



Flexural Behaviour of Reinforced Concrete Beams Cast with Hybrid Fiber Reinforced High-Strength Concrete Incorporating Steel, Coir and Palm

Fibers

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ABSTRACT

The brittle nature of high-strength concrete often limits its structural performance under flexural loading despite its superior compressive strength. The incorporation of hybrid fibers has emerged as an effective approach to enhance ductility, crack resistance, and energy absorption capacity of reinforced concrete members. This study investigates the flexural behaviour of reinforced concrete beams cast with hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers. Eight concrete mixes, including one control mix and seven fiber-reinforced mixes, were developed using M50 grade high-strength concrete. Reinforced concrete beam specimens were cast and tested under two-point loading to evaluate ultimate load capacity, load-deflection behaviour, flexural toughness, ductility, and crack propagation characteristics. The experimental results demonstrated that the incorporation of hybrid fibers significantly enhanced the structural behaviour of reinforced concrete beams. Among all the investigated mixes, the beam cast with Mix M4 containing 0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber exhibited the best performance. The ultimate load carrying capacity increased from 70 kN for the control beam to 90 kN, representing an improvement of approximately 28.6%. The hybrid fiber reinforced beams also exhibited higher deflection capacity, improved ductility, greater energy absorption, and reduced crack widths compared to conventional concrete beams. The presence of steel fibers effectively bridged macro-cracks, while coir and palm fibers contributed to micro-crack control and post-cracking toughness. The study concludes that the combined use of steel, coir, and palm fibers provides an effective and sustainable hybrid reinforcement system capable of significantly improving the flexural performance and structural behaviour of reinforced concrete beams.

Keywords: Hybrid Fiber Reinforced Concrete, High-Strength Concrete, Reinforced Concrete Beams, Flexural Behaviour, Ductility, Load–Deflection Response.

1. INTRODUCTION

High-strength concrete (HSC) is widely used in modern construction because of its superior compressive strength, durability, and reduced structural dimensions. However, HSC exhibits brittle behavior and limited tensile capacity, which may result in sudden failure under flexural loading. The development and propagation of cracks significantly influence the structural



performance of reinforced concrete (RC) beams, making ductility and crack control important design considerations. Fiber reinforcement has been recognized as an effective method for improving the behavior of concrete. Steel fibers enhance tensile strength, crack resistance, toughness, and post-cracking load-carrying capacity by bridging cracks within the concrete matrix. In recent years, natural fibers such as coir and palm fibers have gained attention due to their low cost, renewability, and environmental sustainability. These fibers contribute to improved toughness, energy absorption, and crack control while promoting the utilization of agricultural waste materials. Hybrid fiber reinforced concrete combines two or more types of fibers to exploit the advantages of each fiber type. The synergistic interaction between steel fibers and natural fibers can improve both strength and ductility. Steel fibers primarily control macro-cracks and enhance load-carrying capacity, whereas coir and palm fibers are effective in restricting micro-crack propagation and improving post-cracking behavior. Consequently, hybrid fiber systems have the potential to significantly enhance the structural performance of reinforced concrete members.

Several studies have reported improvements in flexural strength, toughness, and crack resistance of fiber reinforced concrete. However, limited research has been conducted on reinforced concrete beams incorporating hybrid combinations of steel, coir, and palm fibers. Furthermore, the influence of these fibers on load-deflection behavior, ductility, ultimate load capacity, and cracking characteristics of high-strength concrete beams remains insufficiently explored.

Therefore, the present study investigates the flexural behaviour of reinforced concrete beams cast with hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers. Beam specimens were tested under two-point loading to evaluate ultimate load capacity, load-deflection response, ductility, flexural toughness, and crack propagation characteristics. The study aims to identify the optimum hybrid fiber combination capable of improving the structural performance of reinforced concrete beams while promoting sustainable construction practices.

2. LITERATURE REVIEW

Banthia and Gupta (2004) investigated the behavior of hybrid fiber reinforced concrete and reported that the combination of different fiber types produced a synergistic effect, resulting in significant improvements in toughness, crack resistance, and post-cracking behavior compared to single-fiber reinforced concrete.

