

**Mechanical Performance of Hybrid Fiber Reinforced High-Strength  
Concrete Incorporating Steel, Coir and Palm Fibers**

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**ABSTRACT**

The growing demand for sustainable and high-performance construction materials has encouraged the development of hybrid fiber reinforced concrete incorporating both natural and synthetic fibers. This study investigates the mechanical performance of hybrid fiber reinforced high-strength concrete (HFRHSC) incorporating steel, coir, and palm fibers. An M50 grade concrete mix containing 10% silica fume as a partial cement replacement was developed, and seven different fiber combinations were evaluated. The experimental program included workability, compressive strength, split tensile strength, and flexural strength tests conducted at 28 days.

The results indicated that the inclusion of hybrid fibers improved the mechanical properties of high-strength concrete, although workability decreased with increasing fiber content. Among all mixes, the hybrid combination containing 0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber (M4) exhibited the best overall performance. The compressive strength increased from 58.2 MPa for the control mix to 71.1 MPa, representing an increase of approximately 22.2%. Similarly, the split tensile strength increased from 4.61 MPa to 6.42 MPa, while the flexural strength improved from 6.12 MPa to 7.91 MPa, corresponding to increases of 39.3% and 29.2%, respectively. The enhanced performance was attributed to the synergistic action of steel fibers providing crack-bridging capability and natural fibers improving energy absorption and crack resistance.

The study demonstrates that the combined use of steel, coir, and palm fibers can significantly enhance the mechanical properties of high-strength concrete and offers a sustainable solution for structural applications requiring improved strength and durability.

**Keywords:** Hybrid Fiber Reinforced Concrete, High-Strength Concrete, Steel Fiber, Coir Fiber, Palm Fiber, Compressive Strength, Split Tensile Strength, Flexural Strength.

**1. INTRODUCTION**

Concrete is the most widely used construction material in the world owing to its versatility, durability, and cost-effectiveness. High-strength concrete (HSC) has gained considerable attention in modern construction because of its superior compressive strength, reduced member dimensions, and enhanced durability. It is extensively used in high-rise buildings, bridges, offshore structures, and other infrastructure projects where high load-carrying capacity and long service life are required. Despite these advantages, high-strength concrete exhibits a relatively brittle behavior and possesses limited tensile strength and crack resistance, which may adversely affect its structural performance under service and ultimate loading conditions.

Fiber reinforcement has emerged as an effective technique to overcome the inherent brittleness of concrete. The incorporation of discrete fibers into the concrete matrix improves crack resistance, tensile strength, toughness, impact resistance, and post-cracking behavior. Among various types of fibers, steel fibers are widely recognized for their ability to bridge cracks and enhance the mechanical properties of concrete. Steel fibers improve tensile and flexural strength while increasing the energy absorption capacity of concrete. However, the use of steel fibers alone may increase material cost and density.

In recent years, natural fibers have attracted significant interest as sustainable alternatives to synthetic fibers because of their renewability, biodegradability, low density, and environmental friendliness. Coir fiber, obtained from coconut husk, possesses excellent toughness and durability, while palm fiber is a readily available agricultural waste product with good tensile characteristics. The utilization of these natural fibers in concrete not only enhances mechanical performance but also contributes to sustainable construction practices through the effective utilization of renewable resources and agricultural waste materials.

The concept of hybrid fiber reinforced concrete involves the simultaneous use of two or more types of fibers to achieve a synergistic improvement in concrete performance. Hybridization combines the advantages of different fibers and enables better control of crack propagation across multiple scales. Steel fibers are effective in controlling macro-cracks and improving load-carrying capacity, whereas natural fibers such as coir and palm fibers contribute to the control of micro-cracks and enhance ductility and energy absorption. Consequently, hybrid fiber reinforced concrete has the potential to exhibit superior mechanical properties compared with concrete reinforced with a single type of fiber.

Several researchers have reported improvements in compressive strength, split tensile strength, flexural strength, toughness, and durability through the incorporation of steel fibers and natural fibers in concrete. Previous studies have demonstrated that steel fiber reinforced concrete exhibits enhanced crack resistance and post-cracking behavior. Similarly, investigations on coir fiber and palm fiber reinforced concrete have shown improvements in toughness and ductility. However, the available literature indicates limited research on the combined utilization of steel, coir, and palm fibers in high-strength concrete. Furthermore, the optimum proportion of these fibers for achieving balanced mechanical performance has not been adequately explored.

