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Experimental Investigation of Sustainable Hybrid Fiber-Reinforced Concrete Incorporating Coconut Husk, Jute Fiber, and Human Hair

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ABSTRACT: With the increasing demand for sustainable building materials, the use of renewable waste fibers as reinforcement in concrete is gaining attention. Previous research has reported encouraging outcomes when using renewable waste fibers as reinforcement in concrete, which improves its mechanical properties and reduces environmental impacts. An experimental study is carried out to investigate the mechanical behavior of sustainable hybrid fiber reinforced concrete (HFRC) with natural reinforcing materials such as coconut husk fiber, jute fiber, and human hair. The present study examines the synergic effect of the three waste-derived fibers in a hybrid system, unlike previous studies which focused on single-fiber reinforcing. The concrete mixes were prepared with the control mix and different HFRC mixes having different fiber content. The slump was tested for fresh concrete and the compressive strength, split tensile strength and the flexural strength were tested for cured concrete as per the relevant Indian Standards. The results indicated that the highest overall performance was achieved at the optimum hybrid fiber content of 1.5% (0.5% coconut husk + 0.5% jute fiber + 0.5% human hair, by volume). The optimum HFRC mix had a 12.4% increase in compressive strength, 26.8% increase in split tensile strength and 23.5% increase in flexural strength compared with control concrete whereas slump value was reduced by 20.0%. The ductility and post-cracking behavior The hybrid fibers effectively regulated crack initiation and propagation, leading to improved ductility and post-cracking behavior, since they regulated crack initiation and propagation efficiently. The results suggest that the hybrid natural fiber reinforcement is a potential and eco-friendly alternative for structural concrete applications, especially for pavements, precast elements, low-rise buildings, and low-cost housing.

KEYWORDS: Sustainable concrete; hybrid fiber-reinforced concrete; coconut husk fiber; jute fiber; human hair; mechanical properties; green construction.

I. INTRODUCTION

Concrete is one of the most widely used construction materials in the world, due to its better compressive strength, durability, adaptability, and cost-effectiveness. It is the backbone of modern infrastructure such as buildings, bridges, highways, airports, dams, and industrial facilities. The world will produce well over 30 billion tonnes of concrete a year—a stark indicator of the pace of urbanization and infrastructure development [1]. The widespread use of ordinary concrete presents substantial environmental challenges. The cement production process is very energy demanding and accounts for around 7–8% of worldwide anthropogenic carbon dioxide (CO₂) emissions, and the over-extraction of natural aggregates has led to the exhaustion of natural resources. Such environmental concerns have led researchers to design sustainable concrete materials for reducing ecological consequences without sacrificing the structural performance [2].

Among the different sustainable options, the use of renewable and waste fibers in concrete has emerged as a potential alternative. Fibre-reinforced concrete (FRC) has gained significant interest because of the effective enhancement of crack resistance, tensile strength, flexural behaviour, toughness, impact resistance and post-cracking ductility by fibres. Concrete can be reinforced with traditional reinforcing fibers such as steel, polypropylene, glass, and carbon fibers to enhance the mechanical qualities of concrete [3]. The disadvantage of these fibers is that their production is associated with high energy consumption, increased manufacturing costs, and significant environmental implications. The problem with these fibers is that they are energy intensive, expensive to manufacture and have a large environmental impact. These fibers are characterized by high energy consumption, high production costs and environmental impacts. These fibers are associated with high energy consumption, increased manufacturing costs, and considerable

environmental implications. Consequently, natural fibers are increasingly studied for their renewability, biodegradability, low density, abundance, and comparatively minimal environmental impact, as previous research has reported encouraging outcomes [4].

Several natural fibers Previous research has reported encouraging outcomes for coconut husk fiber (coir), jute fiber, and human hair, which have shown outstanding potential as sustainable reinforcing materials for cementitious composites. Coconut husk fiber contains a large amount of lignin and has excellent toughness and resistance to moisture and biological degradation, so it can improve energy absorption and crack resistance [5]. Jute fiber has a relatively high tensile strength and elastic modulus and is effective in improving tensile and flexural performance through crack-bridging action. Human hair is a waste material produced in vast amounts by salons and households based on keratin. Human hair has excellent tensile strength, elasticity, and durability to control micro-crack formation and postpone crack propagation. The incorporation of such materials from wastes enhances the engineering properties of concrete, minimizes the generation of solid waste and favors the implementation of efficient circular economy practices and sustainable resource management [6].