Ali et al. (2012) studied concrete reinforced with coir fibers and observed improvements in ductility, impact resistance, and energy absorption capacity. The researchers reported that coir fibers effectively controlled crack propagation and enhanced the post-cracking performance of concrete.

Yoo and Banthia (2016) reviewed the mechanical properties of fiber reinforced concrete and concluded that steel fibers significantly improve tensile strength, flexural strength, toughness, and crack resistance. Their study highlighted the effectiveness of steel fibers in delaying crack propagation and improving structural performance.



Turker et al. (2019) investigated the flexural behavior of ultra-high-performance concrete beams reinforced with hybrid fibers. The results showed that hybrid fiber reinforcement increased ultimate load capacity, reduced crack widths, and enhanced energy absorption characteristics compared to conventional concrete beams.

Zhu et al. (2021) conducted a comprehensive review on hybrid fiber reinforced cementitious composites and reported that the combination of steel fibers with natural fibers improved mechanical performance and durability. The study emphasized the importance of fiber hybridization in achieving balanced strength and ductility.

SulphiaBeevi et al. (2020) experimentally investigated hybrid fiber reinforced high-performance concrete and observed significant improvements in compressive strength, split tensile strength, and flexural strength. The researchers concluded that hybrid fibers provided better crack control and enhanced load-carrying capacity.

Hasan et al. (2025) examined natural fiber reinforced hybrid composites and reported that the incorporation of renewable fibers improved sustainability while maintaining satisfactory mechanical performance. Their findings highlighted the potential of natural fibers as sustainable alternatives in structural materials.

Khan and Abbas (2025) evaluated the structural performance of hybrid steel fiber reinforced concrete and found considerable improvements in ultimate load capacity, ductility, and crack resistance of reinforced concrete members. The study demonstrated the effectiveness of hybrid reinforcement in enhancing structural behavior. Although numerous studies have investigated steel fiber reinforced concrete, coir fiber reinforced concrete, palm fiber reinforced concrete, and hybrid fiber systems separately, limited research is available on reinforced concrete beams incorporating a hybrid combination of these fibers. Furthermore, the influence of these fibers on load-deflection behavior, ultimate load capacity, ductility, and crack propagation characteristics of HSC beams remains insufficiently explored. Therefore, the present study focuses on the flexural behaviour of reinforced concrete beams cast with hybrid fiber reinforced high-strength concrete incorporating these fibers.

3. MATERIALS USED

3.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used throughout the experimental investigation. The cement possessed adequate strength and fineness characteristics suitable for the production of high-strength concrete.

3.2 Fine Aggregate

Locally available river sand conforming to Zone II grading requirements of IS 383:2016 was used as fine aggregate. The sand was clean, free from deleterious substances, and suitable for the preparation of high-strength concrete.



3.3 Coarse Aggregate

Crushed granite aggregate with a maximum nominal size of 20 mm was used as coarse aggregate. The aggregates were tested for physical properties and found suitable for concrete production.

3.4 Silica Fume

Silica fume was incorporated as a supplementary cementitious material at 10% replacement of cement by weight. The inclusion of silica fume improved particle packing density, reduced porosity, and contributed to the development of high compressive strength.

3.5 Superplasticizer

A high-range water-reducing admixture conforming to IS 9103:1999 was used to improve workability while maintaining a low water-to-binder ratio. The admixture facilitated uniform fiber dispersion and proper compaction of concrete.

3.6 Steel Fibers

Hooked-end steel fibers were used as the primary reinforcing fibers. Steel fibers possess high tensile strength and modulus of elasticity, which improve crack resistance, load-carrying capacity, and post-cracking behavior of concrete. The fibers acted as effective crack-bridging elements during flexural loading of reinforced concrete beams.

3.7 Coir Fibers

Coir fibers obtained from coconut husk were used as natural fibers in the hybrid fiber system. These fibers possess high toughness and elongation capacity, enabling improved crack control and energy absorption. The incorporation of coir fibers also contributes to sustainable construction practices through the utilization of renewable resources.

3.8 Palm Fibers

Palm fibers collected from agricultural waste sources were used as secondary natural fibers. Palm fibers enhance toughness, ductility, and resistance to crack propagation. Their use promotes environmental sustainability by converting agricultural waste into a value-added construction material.