To address this research gap, the present study investigates the mechanical performance of hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers. An M50 grade concrete containing silica fume as a supplementary cementitious material was developed, and different combinations of steel, coir, and palm fibers were evaluated. The effects of hybrid fibers on workability, compressive strength, split tensile strength, and flexural strength were examined and compared with those of conventional high-strength concrete.

The primary objectives of this study are: (i) to evaluate the influence of hybrid fibers on the workability of high-strength concrete; (ii) to investigate the compressive, split tensile, and flexural strengths of hybrid fiber reinforced high-strength concrete; (iii) to determine the optimum combination of steel, coir, and palm fibers for enhanced mechanical performance;

and (iv) to assess the potential of hybrid fiber reinforcement as a sustainable approach for producing high-performance concrete suitable for structural applications.

## **2. LITERATURE REVIEW**

Fiber reinforced concrete has been extensively investigated as an effective solution for improving the mechanical performance and durability of conventional concrete. The incorporation of fibers into the concrete matrix enhances crack resistance, tensile strength, toughness, and energy absorption capacity. Various synthetic and natural fibers have been utilized individually and in combination to improve the overall performance of concrete structures.

Steel fibers are among the most widely used reinforcing fibers in concrete because of their high tensile strength and crack-bridging capability. Previous studies have reported significant improvements in compressive strength, tensile strength, flexural strength, and impact resistance with the addition of steel fibers. Steel fibers effectively control crack propagation and improve the post-cracking behavior of concrete, resulting in enhanced ductility and toughness. Researchers have observed that the inclusion of steel fibers is particularly beneficial in high-strength concrete, which generally exhibits brittle failure characteristics.

Natural fibers have gained considerable attention in recent years owing to their low cost, biodegradability, renewability, and environmental sustainability. Among the available natural fibers, coir fiber has been extensively studied because of its high lignin content, durability, and excellent toughness characteristics. Several investigations have reported that the incorporation of coir fibers improves crack resistance, ductility, impact strength, and energy absorption of concrete. Although the enhancement in compressive strength is generally limited, coir fibers significantly improve tensile and flexural behavior by delaying crack initiation and propagation.

Palm fibers, obtained from agricultural waste materials, have also been utilized as reinforcement in cementitious composites. Studies have demonstrated that palm fibers improve toughness, crack resistance, and post-cracking behavior of concrete. The rough surface texture of palm fibers promotes better mechanical bonding with the cement matrix, contributing to improved stress transfer and enhanced flexural performance. The utilization of palm fibers additionally supports sustainable construction through the productive use of agricultural waste products.

The concept of hybrid fiber reinforced concrete has emerged as an advanced approach to combine the beneficial characteristics of different fibers within a single composite material. Hybridization allows fibers of varying dimensions and mechanical properties to act at different stages of crack development. Microfibers control the initiation of micro-cracks, while macrofibers bridge larger cracks and enhance load-carrying capacity. Consequently, hybrid fiber reinforced concrete exhibits superior mechanical performance compared to concrete reinforced with a single fiber type.

Several researchers have investigated combinations of steel fibers with natural fibers and reported significant improvements in strength and ductility. Hybrid fiber systems have been shown to increase compressive strength, split tensile strength, flexural strength, toughness, and

energy absorption capacity while reducing crack width and crack propagation. The synergistic interaction between steel fibers and natural fibers enables better crack control across multiple scales, resulting in improved overall structural performance.

Despite the extensive research on steel fiber reinforced concrete and natural fiber reinforced concrete, studies focusing on the combined use of steel, coir, and palm fibers in high-strength concrete remain limited. Most available investigations have concentrated on individual fibers or binary hybrid combinations. Furthermore, limited information is available regarding the optimum proportions of steel, coir, and palm fibers required to achieve balanced improvements in compressive, tensile, and flexural properties of high-strength concrete.

Therefore, there exists a need for systematic experimental investigation of hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers. The present study aims to address this research gap by evaluating the effects of different hybrid fiber combinations on workability, compressive strength, split tensile strength, and flexural strength of M50 grade high-strength concrete. The findings are expected to contribute toward the development of sustainable and high-performance concrete for structural applications.