Encouraging results: Positive results have been reported in the literature using single natural fibers in concrete. Coconut fiber was found to enhance toughness, impact resistance and fracture control. Jute fiber has excellent stress transfer across the cracks, thus enhancing tensile and flexural strength. It is also known that human hair increases ductility and decreases crack breadth by limiting the initiation and propagation of micro-cracks. These investigations indicate the efficiency of individual fibers; however, each fiber improves just some aspects of concrete, and high fiber dosage often affects workability due to fiber aggregation and poor dispersion. Hence, the mechanical improvement achieved by using a single fiber is still limited. Therefore, the use of a single fiber still limits the overall mechanical improvement that can be achieved [7].

To overcome these constraints, hybrid fiber-reinforced concrete (HFRC) has evolved as an effective reinforcement approach by mixing numerous fibers with complementary mechanical characteristics. Hybrid reinforcement enables fibers of different lengths, stiffness and tensile strength to cooperate during crack initiation, crack propagation and ultimate failure. The interplay of multiple fibers has a synergistic effect on stress redistribution, crack arrest, toughness, and post-cracking behavior as compared to single-fiber systems. Recently, some research has been carried out on hybrid combinations of natural and synthetic fibers. Few studies have been carried out on the combined use of coconut husk fiber, jute fiber, and human hair, especially in an Indian construction scenario with standard test methods.

Research Gap Most of the available literature is limited to the use of either a single natural fiber or binary fiber combinations and the number of experimental studies on three-fiber hybrid reinforcement systems is limited. Furthermore, the ideal hybrid fiber dose and its influence on workability, compressive strength, split tensile strength, and flexural strength under standard experimental conditions are not well reported [8].

Novelty: A sustainable hybrid fiber-reinforced concrete with coconut husk fiber, jute fiber, and human hair is developed and experimentally investigated in the present work. The uniqueness is to investigate the synergistic interaction of these three waste-derived renewable fibers in a single concrete matrix to increase mechanical performance through complementary crack-bridging mechanisms [9].

Research Objectives: The purpose of this study is to explore the impact of hybrid natural fibers on the workability, compressive strength, split tensile strength, and flexural strength of concrete; to find out the optimum hybrid fiber dosage; and to assess its feasibility for sustainable structural applications.

Research Contribution: The current research experimentally demonstrates the feasibility of using various waste-derived natural fibers as sustainable reinforcement for concrete [10]. The results are relevant to sustainable concrete technology through the promotion of waste valorization, the improvement of crack resistance and mechanical performance, the reduction of environmental impacts, and the facilitation of the development of durable and eco-friendly construction materials for future infrastructure applications [11].

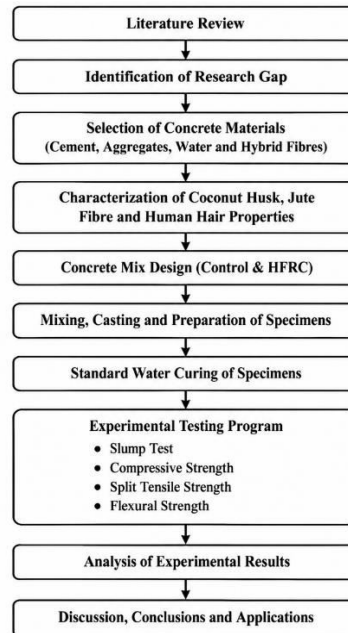


Figure.1. Research Methodology Adopted in the Present Study

II. TEST PROGRAM AND MATERIALS

This section discusses the constituent materials used for the production of the sustainable hybrid fiber-reinforced concrete (HFRC), physical properties of the reinforcing fibers, concrete mix design, specimen preparation and curing technique, and experimental testing program for the performance evaluation of the sustainable HFRC. All the experimental studies were conducted according to the relevant Indian Standards (IS) to ensure accuracy, repeatability, and uniformity of the test results.

2.1 Material Components

53 Grade Ordinary Portland Cement (OPC) as per IS 12269:2013 was the main binder used because of its excellent early strength and suitability for structural concrete. The cement was of a specific gravity of 3.15 and conformed to all the usual physical requirements. The fine aggregate used was natural river sand conforming to Zone II of IS 383:2016. The sand was clean, highly graded, and free from organic contaminants; specific gravity: 2.63; fineness modulus: 2.72. Coarse aggregate was crushed granite with a nominal maximum size of 20 mm. The specific gravity of aggregate was found to be 2.72, and water absorption was 0.80%, and it satisfies the requirement of grading as per IS 383:2016. The concrete was mixed and cured with potable water as per IS 456:2000. Three sustainable fibers from waste were selected as hybrid reinforcement due to their complementary mechanical properties and environmental benefits [12]. The fiber of coconut husk (coir) was obtained from the mature coconut husk, washed, oven-dried, and cut to lengths of 30–40 mm. Coir is highly impact resistant because of high lignin concentration and has excellent toughness and energy absorption [13].

