

Crack Behaviour of Polypropylene Fiber Reinforced Concrete

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Abstract

Polypropylene (PP) fiber reinforced concrete has emerged as a promising solution to enhance the crack resistance and overall mechanical properties of concrete. Cracks in concrete structures can compromise their structural integrity, durability, and serviceability. Therefore, it is crucial to understand and mitigate the crack behaviour in concrete to ensure the long-term performance of structures. This study aimed to determine the effect of crack behaviour and evaluate the flexural strength of reinforced concrete with different percentage of PP fiber. 12 concrete beam specimens with dimensions of 150 mm width, 150 mm height and 600 mm length were manufactured and tested. The test examined concrete samples with varying percentages of PP fiber 1.0%, 1.5%, and 2.0%, while maintaining a constant water-to-cement (w/c) ratio of 0.5. The concrete beam specimens were tested for flexural strength at 28 days. The investigation revealed that the crack behaviour, particularly in terms of crack width control, is optimized at a 1.5% inclusion of PP fibers, achieving maximum loading with a notable value of 74.59 kN. In addition, result that obtained from flexural strength test, concrete beam that contained 1.5% of PP fiber is the optimum strength for this experiment. The experiment validates the hypothesis that PP fiber reinforcement can enhance the material's structural performance by showing the beneficial effects of crack behaviour and flexural strength of concrete.

1. Introduction

The use of concrete in construction is widespread due to its high compressive strength and durability, but it tends to become brittle under tensile stresses, leading to cracking and potential structural compromise (Gagg, 2014). Polypropylene (PP) fiber-reinforced concrete has emerged as a promising solution to enhance tensile strength, ductility, and fracture resistance (F. Shi, 2020). The type, dosage, distribution, and loading conditions impact fiber-reinforced concrete's cracking behavior. The addition of fibers improves properties such as toughness, impact strength, tensile strength, and flexural strength. Polypropylene fiber reinforced concrete is recognized as a promising solution for better crack control in concrete structures (Yanzhu Liu, 2021). Despite these advancements, further investigation is needed to understand the specific impacts of fiber reinforced concrete on crack patterns and behavior, including exploring the influence of varying percentages of polypropylene fiber on crack behavior in concrete. The research aims to evaluate the crack behavior and determine the flexural strength of concrete with different percentages of polypropylene (PP) fiber. Three prism units containing PP fiber at 1.0%,

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1.5%, and 2.0% are compared with three control samples of 150 x 150 x 600 mm size. The specimens undergo testing after a 28-day curing period, and the flexural strength is assessed using a four-point loading test. The distinctive feature of Fiber Reinforced Concrete (FRC) is its significant residual strength after breaking. The addition of polypropylene (PP) fiber to the concrete mix is shown to effectively control crack behavior. In general, incorporating fibers in concrete enhances its resistance to both the formation and propagation of cracks. The studies focus on investigating the crack behavior of PP fiber-reinforced concrete and determining flexural strength across different percentages of PP fiber.

2. Literature review

Polypropylene (PP) fiber is a synthetic reinforcement material widely used in concrete and construction. Derived from the thermoplastic polymer PP, known for its lightweight and durable qualities, these fibers are cost-effective, non-corrosive, and non-magnetic. When added to concrete mixes, PP fibers enhance various mechanical characteristics, including flexural strength, crack resistance, and durability. This reinforcement is particularly beneficial in preventing cracking due to factors such as shrinkage, temperature changes, and external loads, ultimately improving the overall performance and lifespan of concrete structures. Research indicates that adding PP fibers significantly reduces the likelihood of shrinkage cracks in concrete, addressing a common issue during drying and curing (Hossein Mohammadhosseini et al, 2020). PP fiber-reinforced concrete exhibits superior post-cracking behavior and ductility compared to regular concrete, effectively distributing stresses and bridging cracks due to its high tensile strength and flexibility. Properties of polypropylene fiber is shown in Table 1.

Table 1 Properties of Polypropylene Fiber (Ravinder, 2019)

Properties of fiber	Value
Material	Virgin Homo Polymer
Length	45 mm
Type/Shape	Macro/monofilament
Color	White
Specific Gravity	0.91
Acid and salt resistance	High
Tensile strength	620-758 MPa
Absorption	Nil
Fiber content	4-9 kg/m ³ of concrete
Melting point	164C (328F)
Young's modulus	3.5 kN/mm ²
Alkali resistance	Alkali proof

2.1 Flexural strength

Flexural strength, also called rupture modulus or bending strength, is the maximum stress a material can endure before cracking or breaking during bending. Concrete's flexural strength defines how it will behave when bending and deflecting or breaking with the least amount of flexural reinforcement (Mohd. Ahmed, 2016).