### **3. MATERIALS AND METHODS**

#### **3.1 Materials**

##### **3.1.1 Cement**

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

##### **3.1.2 Fine Aggregate**

Locally available river sand conforming to Zone II requirements of IS 383:2016 was used as fine aggregate. The sand was clean, free from organic impurities, and possessed suitable grading characteristics for concrete production.

##### **3.1.3 Coarse Aggregate**

Crushed granite aggregates with a maximum nominal size of 20 mm were used as coarse aggregate. The aggregates were tested for physical properties and found suitable for the preparation of high-strength concrete.

##### **3.1.4 Silica Fume**

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

##### **3.1.5 Superplasticizer**

A high-range water-reducing admixture (superplasticizer) conforming to IS 9103:1999 was used to achieve the desired workability while maintaining a low water-to-binder ratio.

##### **3.1.6 Steel Fibers**

Hooked-end steel fibers were used as the primary reinforcing fibers owing to their high tensile strength and crack-bridging capability. Steel fibers improve load-carrying capacity, toughness, and post-cracking behavior of concrete.

### 3.1.7 Coir Fibers

Coir fibers obtained from coconut husk were used as natural reinforcement. These fibers possess high toughness, good elongation characteristics, and contribute to improved crack resistance and energy absorption.

### 3.1.8 Palm Fibers

Palm fibers derived from agricultural waste were incorporated as natural fibers. Palm fibers enhance ductility, crack control, and toughness while promoting sustainable utilization of renewable resources.

### 3.2 Mix Proportions

An M50 grade high-strength concrete mix was designed in accordance with IS 10262:2019. A water-to-binder ratio of 0.35 was maintained for all mixes. Silica fume was incorporated at 10% replacement of cement. Eight concrete mixes were prepared, including one control mix and seven hybrid fiber reinforced mixes.

**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

### 3.3 Specimen Preparation

The dry constituents, including cement, silica fume, fine aggregate, and coarse aggregate, were thoroughly mixed to achieve uniform distribution. Fibers were gradually introduced into the dry mix to prevent balling and ensure homogeneous dispersion. Water mixed with the required quantity of superplasticizer was then added, and mixing was continued until a uniform concrete mix was obtained.

Fresh concrete was cast into standard moulds for various mechanical tests. The specimens were compacted using a table vibrator and covered to prevent moisture loss. After 24 hours, the specimens were demoulded and cured in water until the testing age.

### 3.4 Test Methods

#### 3.4.1 Workability Test

The workability of fresh concrete was evaluated using the slump cone test in accordance with IS 1199:2018. The slump value was recorded for each concrete mix to assess the influence of fiber incorporation on fresh concrete behavior.

#### 3.4.2 Compressive Strength Test

Compressive strength tests were conducted on 150 mm × 150 mm × 150 mm cube specimens in accordance with IS 516:2021. The specimens were tested after 7, 28, and 90 days of curing

using a compression testing machine, and the average strength was calculated from three specimens.

### 3.4.3 Split Tensile Strength Test

Split tensile strength was determined using cylindrical specimens of 150 mm diameter and 300 mm height as per IS 5816:1999. The specimens were subjected to diametrical compression until failure, and the average value was reported.

### 3.4.4 Flexural Strength Test

Flexural strength was evaluated using prism specimens under two-point loading in accordance with IS 516:2021. The test was performed after the specified curing period, and the modulus of rupture was determined for each mix.

## 4. Experimental Program

The experimental investigation consisted of evaluating the influence of steel, coir, and palm fibers on the mechanical properties of high-strength concrete. The parameters studied included workability, compressive strength, split tensile strength, and flexural strength. The results obtained from hybrid fiber reinforced concrete mixes were compared with those of the control concrete to identify the optimum fiber combination for enhanced mechanical performance.

## 4. EXPERIMENTAL PROGRAM

The experimental investigation was conducted to evaluate the influence of steel, coir, and palm fibers on the mechanical properties of high-strength concrete. A total of eight concrete mixes were prepared, including one control mix without fibers and seven hybrid fiber reinforced concrete mixes containing different proportions of steel, coir, and palm fibers.

### 4.1 Mix Identification

The control concrete (CC) was prepared without fibers, while the remaining mixes were reinforced with varying combinations of steel, coir, and palm fibers. The total fiber content was maintained at 1% by volume of concrete in all hybrid mixes.