Natural jute bunches were used to obtain the fiber economically. The fibers were washed, dried, and cut to a length of 25–30 mm. Jute has high tensile strength and elastic modulus and is useful in the bridging of fracture and tensile reinforcement. Local hair salons donated human hair. Hair was washed with detergent, disinfected, air-dried and cut to lengths of 25–35mm prior to use [14]. Cleaning removed grease and surface contaminants, which enhanced the bond between the fibers and cement matrix. Human hair is made of keratin protein. It has excellent tensile strength and elasticity, which helps in effectively managing the onset of micro-cracks [15].

Table.1. Physical Properties of Constituent Materials

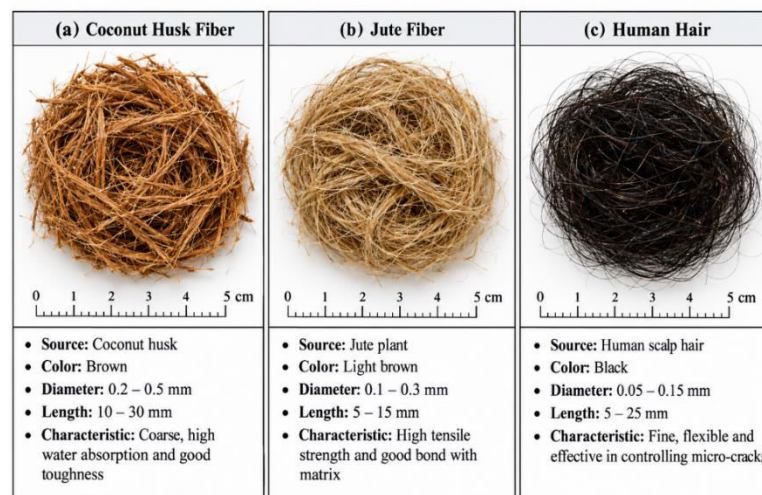
Material	Standard	Important characteristics
OPC 53 Grade Cement	IS 12269:2013	Specific gravity = 3.15
River Sand (Zone II)	IS 383:2016	Specific gravity = 2.63; Fineness modulus = 2.72
Crushed Aggregate (20 mm)	IS 383:2016	Specific gravity = 2.72; Water absorption = 0.80%
Potable Water	IS 456:2000	Suitable for mixing and curing
Coconut Husk Fiber	ASTM D3822	Length = 30–40 mm
Jute Fiber	ASTM D3822	Length = 25–30 mm
Human Hair	Literature-based characterization	Length = 25–35 mm

2.2 Hybrid Reinforcement Fibers – Physical Properties

The three fibers display different mechanical properties, which allow for complementary reinforcement in the concrete matrix. Coconut husk fiber mainly promotes toughness and impact resistance because of its high lignin content and rough surface roughness that is beneficial for mechanical interlocking with hydrated cement paste. Jute fiber has increased tensile strength and stiffness, which leads to effective fracture bridging and improved load transmission across growing cracks. The diameter of human hair is tiny, and it has excellent flexibility, which is very effective to control the micro-crack formation during early phases of loading [16].

The hybrid combination was chosen to provide multi-scale fracture resistance, where human hair controlled the micro-cracks, jute fiber bridged the intermediate cracks, and coconut husk fiber imparted toughness during the propagation of macro-cracks, thereby improving the overall mechanical performance [17].

(coconut husk fiber, jute fiber, and human hair).



All fibers were cleaned, air-dried, and cut to the required length before use in concrete.

Figure.2. Natural fibers used in the study

Table.2. Physical Properties of Hybrid Reinforcing Fibers

Property	Coconut Husk	Jute Fiber	Human Hair
Density (g/cm ³)	1.15	1.30	1.32
Tensile Strength (MPa)	120–220	350–800	200–380
Fiber Length (mm)	30–40	25–30	25–35
Diameter (mm)	0.20–0.40	0.15–0.30	0.06–0.10
Water Absorption	High	Moderate	Very Low
Primary Function	Toughness	Crack Bridging	Micro-crack Control

2.3 Mix Design and Specimen Preparation for Concrete

The concrete of M30 grade was designed as per IS 10262:2019 with a uniform water-cement ratio of 0.45. A control mix (CM) without any fibers and four hybrid fiber reinforced concrete mixes (HFRC-1 to HFRC-4) with varying total fiber dosage were prepared. Fiber proportions were taken from previous research and preliminary trial mixes to achieve optimum workability and reduce fiber balling.

The dry ingredients were mixed initially for around 2 minutes with the addition of the pre-cut fibers over a period of time to guarantee a uniform dispersion [18]. The water was then added slowly, and the mixing was continued for another 3-4 minutes till a homogeneous concrete mixture was achieved. The fresh concrete was cast into steel molds in three equal layers and crushed with a table vibrator [19].