The three-point or four-point bending test is a common flexural test used to determine the flexural strength of a beam. In these tests, a beam specimen is loaded at specific locations along its length and supported at its ends. The flexural strength of the material is assessed by measuring the resulting deflection and the applied loads. The test involves applying a force to the beam, creating bending stresses, and analyzing the material's ability to withstand these stresses. Figure 1 shows the illustrations of three-point and four-point flexural test.

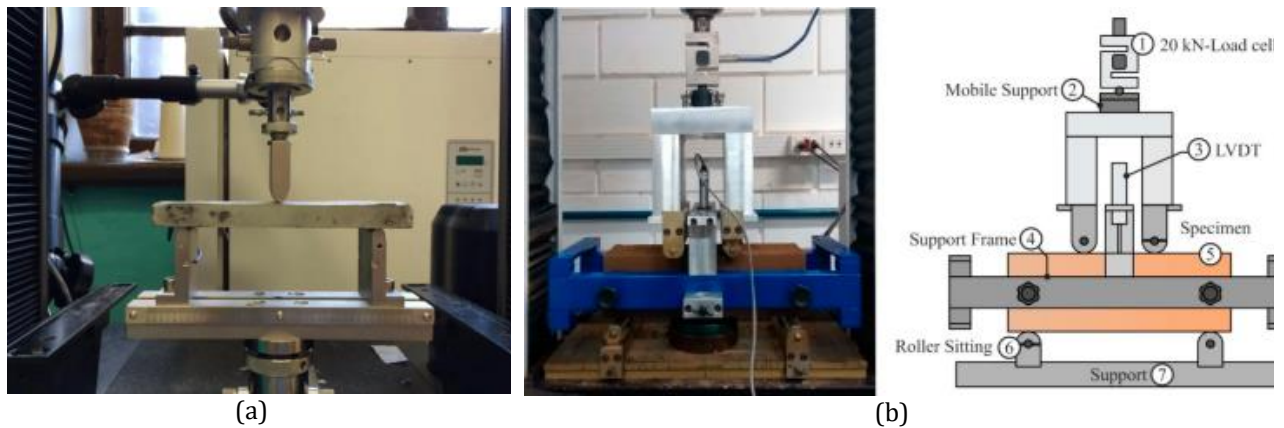


Fig. 1 (a) Three-point loading test (Anna Volkovaa, 2016); (b) Four-point loading test (Pedroso GOM, 2023)

The primary difference between three-point and four-point bending tests lies in the distribution of stress on the beam. In the four-point bending test, the addition of a fourth bearing maximizes stress on the section between the two loading points. Conversely, in the three-point bending test, only the material directly under the central bearing experiences maximum stress. This distinction is particularly important in the study of brittle materials, as it directly influences flexural strength and crack initiation based on the quantity and type of defects exposed to the highest stress.

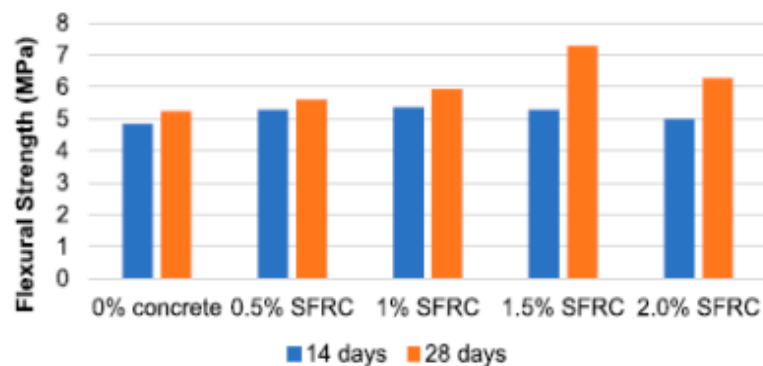


Fig. 2 Flexural strength against fiber content at 14 and 28 days curing period (Louis Du Preez, 2023)

As shown in Figure 2, the researchers found that flexural strength increases with fiber content up to 1.5% in Steel Fiber Reinforced Concrete (SFRC). However, at 2.0% SFRC, flexural strength decreases compared to 1.5% SFRC, although it remains higher than the flexural strength of the reference sample. The most significant strength improvement, amounting to 39%, was observed in 1.5% SFRC after a 28-day curing period.