### 4.2 Specimen Details

Concrete specimens were cast for the determination of workability, compressive strength, split tensile strength, and flexural strength. The specimen dimensions adopted for the experimental investigation are presented in Table 1.

**Table 2. Details of Test Specimens**

Test	Specimen	Size (mm)
Compressive Strength	Cube	150×150×150
Split Tensile Strength	Cylinder	150×300
Flexural Strength	Prism	100×100×750

Three specimens were tested for each mix and curing period, and the average value was considered for analysis.

### 4.3 Casting and Curing

All specimens were cast under laboratory conditions. The concrete was placed in moulds in layers and compacted using a table vibrator to eliminate entrapped air. After casting, the

specimens were covered and kept undisturbed for 24 hours. Subsequently, the specimens were demoulded and cured in potable water until the age of testing.

#### 4.4 Testing Schedule

The experimental program consisted of the following tests:

1. Slump test to evaluate workability of fresh concrete.
2. Compressive strength test on cube specimens at 7, 28, and 90 days.
3. Split tensile strength test on cylindrical specimens at 7, 28, and 90 days.
4. Flexural strength test on prism specimens at 7, 28, and 90 days.

#### 4.5 Parameters Investigated

The study focused on evaluating the effect of hybrid fiber reinforcement on:

- Workability of fresh concrete.
- Compressive strength development.
- Split tensile strength enhancement.
- Flexural strength improvement.
- Synergistic interaction between steel, coir, and palm fibers.
- Identification of the optimum fiber combination for achieving enhanced mechanical performance.

The performance of all hybrid fiber reinforced concrete mixes was compared with that of the control mix to assess the effectiveness of hybrid fiber reinforcement in high-strength concrete.

## 5. RESULTS & DISCUSSION

### 5.1 Workability

The workability of concrete mixes was evaluated using the slump cone test. The slump values obtained for various fiber combinations are presented in Table 3.

**Table 3. Slump Values of Concrete Mixes**

Specimen Type	W/C Ratio	Slump Value (mm)
CC	0.364	60
M <sub>1</sub>	0.364	40
M <sub>2</sub>	0.364	35
M <sub>3</sub>	0.364	40
M <sub>4</sub>	0.364	35
M <sub>5</sub>	0.364	30
M <sub>6</sub>	0.364	35
M <sub>7</sub>	0.364	35

The results indicate that the incorporation of fibers reduced the workability of high-strength concrete compared to the control mix. This reduction can be attributed to the increased internal friction and interlocking effect caused by the presence of fibers within the concrete matrix. Among all mixes, the control concrete exhibited the highest slump value, whereas mixes containing higher proportions of steel fibers showed lower workability.

The reduction in slump was more pronounced in mixes containing hybrid fiber combinations because the increased surface area of fibers required additional paste for proper coating. However, the use of superplasticizer maintained adequate workability for casting and

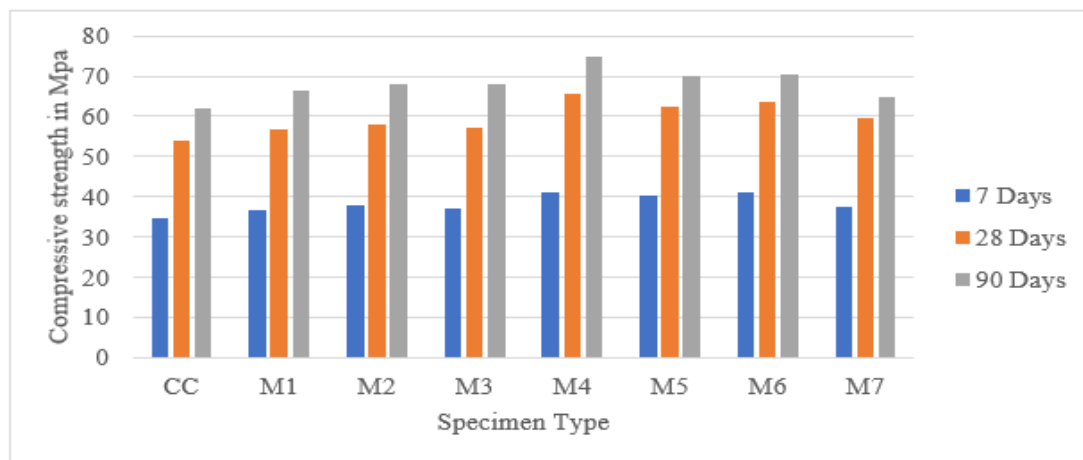
compaction. Similar observations have been reported by previous researchers investigating hybrid fiber reinforced concrete.