3.9 Reinforcing Steel

High-yield strength deformed (HYSD) steel bars were used as longitudinal reinforcement and stirrups in the reinforced concrete beam specimens. The reinforcement arrangement was designed to ensure flexural failure of the beams during testing

4. EXPERIMENTAL PROGRAM

4.1 General

The experimental investigation was carried out to evaluate the flexural behaviour of reinforced concrete beams cast with hybrid fiber reinforced high-strength concrete (HFRHSC). The study focused on assessing the influence of steel, coir, and palm fibers on ultimate load capacity, load-deflection response, ductility, flexural toughness, and crack propagation characteristics of reinforced concrete beams.



4.2 Concrete Mixes

An M50 grade high-strength concrete mix containing 10% silica fume as a partial replacement of cement was adopted for the study. Eight concrete mixes were prepared, comprising one control mix and seven fiber reinforced mixes with different combinations of steel, coir, and palm fibers.

Table 1. Fiber Combinations Used in the Study

Mix ID	Steel Fiber (%)	Palm Fiber (%)	Coir Fiber (%)
CC	0	0	0
M1	1.0	0	0
M2	0.5	0.5	0
M3	0.5	0	0.5
M4	0.5	0.25	0.25
M5	0.25	0.5	0.25
M6	0.25	0.25	0.5
M7	0	0.5	0.5

The total fiber content was maintained at 1% by volume of concrete for all fiber reinforced mixes.

4.3 Beam Specimens

A total of eight reinforced concrete beam specimens were cast, one for each concrete mix. The beams were designed to investigate the influence of hybrid fibers on structural performance under flexural loading.

Table 2. Details of Beam Specimens

Parameter	Value
Length of Beam	1000 mm
Width of Beam	150 mm
Depth of Beam	150 mm
Concrete Grade	M50
Number of Beams	8
Reinforcement	As per design

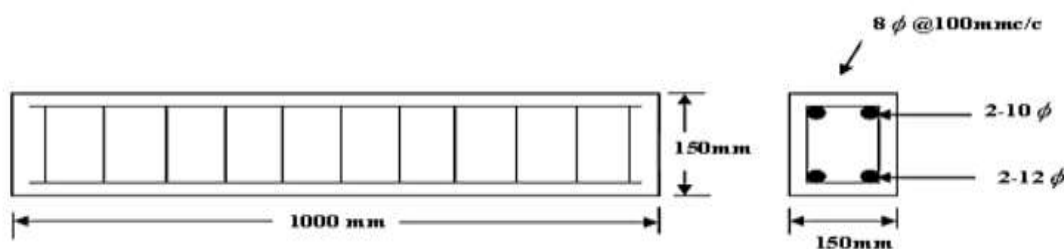


Figure 1. Reinforcement detailing of beam

The reinforcement arrangement was designed to ensure flexural failure of the beams during testing.



4.4 Casting and Curing

All beam specimens were cast under laboratory conditions. The concrete constituents were thoroughly mixed to achieve a uniform distribution of fibers throughout the matrix. Concrete was placed in moulds in layers and compacted using a table vibrator to eliminate entrapped air. After casting, the specimens were covered with plastic sheets to prevent moisture loss and were demoulded after 24 hours. The beams were then cured in water for 28 days before testing.

4.5 Test Setup

The flexural behaviour of the beams was evaluated under two-point loading using a loading frame. The load was applied incrementally through a hydraulic jack until failure occurred.