2.2 Flexural crack

Flexural cracks result from flexural stress when high flexural stress and mild shear stress are applied to beams. The control of these cracks can be achieved by providing appropriate tension reinforcement. Flexural tension typically occurs near the middle span of the beam, where the stress is the greatest. The bending moment is greatest towards the centre of the beam's span, where cracks caused by higher bending stress in beams (Słowik, 2019). These cracks are formed as a result of the tensile stress on the bottom of the beam. Flexural cracks are usually vertical and can be seen on the underside of the beam.

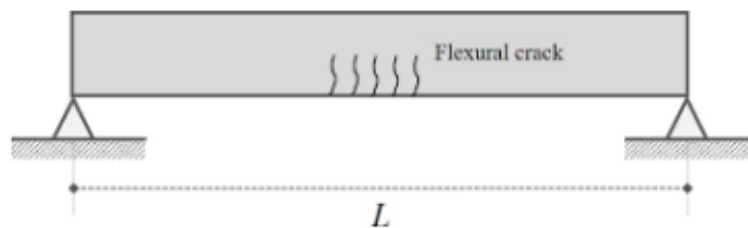


Fig. 3 Illustration of flexural crack

Fiber reinforced concrete (FRC) has been found to have a positive effect on the cracked pattern of concrete beams. The addition of fibers composition to concrete improves the tensile strength and controls the propagation of cracks in reinforced concrete (Govindasami, 2018). The existence of steel fibers inhibits crack propagation, decreases the width, length, and spacing of cracks (ÇANKAYA, 2023). The overall crack length increases as the fiber content increases, but the crack width varies along the crack length (Berrocal, 2016).

3. Material and experimental methods

3.1 Material

In this study, Type I Ordinary Portland Cement (OPC) was utilized, as depicted in Figure 4. Ordinary General Purpose Portland Cement, or OPC, is the most commonly employed type of cement. It is suitable for all applications when specific performance requirements, such as reduced sulfate exposure, are not necessary (ASTM C150:2019). Chemical composition is shown in Table 2.

Table 2 Chemical composition of the Portland Cement

Chemical analysis (%)	Portland Cement
Loss on ignition	4.40
Silica (SiO ₂)	18.08
Iron oxide (Fe ₂ O ₃)	2.43
Alumina (Al ₂ O ₃)	4.72
Calcium oxide (CaO)	61.94
Magnesium oxide (MgO)	2.54
Sulphur trioxide (SO ₃)	2.74
Alkali-sodium oxide (Na ₂ O)	0.18
Alkali-potassium oxide (K ₂ O)	0.99

Selection of aggregates aims for optimal strength, hardness, and durability. As per BS 882:1992, fine aggregates pass through a 4.75 mm sieve, while coarse aggregates are retained above No. 4 sieve. The standard specifies a maximum size of 20 mm for crushed coarse aggregates and a minimum size of 0.075 mm for fine particles.

This study utilized polypropylene fiber in proportions of 1.0%, 1.5%, and 2.0% by weight of cement. The ease of handling and incorporation, adaptability to different concrete mix designs, lightweight nature for even distribution, corrosion resistance, and strong adherence to the cement matrix are notable benefits of polypropylene fibers, contributing to improved crack behavior in the material. Figure 4 shows polypropylene fiber used in this study.



Fig. 3 Polypropylene fiber

3.2 Experimental design

The experimental concrete mix included 410 kg of cement, 205 kg of water, 190 kg of fine aggregate, and 965 kg of coarse aggregate in each variation with different fiber content, as indicated in Table 3. The amount of polypropylene fiber in each mix is determined as a percentage of the total weight of the cement.

Table 3 Varying polypropylene fiber content in experimental mix


Mix design	Polypropylene fiber (kg/m ³)
Controlled	0
1.0%	0.06
1.5%	0.09
2.0%	0.11

Beam specimens were made with size of 150 x 150 x 600 mm in order to conduct this research. The specimens were made to achieve M30 grade of concrete.

