength, their role in a hybrid fiber system may be more concerned with improving other mechanical properties such as ductility and cracking resistance. (Thirumurugan & Sivakumar, 2013; Yao & Zhong, 2007).

Table 3. Results of Compression Test in Concrete Samples.

Sample	Maximum Load Failure (kN)	Maximum compressive strength (MPa)
Plain	783.5	35.6
Commercial Fiber PP	761.1	34.8
Fiber Braid PP	1100.4	48.5
Commercial Fiber - Fiber Braid	1056.6	46.9

Polypropylene fibers have the potential to contribute to sustainable building practices by enhancing the durability of concrete structures, thereby facilitating the development of earthquake-resistant building designs. This can be achieved by incorporating fibers, which offer an economical method of enhancing the seismic resistance capability of a structure. Beyond enhancing ductility and mitigating crack development, the toughness of concrete members can be augmented by constraining the time-dependent development of micro-cracks due to environmental effects, a process facilitated by the presence of polypropylene fibers (Jusoh et al., 2015).

5. Discussions

The dispersion of polymeric fibers within concrete has been demonstrated to enhance its elasticity, thereby increasing the structure's resilience against dynamic loads and stresses (Anbuvelan et al., 2007). This enhancement in elasticity has been shown to improve the structural performance of the concrete, enabling it to effectively absorb and distribute forces, and consequently, reducing the probability of failure under tensile stress. Furthermore, the incorporation of polymeric fibers enhances crack resistance, thereby mitigating the risk of failure and extending the lifespan of concrete under various conditions (Y. Wu, 2002). This innovative concreting approach offers environmental benefits as well. By potentially reducing the amount of traditional reinforcement required, it can lower the structure's carbon footprint (Qian & Stroeven, 2000).

The enhancement of elasticity not only fortifies the concrete but also aids in curtailing or circumscribing the genesis and progression of microcracks, which are frequently the genesis of long-term structural vulnerabilities. Polymeric fibers adeptly disperse stress throughout the concrete matrix, thereby diminishing the likelihood of catastrophic failur (Kurtz & Balaguru, 2000; Y. Wu, 2002). From an economic perspective, the use of fibers in concrete reinforcement can result in cost savings over the structure's lifespan due to the enhanced durability, which can reduce the need for maintenance and repairs. This advantage is particularly relevant for high-load applications where durability and longevity are paramount (Manolis et al., 1997).

Polymeric fibers increase the elasticity of concrete, enabling it to withstand various stress factors without cracking, thereby enhancing its resilience under different types of pressure. Additionally, the incorporation of these fibers provides substantial protection against environmental influences, such as freeze-thaw cycles and chemical exposure, making them particularly well-suited for structural applications in harsh climates (Bayasi & Zeng, 1993; Brown, 1955).

6. Conclusions

Finally, it should be noted that the incorporation of short, discontinuous fibers dispersed randomly into composite cementitious materials has been shown to enhance the mechanical behavior of the material substantially (Selvi & Thandavamoorthy, 2013). Specifically, flexural strength was found to increase by 25%, while the elongation increased by 50% in comparison with unreinforced concrete. Additionally, increased strength was observed in fiber-reinforced specimens under uniaxial loading. These outcomes underscore the structural support provided by polymeric fibers along the three axes, considering the phase distribution. The findings may serve as a foundation for future advancements in the field of fiber-reinforced concrete and may inform further investigations aimed at expanding the knowledge base and professional expertise (M. J. Patel & KULKARNI, 2013; Ramujee, 2013).

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