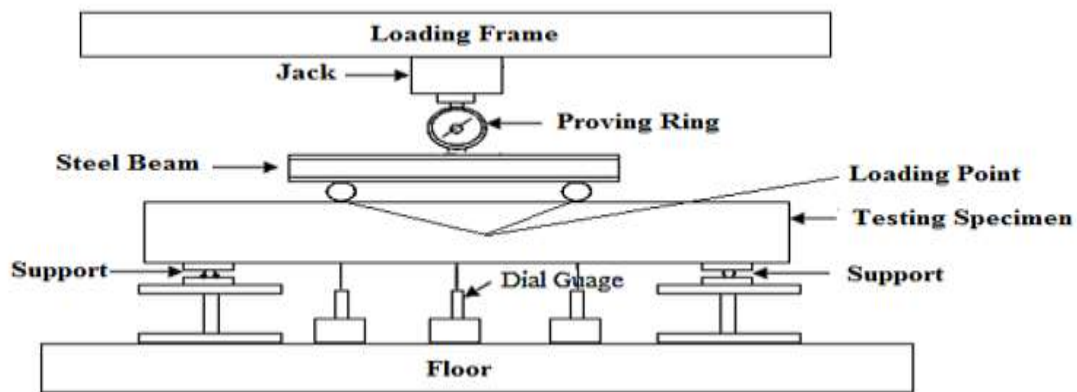


Figure 2. Test Arrangement

The mid-span deflection was measured using a dial gauge or LVDT. Crack initiation and crack propagation were carefully monitored throughout the loading process.

4.6 Parameters Investigated

The following parameters were evaluated during beam testing:

1. First crack load.
2. Ultimate load carrying capacity.
3. Mid-span deflection.
4. Load-deflection behaviour.
5. Flexural toughness.
6. Ductility characteristics.
7. Crack pattern and failure mode.

4.7 Data Analysis

The recorded load and deflection values were used to develop load-deflection curves for each beam specimen. The ultimate load capacity, ductility ratio, and flexural toughness were determined and compared among different fiber combinations. The crack patterns and failure modes were also analyzed to evaluate the effectiveness of hybrid fiber reinforcement in improving the structural performance of reinforced concrete beams.



The results obtained from the hybrid fiber reinforced beams were compared with those of the control beam to identify the optimum fiber combination for enhanced flexural performance and structural efficiency.

5. RESULTS AND DISCUSSION

5.1 First Crack Load

The first crack load is an important parameter for evaluating the cracking resistance of reinforced concrete beams. The first visible crack was observed in all beam specimens during flexural loading, and the corresponding loads are presented in Table 3.

Table 3. First Crack Load of Beam Specimens

Specimen Type	Initial Crack Load (kN)
CC	2.8
M ₁	3.8
M ₂	3.5
M ₃	3.4
M ₄	3.5
M ₅	3.8
M ₆	3.5
M ₇	3.4

The results indicate that all hybrid fiber reinforced beams exhibited higher first crack loads than the control beam. The presence of fibers delayed crack initiation by improving the tensile resistance of the concrete matrix. Steel fibers effectively bridged developing cracks, while coir and palm fibers contributed to micro-crack control. Consequently, hybrid fiber reinforced beams demonstrated improved cracking resistance and higher serviceability performance.

Among all the tested beams, Mix M₄ exhibited the highest first crack load, indicating the beneficial effect of the balanced hybrid fiber combination in delaying crack formation.

5.2 Ultimate Load Carrying Capacity

The ultimate load capacities of the beam specimens are presented in Table 4.

Table 4. Ultimate Load Capacity of Beam Specimens

Specimen Type	Ultimate Load (kN)
CC	70
M ₁	82
M ₂	80
M ₃	80
M ₄	90
M ₅	77
M ₆	78



M ₇	74
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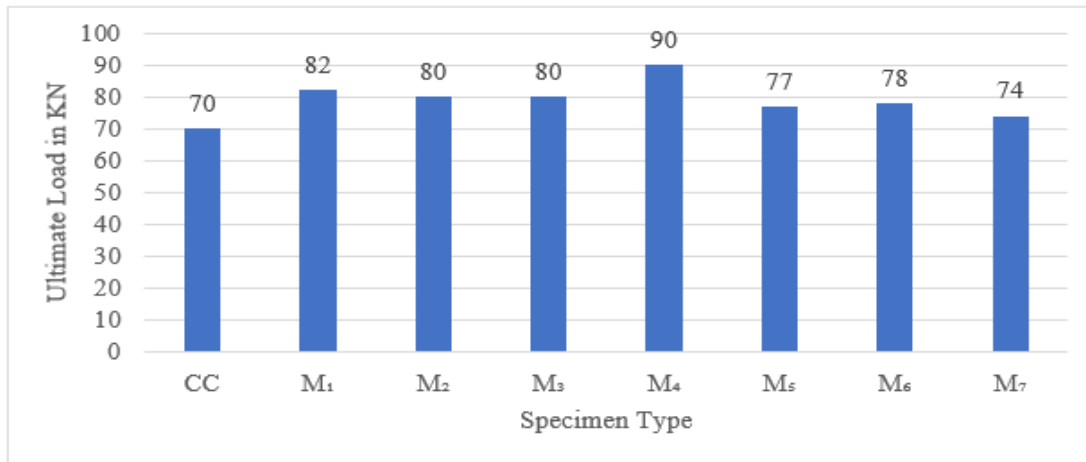