3.2 Preparation of the specimens

In this study, concrete beam samples measuring 150 mm x 150 mm x 600 mm were used, with a minimum of 12 samples for testing, each having varying percentages of polypropylene fiber. The total volume for M30 concrete was 0.014 m³ for each percentage. Batching was done using an electric mini concrete mixer, where coarse aggregate, fine aggregate, cement, and water were mixed for a specific duration.

Table 4 Procedure of beam specimen

Steps	Description
1 	The mould was made by wood with size of 150 x 150 x 600 mm. Then, applying mould, the surface needed to be greased.

2



The main reinforcement bars should be 10 mm in size, while the links should be 6 mm. Spacing between links was about to 100 mm.

3



Reinforcement bars, providing a 30 mm concrete cover, were placed in the mold and secured using steel wire. The mold was then filled with concrete from the mixer, ensuring proper compaction with a tamping rod to eliminate air bubbles.

4



After 28 days has reached, carefully remove the mould. Painted the beam with white colour on both sides and draw a gridline on the surface for reference.

3.3 Four-point flexural test

Flexural strength is the capacity of a reinforced concrete beam to withstand bending due to applied stress. For every test beam, a four-point flexural test was used. The test set up is illustrated in Figure 4. Following the curing period, the specimens were subjected to the four-point flexural test. The ASTM C1609/C1609-12 universal testing machine (UTM) was used to conduct the test. As seen in Figure 5, the beams were centered and oriented parallel to the rollers seating support.

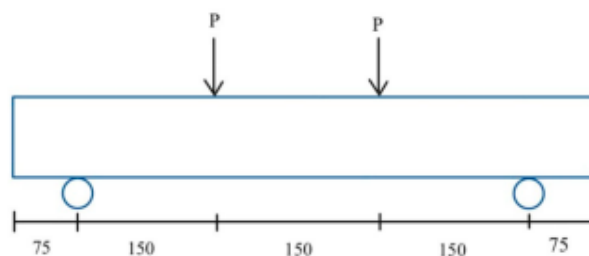


Fig. 4 Test set up for overall specimens

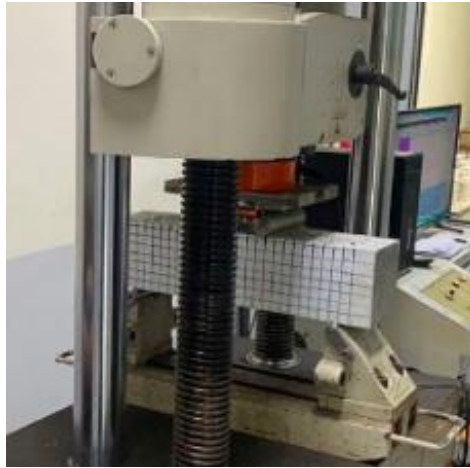


Fig. 5 Four-point loading test machine with beam

For the maximum load applied on concrete by testing machine, the formula in equation (1) was used to determine the flexural strength of concrete.

$$F = PL / bd^2 \quad (1)$$

Where F is flexural strength (N/mm²), P is load at the fracture point (N), L is length of the support span (m), b is width of the concrete and d is thickness of the concrete (mm).

4. Result and Discussion

4.1 Four-point flexural test

The ability of a reinforced concrete beam to withstand bending as a result of an applied load is referred to as flexural strength. The formula in equation (1) is used to compute the flexural strength of concrete specimens, which is based on the greatest load applied, as stated in Table 5. Figure 6 also includes a calculation and tabulation of the flexural strength results.

Table 5 Maximum load applied and the corresponding flexural strength

Specimen	Polypropylene fiber (kg/m ³)				Flexural strength (MPa)
	1	2	3	Average	
Controlled	58.71	57.93	58.22	58.29	7.77
1.0%	64.77	64.29	65.31	64.79	8.64
1.5%	74.59	73.88	74.81	74.53	9.94
2.0%	61.87	62.19	62.85	62.30	8.31