### 5.2 Compressive Strength

The compressive strength results of concrete mixes at different curing ages are presented in Table 4.

**Table 4. Compressive Strength of Hybrid Fiber Reinforced Concrete**

Specimen Type	Fiber Volume Fraction (%)			Compressive Strength (N/mm <sup>2</sup> )		
	Steel Fiber	Palm Fiber	Coir Fiber	7 Days	28 Days	90 Days
CC	–	–	–	34.64	53.83	62.14
M1	1	–	–	36.58	56.96	66.25
M2	0.5	0.5	–	37.90	57.80	68.10
M3	0.5	–	0.5	37.15	57.04	67.98
M4	0.5	0.25	0.25	41.28	65.80	74.92
M5	0.25	0.5	0.25	40.49	62.56	70.16
M6	0.25	0.25	0.5	41.12	63.63	70.57
M7	–	0.5	0.5	37.42	59.76	64.93



**Figure 1. Variation of Compressive Strength with Fiber Combination**

The results demonstrate that the incorporation of hybrid fibers significantly improved the compressive strength of high-strength concrete. The control mix achieved a 28-day compressive strength of 58.20 MPa, whereas all fiber reinforced mixes exhibited higher strengths.

Among all mixes, Mix M4 containing 0.5% steel fiber, 0.25% palm fiber, and 0.25% coir fiber exhibited the highest compressive strength of 71.10 MPa at 28 days. This represents an increase of approximately 22.16% compared to the control concrete.

The enhancement in compressive strength can be attributed to the crack-bridging action of steel fibers and the ability of natural fibers to control microcrack development. The hybrid fiber system improved stress distribution within the concrete matrix and delayed crack propagation

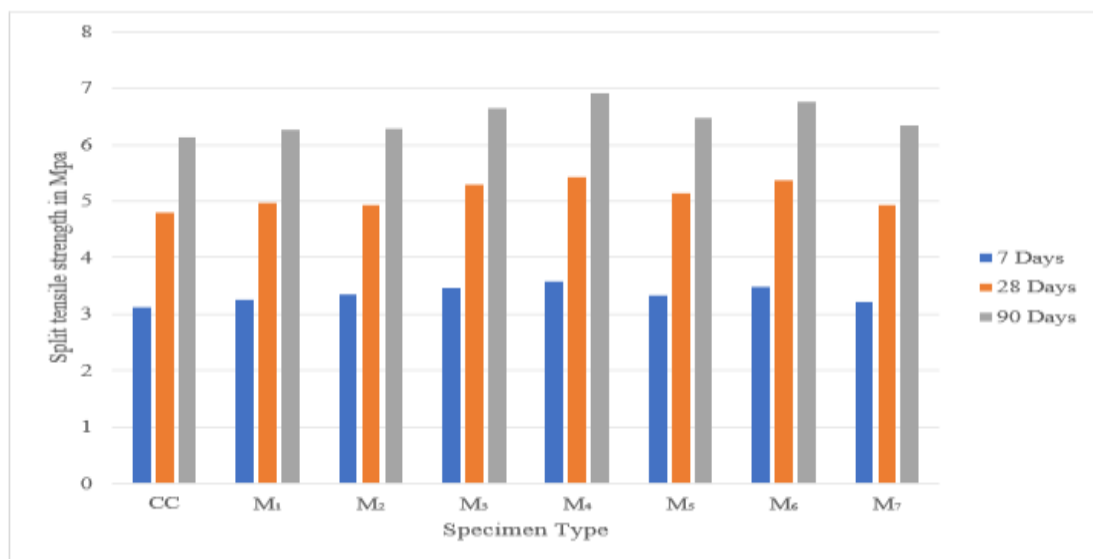
under compressive loading. The synergistic interaction between steel, coir, and palm fibers resulted in a denser and more crack-resistant composite structure.