For each mix, three cube specimens (150 × 150 × 150 mm) were cast for compressive strength, three cylinders (150 × 300 mm) for split tensile strength, and three beams (100 × 100 × 500 mm) for flexural strength to have enough replicates for reliable average test data.

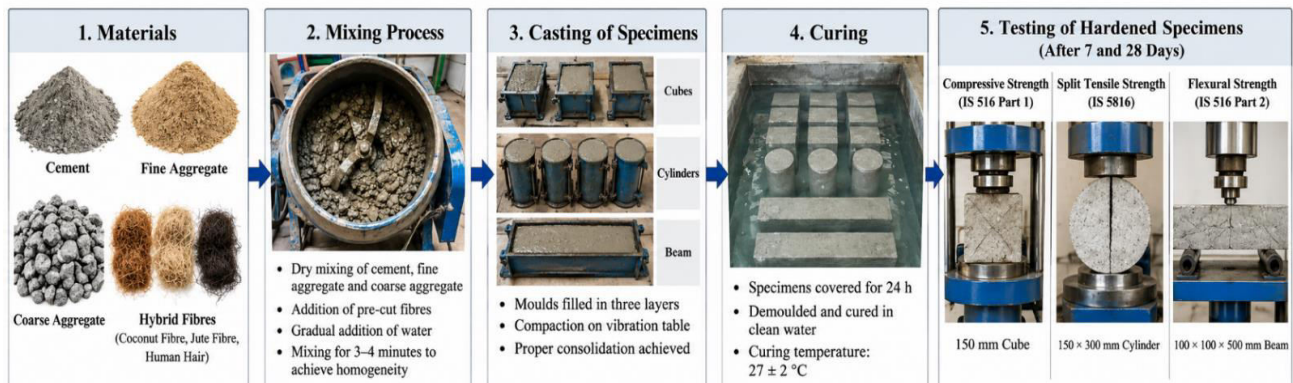


Figure.3. Specimen preparation and experimental procedure

2.4 Curing Process and Experimental Tests

After casting, all specimens were covered with plastic sheets for 24 h, demoulded, and cured in clean water at $27 \pm 2^\circ\text{C}$ till testing. The mechanical performance at early age and later age was evaluated using standard curing times of 7 and 28 days, respectively. The workability of fresh concrete was found out by the slump cone test as per IS 1199 (Part 2):2018. Hardened concrete properties were tested as per standard laboratory procedures, including compressive strength on cube specimens as per IS 516 (Part 1/Sec 1):2021, split tensile strength on cylinders as per IS 5816:1999, and flexural strength under two-point loading as per IS 516 (Part 2/Sec 1):2021. Analysis of duplicated specimens was made using average values, and the findings were compared with the control mix to assess the influence of hybrid natural fibers and to find the optimum fiber dosage for the sustainable structural concrete applications [20].

III. RESULTS AND DISCUSSION

3.1 Workability

Workability is an important feature of new concrete, as it affects the ease of mixing, transporting, placing, compacting, and finishing concrete. Excellent workability helps to avoid the formation of voids, secure proper consolidation, and lead to better strength and durability [21]. Workability was conducted by slump cone test as per IS 1199 (Part 2): 2018 in the present enquiry, and results are shown in Table 3. The experimental results indicated that the slump value decreased gradually with the increase in hybrid natural fiber dosage. The control mix (CM) showed the maximum slump of 95 mm, while the slump of HFRC-1, HFRC-2, HFRC-3, and HFRC-4 fell to 88 mm, 82 mm, 76 mm, and 70 mm, accordingly. The reductions in slump were 7.4%, 13.7%, 20.0%, and 26.3%, respectively, compared to the control concrete [22].

The reduction in workability is primarily caused by the increase in the specific surface area of the fibers and the internal friction generated within the concrete matrix. The coconut husk and jute fibers absorbed part of the mixing water due to their porous structure. On the other side, the long and flexible human hair developed a connected fiber network that restrained the free flow of fresh concrete [23]. Thus, increasing the fiber content increased the energy needed to compact the concrete. However, all mixes were workable enough to be cast in the laboratory by mechanical vibration, and no substantial segregation or fiber balling was seen as fibers were gradually added during mixing. Similar reductions in slump have been found in recent investigations on hybrid natural fiber-reinforced concrete, indicating that a minor loss of workability is a prevalent feature of fiber incorporation [24].