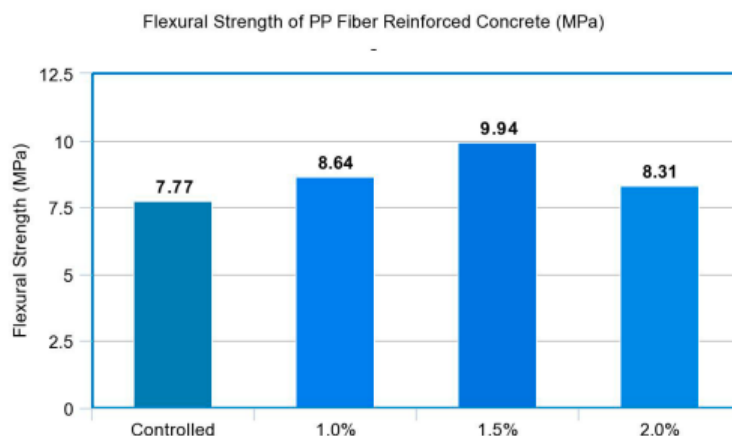


Fig 6 Flexural strength of polypropylene fiber reinforced concrete

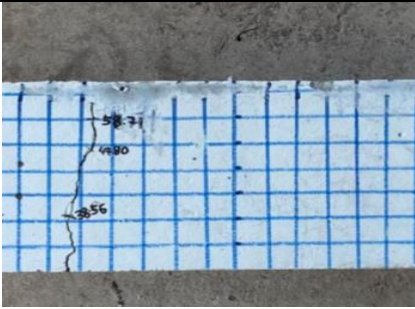
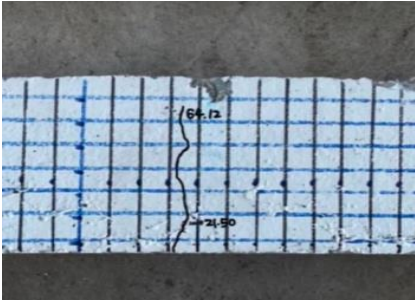
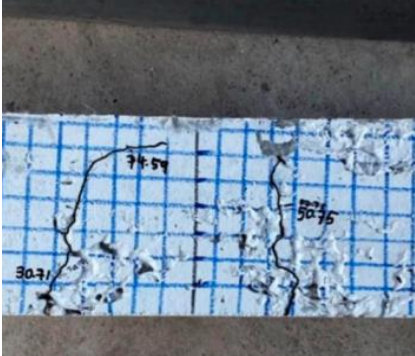
The graph depicts a positive correlation between polypropylene (PP) fiber content and flexural strength in concrete. Introduction of 1.0% PP fibers results in an increase to 8.64 Mpa, indicating reinforcement. At 1.5%, flexural strength further rises to 9.94 Mpa, showcasing enhanced resistance to bending stresses. The peak strength is achieved at 1.5%, suggesting an optimal balance. Surprisingly, at 2.0%, a slight decrease to 8.31 Mpa occurs, possibly due to fiber-related issues. Overall, careful consideration of fiber content is crucial, with an optimal balance observed at 1.5% for desired mechanical properties in PP fiber reinforced concrete for flexural applications.

4.2 Crack pattern and mode of failure

Initially, under loading, tiny cracks emerge, often concentrated around stress points like the mid-span of the beam. As the load increasing, these failures propagate, extending and merging into larger cracks that traverse the concrete's surface. The presence of polypropylene (PP) fibers alters the crack pattern, offering increased resistance to crack propagation and controlling the width of cracks.

Regarding the mode of failure, flexural failure, often observed in beams, happens when the concrete cannot withstand bending stresses, leading to fracture along the beam's span. Understanding both crack patterns and failure modes is essential for assessing the structural integrity and performance of concrete beams in practical applications.

Table 6 Mode of failure of the specimen

	Steps	Description
Controlled		The first crack at the mid-span when subjected to a load of 38.56 kN. As the load increased, the crack propagated upwards, reaching the top of the beam at a maximum load of 58.1 kN.
1.0%		The initial fracture emerged at 21.5 kN, advancing to the top of the beam until reaching failure at 64.12 kN.
1.5%		The width of the fracture for the beam with 1.5% PP fiber reached the top at 74.59 kN.