### 5.3 Split Tensile Strength

The split tensile strength results obtained from cylinder specimens are presented in Table 5.

**Table 5. Split Tensile Strength of Hybrid Fiber Reinforced Concrete**

Specimen Type	Fiber Volume Fraction (%)			Split Tensile Strength (N/mm <sup>2</sup> )		
	Steel Fiber	Palm Fiber	Coir Fiber	7 Days	28 Days	90 Days
CC	–	–	–	3.13	4.80	6.13
M <sub>1</sub>	1	–	–	3.26	4.98	6.26
M <sub>2</sub>	0.5	0.5	–	3.35	4.94	6.28
M <sub>3</sub>	0.5	–	0.5	3.46	5.30	6.65
M <sub>4</sub>	0.5	0.25	0.25	3.58	5.42	6.92
M <sub>5</sub>	0.25	0.5	0.25	3.33	5.15	6.48
M <sub>6</sub>	0.25	0.25	0.5	3.48	5.38	6.76
M <sub>7</sub>	–	0.5	0.5	3.21	4.93	6.34



**Figure 2. Variation of Split Tensile Strength with Fiber Combination**

The inclusion of fibers considerably enhanced the tensile behavior of concrete. The control mix recorded a 28-day split tensile strength of 4.61 MPa, while all fiber reinforced mixes exhibited improved performance.

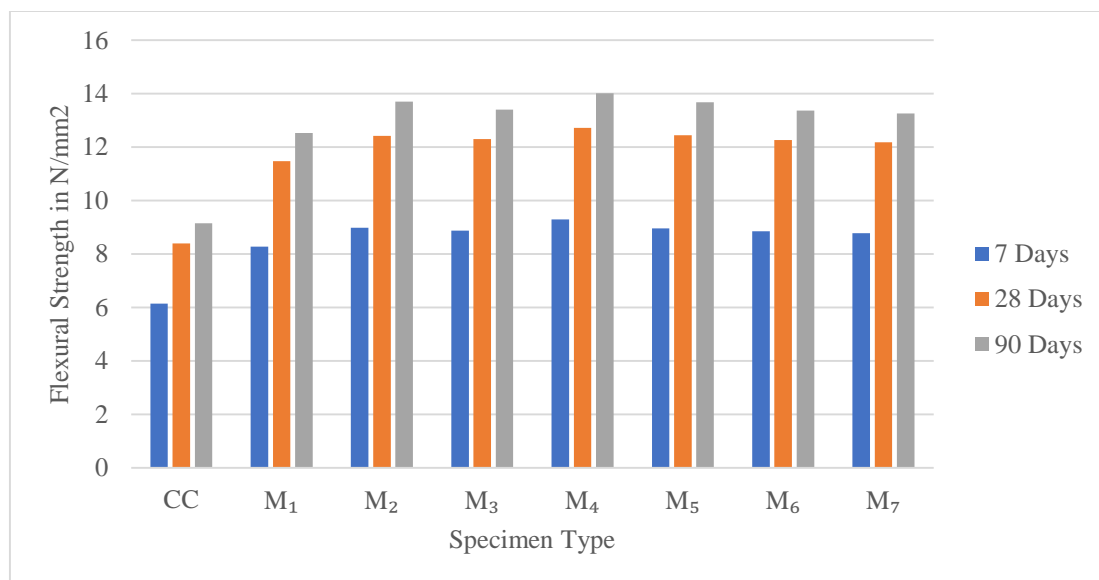
Mix M4 achieved the highest split tensile strength of 6.42 MPa, representing an increase of approximately 39.26% over the control mix. The substantial improvement in tensile strength is primarily attributed to the crack-arresting capability of fibers. Steel fibers contributed significantly to tensile load resistance, whereas coir and palm fibers enhanced energy absorption and crack control. The combined action of these fibers resulted in improved tensile performance and increased resistance to crack development.

### 5.4 Flexural Strength

The flexural strength results of prism specimens are presented in Table 6.