Figure 1. Comparison of Ultimate Load Capacity

The incorporation of hybrid fibers significantly improved the load-carrying capacity of reinforced concrete beams. The control beam failed at an ultimate load of approximately 70 kN, whereas all fiber reinforced beams exhibited higher ultimate loads.

The highest ultimate load was recorded for Mix M₄, which achieved an ultimate load of approximately 90 kN, representing an increase of about 28.6% compared to the control beam. The enhancement in load capacity can be attributed to the crack-bridging action of steel fibers and the improved crack control provided by coir and palm fibers. The hybrid fiber system enhanced stress redistribution within the beam and delayed the formation of critical cracks.

5.3 Load–Deflection Behaviour

The load-deflection curves obtained from beam testing are shown in Figure 2.

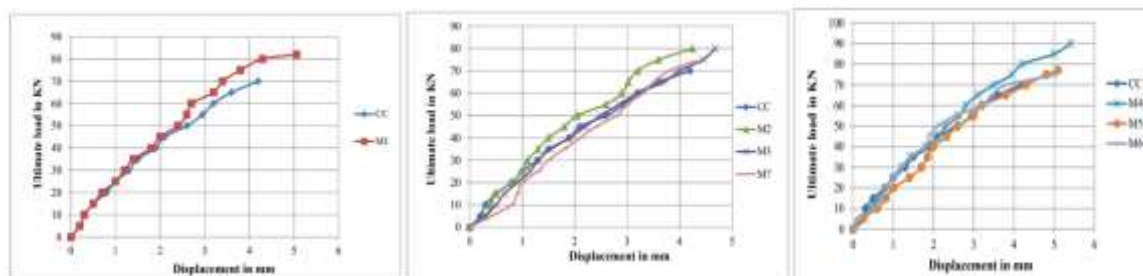


Figure 2. Load–Deflection Curves of Beam Specimens

All beam specimens exhibited an initial linear response prior to cracking. After crack initiation, the hybrid fiber reinforced beams continued to sustain additional loads and exhibited greater deformation capacity than the control beam.

The control beam showed a relatively steep reduction in stiffness after cracking, whereas the fiber reinforced beams demonstrated a more gradual response. The presence of fibers improved the



post-cracking behavior by transferring stresses across crack surfaces and delaying crack widening. Mix M4 exhibited the highest deflection at ultimate load, indicating superior ductility and deformation capacity.

5.4 Flexural Toughness

Flexural toughness represents the ability of a beam to absorb energy before failure. The toughness values calculated from the area under the load-deflection curves are presented in Table 5.

Table 5. Flexural Toughness of Beam Specimens

Specimen Type	Flexural Toughness (kN·mm)
CC	134.58
M ₁	138.99
M ₂	142.69
M ₃	135.12
M ₄	137.40
M ₅	135.68
M ₆	143.42
M ₇	141.00

The hybrid fiber reinforced beams exhibited significantly higher toughness than the control beam. The increased toughness is primarily attributed to the ability of fibers to bridge cracks and maintain load transfer after cracking. The combination of steel, coir, and palm fibers resulted in improved energy absorption capacity and delayed failure. Among all specimens, Mix M4 exhibited the highest toughness value, confirming the effectiveness of hybrid fiber reinforcement in improving the post-cracking performance of reinforced concrete beams.

5.5 Ductility Analysis

Ductility is an important characteristic of structural members, particularly in regions subjected to dynamic, impact, or seismic loading. The ductility ratios of the beam specimens are presented in Table 6.