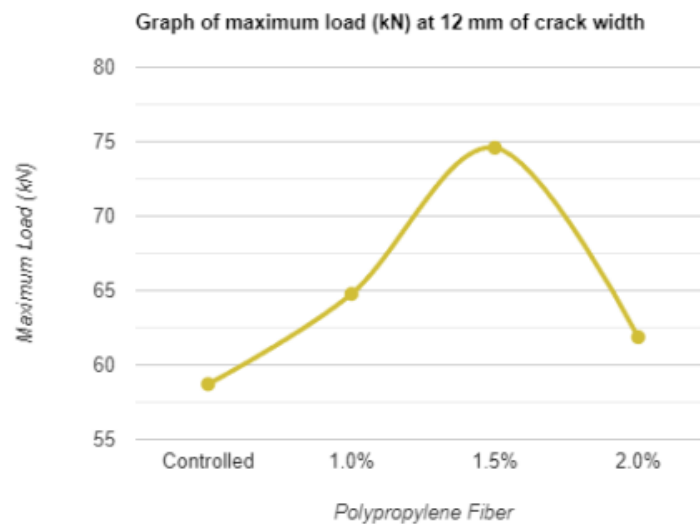
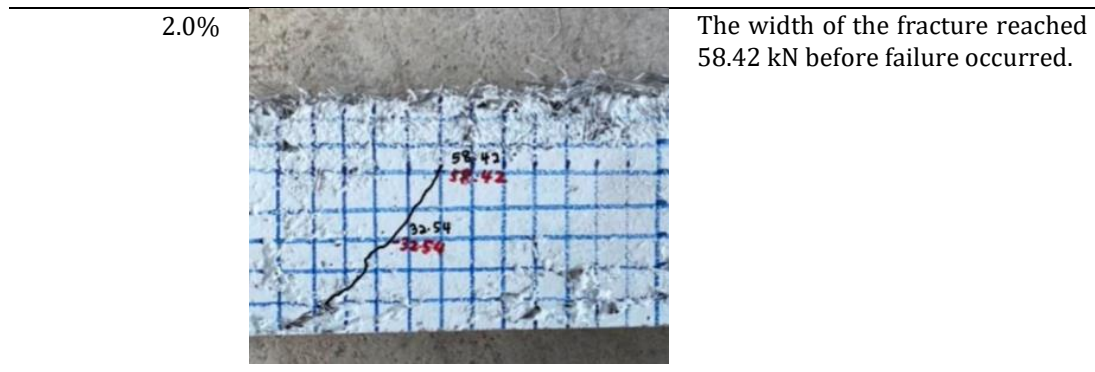


Fig. 8 Graph of maximum load (kN) at 12 cm of crack width

The results show that the addition of polypropylene (PP) fiber significantly influences crack patterns and behavior in concrete beams. A lower percentage, 1.0%, demonstrates enhanced crack resistance and delayed failure, while a higher percentage, 1.5%, further improves crack control. However, the balance is observed with 2.0% PP fiber content, indicating that excessive fibers might lead to a less favorable crack pattern. This observed variation in crack patterns is attributed to the reinforcing function of PP fibers within the concrete matrix, forming a network that enhances load distribution and transfer. The findings suggest an optimal percentage of 1.5% PP fibers that maximizes crack control and load-carrying capacity.

5. Conclusion

In conclusion, the investigation into crack behavior in polypropylene (PP) fiber-reinforced concrete, incorporating varied fiber percentages, reveals valuable insights. Experimental results highlight the influence of PP fibers on crack patterns, with an optimal percentage of 1.5% showing effectiveness in enhancing concrete's resistance to cracking under bending loads. While overall crack behavior improves with PP fibers, careful consideration of the percentage is crucial, as higher levels may reduce mechanical properties. PP fibers play a role in controlling crack widths, acting as a barrier to prevent rapid widening and potential structural failure. The findings emphasize the importance of thoughtful fiber content selection for improved crack resistance and overall structural performance in fiber-reinforced concrete applications.

In summary, the investigation into flexural strength of polypropylene (PP) fiber-reinforced concrete reveals a notable improvement compared to controlled concrete. The data indicates that the inclusion of PP fibers enhances flexural strength, particularly at lower percentages. The results show that 1.5% PP fiber content in reinforced concrete achieves the highest flexural strength at 9.94 MPa. The experiment underscores the positive impact of PP fibers on concrete flexural strength, emphasizing their contribution to the material's structural performance.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

This journal requires that all authors take public responsibility for the content of the work submitted for review. The contributions of all authors must be described in the following manner:

*The authors confirm contribution to the paper as follows: **study conception and design:** Nuraisyah Amirah Md Esak; **data collection:** Nuraisyah Amirah Md Esak; **analysis and interpretation of results:** Nuraisyah Amirah Md Esak, Sallehuddin Shah Ayop; **draft manuscript preparation:** Nuraisyah Amirah Md Esak. All authors reviewed the results and approved the final version of the manuscript.*

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