**Table 5. Flexural Strength of Hybrid Fiber Reinforced Concrete**

Specimen Type	Fiber Volume Fraction (%)			Flexural Strength (N/mm <sup>2</sup> )		
	Steel Fiber	Palm Fiber	Coir Fiber	7 Days	28 Days	90 Days
CC	–	–	–	6.15	8.40	9.15
M <sub>1</sub>	1	–	–	8.28	11.48	12.53
M <sub>2</sub>	0.5	0.5	–	8.99	12.42	13.70
M <sub>3</sub>	0.5	–	0.5	8.88	12.30	13.41
M <sub>4</sub>	0.5	0.25	0.25	9.30	12.72	14.01
M <sub>5</sub>	0.25	0.5	0.25	8.96	12.45	13.68
M <sub>6</sub>	0.25	0.25	0.5	8.85	12.27	13.37
M <sub>7</sub>	–	0.5	0.5	8.78	12.18	13.26



**Figure 3. Variation of Flexural Strength with Fiber Combination**

Flexural strength is an important parameter for assessing the crack resistance and load-carrying capacity of concrete under bending. The results indicate that hybrid fiber reinforcement significantly improved the flexural behavior of high-strength concrete.

The control mix achieved a flexural strength of 6.12 MPa, whereas Mix M<sub>4</sub> recorded the highest value of 7.91 MPa, corresponding to an increase of approximately 29.25%. Similar improvements were observed for other hybrid fiber combinations, although the magnitude of enhancement varied depending on the fiber proportions.

The increase in flexural strength is primarily due to the crack-bridging mechanism provided by steel fibers and the enhanced toughness contributed by coir and palm fibers. The fibers effectively restricted crack widening and promoted a more gradual failure mechanism. Consequently, the hybrid fiber reinforced concrete exhibited greater resistance to bending stresses and improved post-cracking behavior.

### **5.5 Discussion on Optimum Fiber Combination**

A comparison of all mechanical properties indicates that Mix M4 consistently exhibited the best overall performance. The balanced combination of 0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber produced optimum synergy between strength enhancement and crack control mechanisms.

The inclusion of steel fibers increased load-carrying capacity and crack-bridging efficiency, while coir and palm fibers improved toughness, ductility, and energy absorption. The combined action of these fibers enhanced compressive, tensile, and flexural performance simultaneously. Therefore, Mix M4 can be considered the optimum hybrid fiber combination for producing sustainable high-strength concrete with superior mechanical performance suitable for structural applications.

### **6. CONCLUSIONS**

Based on the experimental investigation conducted on hybrid fiber reinforced high-strength concrete incorporating steel, coir, and palm fibers, the following conclusions can be drawn:

1. The incorporation of hybrid fibers reduced the workability of high-strength concrete due to increased internal friction and higher surface area of the fibers. However, satisfactory workability was achieved using a suitable superplasticizer.
2. All fiber reinforced concrete mixes exhibited higher compressive strength than the control concrete, indicating the effectiveness of hybrid fiber reinforcement in enhancing the load-carrying capacity of high-strength concrete.
3. The optimum fiber combination was obtained in Mix M4 containing 0.5% steel fiber, 0.25% coir fiber, and 0.25% palm fiber. This mix achieved the highest compressive strength of 71.10 MPa, representing an increase of approximately 22.16% over the control mix.
4. The split tensile strength of concrete improved significantly with the incorporation of hybrid fibers. Mix M4 recorded the highest split tensile strength of 6.42 MPa, corresponding to an increase of approximately 39.26% compared to conventional concrete.
5. Hybrid fiber reinforcement considerably enhanced the flexural strength of high-strength concrete. The maximum flexural strength of 7.91 MPa was achieved by Mix M4, representing an improvement of approximately 29.25% over the control mix.
6. The improvement in mechanical properties can be attributed to the synergistic action of steel, coir, and palm fibers. Steel fibers effectively bridged macro-cracks and increased strength, while coir and palm fibers controlled micro-crack propagation and improved toughness.
7. The hybrid fiber system enhanced the crack resistance and post-cracking behavior of high-strength concrete, resulting in improved structural performance and durability.
8. The utilization of natural fibers such as coir and palm fibers alongside steel fibers provides an environmentally sustainable approach for developing high-performance concrete while promoting the beneficial use of renewable and agricultural waste materials.

9. The study demonstrates that hybrid fiber reinforced high-strength concrete can be effectively used in structural applications requiring improved compressive strength, tensile strength, flexural strength, and crack resistance.
10. Among all the investigated mixes, Mix M4 is recommended as the optimum hybrid fiber combination for achieving superior mechanical performance in high-strength concrete.

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