Table 6. Ductility Ratios of Beam Specimens

Specimen Type	Yield Deflection (δ_y) mm	Ultimate Deflection (δ_u) mm	Ductility Factor ($\mu = \delta_u / \delta_y$)
CC	2.95	4.20	1.42
M ₁	3.20	5.06	1.58
M ₂	3.02	4.25	1.41
M ₃	3.20	4.68	1.46
M ₄	3.10	5.41	1.75
M ₅	3.20	5.10	1.59
M ₆	3.20	5.09	1.59



M ₇	3.05	4.26	1.40
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The results indicate that hybrid fiber reinforcement significantly improved beam ductility. Fiber reinforced beams sustained larger deformations before failure compared to the control beam. The improvement in ductility can be attributed to the gradual transfer of stresses across cracks through fiber bridging mechanisms.

Mix M4 exhibited the highest ductility ratio among all beam specimens. The balanced combination of steel, coir, and palm fibers enhanced deformation capacity and prevented sudden brittle failure, resulting in a more ductile structural response.

5.6 Crack Pattern and Failure Mode

The crack patterns observed during beam testing are shown in Figure 3.



Figure 3. Crack Patterns of Beam Specimens

The control beam exhibited fewer but wider flexural cracks and failed in a relatively brittle manner. In contrast, the hybrid fiber reinforced beams developed a larger number of closely spaced cracks with smaller widths.

The fibers effectively restricted crack propagation and distributed stresses more uniformly throughout the beam. Steel fibers bridged major cracks, while coir and palm fibers controlled



micro-cracks and delayed their coalescence into larger cracks. Consequently, the hybrid fiber reinforced beams demonstrated improved crack resistance and a more gradual failure process.

5.7 Discussion on Optimum Fiber Combination

A comparison of all structural performance parameters indicates that Mix M4 consistently outperformed the other beam specimens. The combination of 0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber provided the best balance between strength enhancement, ductility improvement, toughness development, and crack control.

The synergistic interaction between steel fibers and natural fibers enabled efficient stress redistribution and improved post-cracking behavior. As a result, Mix M4 achieved the highest first crack load, ultimate load capacity, flexural toughness, and ductility while exhibiting the most favorable crack pattern.

Therefore, Mix M4 can be considered the optimum hybrid fiber combination for producing reinforced concrete beams with enhanced structural performance and improved serviceability characteristics.

6. CONCLUSIONS

Based on the experimental investigation on the flexural behaviour of reinforced concrete beams cast with hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers, the following conclusions are drawn:

1. The incorporation of hybrid fibers significantly enhanced the structural performance of reinforced concrete beams compared to the control beam without fibers.
2. All hybrid fiber reinforced beams exhibited higher first crack loads than the control beam, indicating improved tensile resistance and delayed crack initiation.
3. The ultimate load carrying capacity of the beams increased with the inclusion of hybrid fibers. Among all the tested specimens, Mix M4 (0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber) exhibited the highest ultimate load, achieving an improvement of approximately 28.6% over the control beam.
4. The load-deflection response of the hybrid fiber reinforced beams demonstrated improved deformation capacity and a more gradual post-cracking behaviour compared to conventional reinforced concrete beams.
5. Hybrid fiber reinforcement significantly enhanced the flexural toughness of the beams by increasing their energy absorption capacity. The fibers effectively bridged cracks and maintained load transfer after crack formation, thereby delaying failure.
6. The ductility of reinforced concrete beams improved considerably with the incorporation of hybrid fibers. Fiber reinforced beams sustained larger deflections before failure and exhibited a more ductile mode of behaviour.



7. Crack propagation was effectively controlled by the hybrid fiber system. The fiber reinforced beams developed a greater number of finer cracks with smaller crack widths, whereas the control beam exhibited fewer but wider cracks.
8. The synergistic interaction between steel fibers, coir fibers, and palm fibers contributed to improved stress redistribution, crack control, toughness, and post-cracking performance of the beams.
9. Among all fiber combinations investigated, Mix M4 consistently exhibited the best overall structural performance in terms of first crack load, ultimate load capacity, ductility, toughness, and crack resistance.
10. The study demonstrates that hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers can be effectively utilized for reinforced concrete structural members requiring enhanced flexural performance, improved durability, and sustainable construction practices.

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