3.2 Compressive Strength

The main parameters to evaluate the structural quality of concrete are its ability to withstand the placing and compacting and its compressive strength. The cube specimens were assessed for the effect of hybrid fibers after 28 days of curing in water, as provided in 6 (Part 1/Sec 1):2021, and the average findings are provided in Table 3 and Figure 4. The addition of hybrid fibers caused a remarkable increment in compressive strength up to the optimum fiber dosage. The control mix developed a compressive strength of 38.2 MPa. The compressive strength of HFRC-1, HFRC-2, HFRC-3, and HFRC-4 was 39.6 MPa, 41.3 MPa, 42.5 MPa, and 41.7 MPa, respectively, which is an increase of 3.7%, 8.1%, 11.3%, and 9.2%, respectively. The highest strength was recorded for HFRC-3, which indicated that the selected hybrid fiber dosage was the best reinforcement.

The increase in compressive strength is due to the synergistic action of the three natural fibers. It was shown that human hair restricts the onset of micro-cracks, jute fibers effectively transmit stresses across the forming cracks by crack-bridging action, and coconut husk fibers enhance toughness by delaying the crack propagation through fiber pull-out mechanisms [25]. Their combined impact was to lower the stress concentration, enhance the internal stress redistribution, and delay brittle failure, thus increasing the load-carrying capacity. However, the high fiber content resulted in poor workability of HFRC-4 and localized fiber aggregation, which slightly reduced strength and seriously affected the concrete's homogeneity. In summary, the results confirm that a well-designed hybrid fiber system can significantly augment the compressive performance of sustainable concrete.

Table.3. Fresh and Mechanical Properties of Control and Hybrid Fiber-Reinforced Concrete

Mix ID	Total Fiber Content (%)	Slump (mm)	Reduction in Slump (%)	Compressive Strength (MPa)	Increase (%)
CM	0.0	95	—	38.2	—
HFRC-1	0.5	88	7.4	39.6	3.7
HFRC-2	1.0	82	13.7	41.3	8.1
HFRC-3	1.5	76	20.0	42.5	11.3
HFRC-4	2.0	70	26.3	41.7	9.2

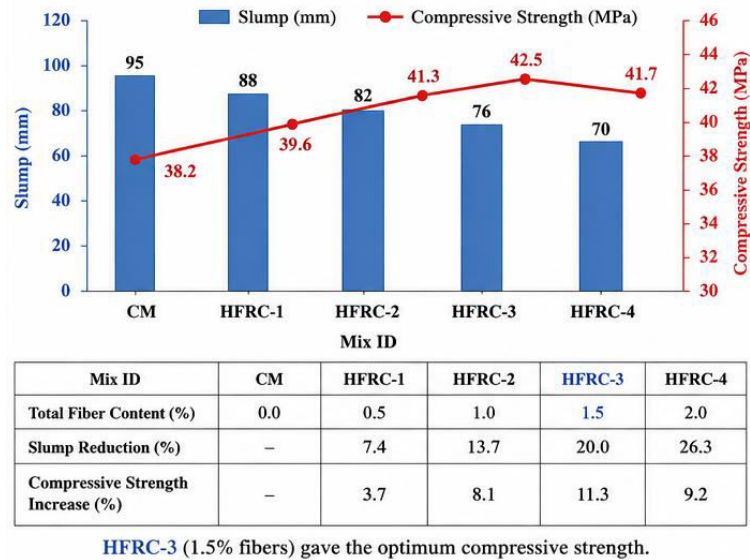


Figure.4. Comparison of workability and compressive strength of control and hybrid fiber-reinforced concrete

Fig.4. Variation of slump and 28-day compressive strength of control mix (CM) and hybrid fiber-reinforced concrete (HFRC) mixtures. The workability increased; increasing the dosage of the fiber decreased workability due to higher internal friction and water absorption of natural fibers. The compressive strength was raised up to an optimal hybrid fiber content (HFRC-3) due to effective crack arrest, stress redistribution, and fiber-bridging mechanisms. The small reduction in strength of HFRC-4 suggests that the high fiber content influenced the homogeneity and compaction of concrete adversely [26].

3.3 Strength of the Split

Split tensile strength is an important mechanical parameter that indicates the resistance of concrete to tensile stresses and the onset of cracks. Concrete is weak in tension, so it is important to improve its tensile capacity to enhance structural durability and service life. The split tensile strength of cylindrical specimens was found out after 28 days of curing period in water in the present investigation as per the IS 5816:1999, and the results are tabulated in Table 3 and Figure 4. The hybrid natural fibers significantly improved the split tensile strength of concrete [27]. The tensile strength of control mix (CM) was 3.25 MPa. Tensile strengths of HFRC-1, HFRC-2, HFRC-3, and HFRC-4 were 3.52 MPa, 3.88 MPa, 4.12 MPa, and 3.98 MPa, respectively. The equivalent increases were 8.3, 19.4, 26.8, and 22.5%, respectively, over the control mixture. The HFRC-3 mixture had the highest tensile strength of all the mixtures, indicating that the hybrid fiber dosage selected was the most effective reinforcement to resist tensile cracking.

The tensile strength improvement is due to the synergy between the three natural fibers in the concrete matrix. The low diameter and high elasticity of human hair efficiently controlled the onset of micro-cracks. The jute fiber, having relatively higher tensile strength and elastic modulus, was able to bridge the forming cracks and transfer the tensile loads across the crack sides. The coconut husk fiber increased the toughness and slowed the crack propagation by effective fiber pull-out and energy absorption methods. These complementary reinforcement actions lowered the stress concentration, slowed the crack widening, and improved the global tensile resistance of the concrete. However, it was noted that there was a minor drop in tensile strength in HFRC-4, suggesting the reduction in reinforcing efficiency due to the unfavorable effects of increased fiber content on fiber dispersion and homogeneity of concrete [28].

Statistical interpretation: The experimental results showed good repeatability with low variability of the mean values for each combination obtained from three specimens, indicating similar specimen preparation and testing techniques. The trends of the compressive and tensile strength had an obvious increasing trend from CM to HFRC-3 and a slightly decreasing trend for HFRC-4. The optimum HFRC-3 mix gave a 26.8% increase in split tensile strength compared to the control concrete. This indicates that the hybrid fiber reinforcement was statistically significant and not due to

random variation of experimental results. This trend also suggests that the optimum fiber dosage provided a balanced combination of workability, fiber dispersion, and crack-bridging efficiency [29].

Compared to Previous Studies

The reported results are in agreement with recent work on natural and hybrid fiber-reinforced concrete. Natural fibers are known to play a key role to enhance the tensile properties by effective fracture bridging and stress redistribution (Ahmad et al. 2022). The reason is that different fibers control the cracks at different levels. Ali et al. (2024) showed that hybridization of such fibers with complementary mechanical properties can be utilized to enhance ductility and energy absorption capacity after fracture. The increase in split tensile strength in present study is 26.8% which is comparable or slightly better than the improvements reported in the recent literature [30]. This proves the strength of the mixture of coconut husk fiber, jute fiber and human hair in a single concrete matrix. The results indicate that the proposed hybrid reinforcement system is a feasible and sustainable alternative to traditional fiber reinforced concrete for structural applications requiring the improved fracture resistance and tensile performance.

3.4 Bending Strength

Flexural strength is an important index to evaluate the bending resistance and crack propagation characteristics of concrete, especially for structural members such as pavements, beams, bridge decks, and precast members. Concrete is brittle in nature under tensile strains. The addition of fibers can greatly enhance the post-cracking load-carrying capability of concrete. The flexural strength of the beam specimen was tested at 28 days of water curing by two-point loading as per IS 516 (Part 2/Sec 1):2021. The results are given in Table 3 and Figure 4. The results show the flexural performance of the concrete has been greatly improved by the hybrid fiber reinforcements [31]. The flexural strength of control mix (CM) was 4.65 MPa, and HFRC-1, HFRC-2, HFRC-3, and HFRC-4 were obtained at 4.91 MPa, 5.36 MPa, 5.74 MPa, and 5.58 MPa, respectively. These values are 5.6%, 15.3%, 23.4%, and 20.0%, respectively, in comparison with the control concrete. Maximum flexural strength was obtained with the HFRC-3 mix, indicating the best compromise of workability, fiber dispersion, and reinforcing efficiency with the selected hybrid fiber dose.

The enhancement in flexural strength is mainly due to the fiber bridging mechanism in the concrete matrix. The human hair efficiently prevented the growth of microfractures; the jute fibers efficiently transported the tensile loads across the opening cracks due to their high tensile strength; and the coconut husk fibers improved toughness by fiber pullout and energy absorption. These synergistic mechanisms had a role in reducing the fracture propagation and crack breadth and allowed the concrete to bear a larger bending stress before collapse [32]. The modest reduction in the case of HFRC-4 shows that the excess amount of fiber negatively influenced workability and caused the local agglomeration of fiber, which reduced the efficacy of transferring workability and caused the local agglomeration of fiber, which reduced the efficacy of transferring the stress through the concrete matrix.

3.5 Failure Pattern Analysis

The failure behavior of the tested specimens clearly revealed the positive effect of hybrid natural fibers on the crack growth and post-cracking behavior. The control concrete specimens failed suddenly in a brittle manner with rapid fracture development and full separation just after the peak load [33]. Such behavior is typical; concrete exhibits such behavior due to its low tensile strength and inability to redistribute stress after breaking.

The HFRC specimens, on the other hand, displayed a slow and more ductile failure mechanism [34]. A lot of fine cracks were observed before the final compression failure, indicating a better stress redistribution in the concrete matrix. The fibers acted as effective bridges across the growing fracture surfaces and retarded the spreading of the crack and so avoided the immediate separation of the specimen during the split tensile test. Similarly, in the flexural test, several visible cracks instead of a major crack were seen, signifying increased toughness and energy absorption.

Among all the mixtures, HFRC-3 showed the most favorable failure pattern, with controlled crack propagation, effective fiber pull-out, and strong fiber bridging across the fractured parts. These observations proved that the hybrid mix of coconut husk fiber, jute fiber, and human hair got a significant increase in ductility and post-cracking resistance compared to the conventional concrete [35]. The experimental results are consistent with recent studies on hybrid natural fiber reinforced concrete that have shown that the combination of fibers with different mechanical properties can provide better crack control and structural robustness than single-fiber reinforcement.

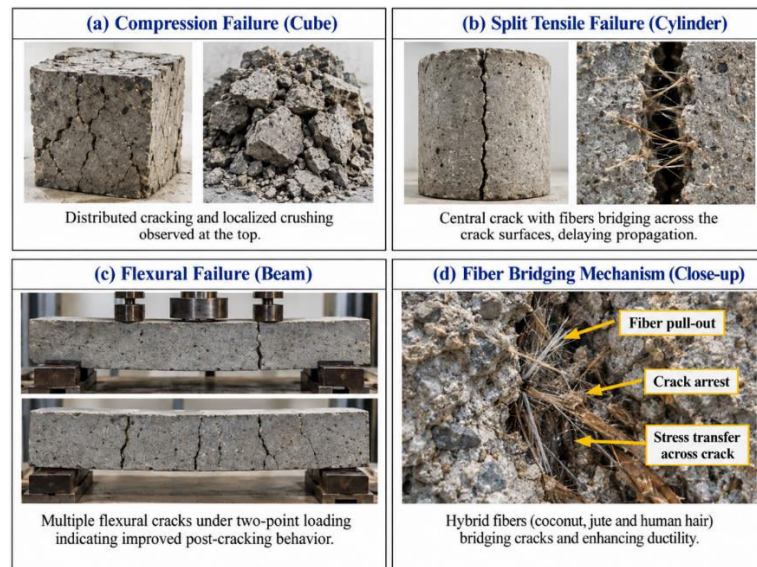


Figure.5. Typical Failure Patterns of Hybrid Fiber-Reinforced Concrete

Figure.5. Typical failure patterns observed in the experimental testing of hybrid fiber-reinforced concrete specimens:

- (a) Compressive failure with distributed cracking;
- (b) Split tensile failure with fiber bridging across the crack plane;
- (c) Flexural failure with multiple crack development under two-point loading; and
- (d) Enlarged view of the fiber bridging and pull-out mechanism responsible for delaying crack propagation and improving post-cracking ductility.

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3.6 Comparison with the state of the art

The present examination results are in good agreement with recent studies indicating the efficiency of natural fiber reinforcement in increasing the mechanical performance of concrete [36]. The previous studies have shown that coconut husk fiber is responsible for enhancing the toughness and impact resistance due to high lignin content and energy absorption capacity, while jute fiber may greatly boost the tensile and flexural properties by effective crack-bridging action. Similarly, discarded human hair has been reported as an effective reinforcement with the ability to delay micro-crack onset and increase ductility. However, the prior studies mostly investigated the application of single fibers or binary combinations of fibers.

In contrast, the present study employed a hybrid reinforcing system of coconut husk fiber, jute fiber, and human hair. The results of trial showed that the optimum hybrid mix (HFRC-3) resulted in an improvement of 11.3%, 26.8% and 23.4% in the compressive strength, split tensile strength and flexural strength respectively compared to the normal concrete. Such gains are at least comparable to those described in recent literature, which indicate that the synergistic interaction among the three fibers provides superior fracture management and stress redistribution. Furthermore, the hybrid system significantly enhanced the post-cracking behavior with acceptable workability, demonstrating that the appropriately proportioned natural fibers can lead to durable and sustainable structural concrete. Thus, the experimental data prove the effectiveness of hybrid natural fiber reinforcement and also provide more evidence for its use in eco-friendly building.

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Table.4. Comparison of the Present Study with Previous Investigations

Study	Fiber Type	Major Findings	Comparison with Present Study
Ahmad. et al.' (2022)	Coconut-fiber	Improved toughness and crack resistance	Present study achieved higher overall mechanical performance through hybrid reinforcement.
Ahmad. et al., (2022)	Jute-fiber	Enhanced tensile and flexural strengths	Similar improvements observed; hybrid fibers produced greater crack control.
Sharma & Singh (2023)	Hybrid-natural-fibers	Improved tensile strength and ductility	Present study reported comparable trends with additional improvement in compressive strength.
Ali et al., (2024)	Sustainable hybrid fibers	Enhanced crack bridging and energy absorption	Present study confirms synergistic fiber action using three renewable waste-derived fibers.
Present Study	Coconut husk + Jute + Human hair	+11.3% compressive, +26.8% split tensile, +23.4% flexural strength	Demonstrates optimum multi-fiber reinforcement for sustainable structural concrete.

3.7 Practical Implications

The study concluded that hybrid reinforcement using coconut husk fiber, jute fiber, and human hair is an eco-friendly alternative to normal fiber-reinforced concrete. The higher compressive, tensile, and flexural strengths and the resistance to cracking and post-crack ductility indicate that the developed HFRC is suitable for use in rigid pavements, industrial floors, precast concrete products, low-rise buildings, footpaths, retaining structures, and affordable housing projects [37]. The use of agricultural and human waste materials supports the principles of resource conservation, waste valorization, and circular economy and thus reduces the environmental burden created by traditional construction materials. The optimum hybrid fiber dosage is an engineering compromise between workability and mechanical properties, and the material can be used for field applications without major modifications to traditional concrete manufacturing processes. The results provide useful recommendations to researchers, practicing engineers and building businesses who are seeking sustainable reinforcing solutions for improving durability with minimal environmental impacts. Future works can study more in detail the long-term durability, shrinkage behavior, and structural performance of hybrid natural fiber-reinforced concrete at a wide scale under different environmental circumstances [38].

IV. CONCLUSION

In the present work, the experimental feasibility of constructing sustainable hybrid fiber-reinforced concrete (HFRC) using coconut husk fiber, jute fiber, and human hair as renewable reinforcing materials was assessed. The experimental examination was conducted to examine the effect of hybrid fibers on workability, compressive strength, split tensile strength, and flexural strength of M30-grade concrete. From the experimental data, the following conclusions are drawn:

1. The use of hybrid natural fibers greatly boosted the mechanical performance of concrete and encouraged the sustainable use of agricultural and human waste materials and, therefore, environmentally responsible construction practices.
2. Workability of fresh concrete deteriorated steadily with an increase of fiber dosage. The best combination (HFRC-3, with 1.5% of total hybrid fibers) showed a slump reduction of 20.0%, whereas the highest reduction of 26.3% was obtained with HFRC-4. This reduction did not affect the suitability of all concrete mixtures for casting with correct vibration and compaction procedures.
3. Hybrid fiber reinforcement successfully suppressed crack growth and stress distribution and improved the compressive strength of concrete. The optimum mix of HFRC-3 had 42.5 MPa compressive strength at 28 days, which was 11.3% higher than the control concrete.
4. The maximum % increase in all the mechanical properties was observed in the split tensile strength. The HFRC-3 mix showed an improvement of 26.8% over the control mix, confirming the effectiveness of the hybrid fiber system in controlling the initiation of cracks by the multi-scale crack bridging mechanisms.
5. The optimum hybrid fiber combination resulted in an increase of 23.4% in the flexural strength because of the synergistic effect of coconut husk fiber, jute fiber and human hair. The hybrid reinforcement was effective in retarding the crack propagation and improving the post-cracking ductility and energy absorption capacity of concrete.
6. The HFRC-3 mixture, among the evaluated mixtures, presented the best combination of mechanical properties and workability. The incorporated high fiber content (HFRC-4) exhibited marginal loss in strength because of the lower workability, localized fiber aggregation, and less uniform fiber dispersion.
7. The uniqueness of the present work is the experimental demonstration of the synergistic reinforcement effect of a three-fiber hybrid system containing coconut husk fiber, jute fiber, and human hair. The proposed hybrid system successfully controlled crack development at several scales, unlike conventional single-fiber reinforcement, resulting in better compressive, tensile, and flexural performance.
8. The suggested HFRC shows great promise for practical uses in rigid pavements, industrial floors, precast concrete products, low-rise buildings, retaining structures, rural infrastructure and inexpensive housing where enhanced resistance to crack formation and sustainability are needed.

Further investigations are needed to explore the long-term durability, shrinkage and creep characteristics, permeability, chloride penetration, sulfate resistance, freeze and thaw durability and microstructural properties by SEM, XRD, FTIR and CT scanning. In addition, life-cycle assessment (LCA), cost-benefit analysis, and full-scale structural validation should be carried out to support the large-scale implementation of hybrid natural fiber reinforced concrete in sustainable infrastructure.

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