

A study on the flexural behavior of fiber reinforced concrete with hybrid sisal and bamboo fibers

Krishna Chaitanya Panchangam¹, Dr. Archana D P²

¹Student, Department of Structural Engineering, Bangalore Institute of Technology, Bangalore-560079

² Assistant Professor, Department of Civil Engineering, Bangalore Institute of Technology, Bangalore-560079

Abstract—Sisal and bamboo fibers are being used extensively as they are eco-friendly when compared to artificial fibers and also have a low environmental impact. The hybridization of these two natural fibers is selected to focus on the low ductility of concrete and boost the flexural strength and tensile strength. Moreover, incorporating natural fibers in place of synthetic or artificial ones enhances the sustainability of concrete.

Concrete specimens were prepared with varying fiber dosages and tested for compressive, split tensile, and flexural strengths, alongside reinforced concrete beams subjected to flexural loading. The findings indicate that the most effective dosage is 1% by weight of cement (0.5% sisal + 0.5% bamboo). At this level, compressive strength remained equivalent to conventional concrete, while split tensile and flexural strengths increased by 12% and 6.4%, respectively. Additionally, reinforced beams demonstrated a 7% improvement in ultimate load capacity, finer crack patterns, and higher ductility. These results suggest the potential of hybrid natural fibers as a sustainable and effective reinforcement alternative in structural applications.

Future studies can focus on optimizing the hybrid fiber proportions by exploring a wider range of dosages and various treatment methods to further enhance durability and mechanical performance. The long-term behavior of hybrid fiber reinforced concrete under varying environmental and loading conditions should also be investigated to assess its service life. Additionally, large-scale structural applications and cost-benefit analysis can be carried out to evaluate the practical feasibility of implementing this material in modern sustainable construction.

Index Terms—Natural Fiber Reinforced Concrete, Concrete Strengthening, Bamboo and Sisal Fibers, Hybrid Fiber,

I. INTRODUCTION

Concrete continues to be one of the most widely used construction materials because of its high compressive strength and durability. It plays an indispensable role in the development of modern infrastructure—ranging from residential and commercial buildings to highways, bridges, and dams—because of its versatility, ease of moulding, and local material availability. Nevertheless, it is naturally brittle and has limited tensile and flexural capacity. This brittleness often leads to the formation of cracks under loading, which not only affects structural strength but also reduces long-term durability and service life. To address these limitations, Fiber Reinforced Concrete (FRC) was introduced, in which short, randomly distributed fibers are added to the mix. The inclusion of fibers enhances toughness, ductility, and post-cracking performance of the material.

Over time, numerous types of fibers have been incorporated into concrete to modify its mechanical and structural behavior. A wide range of synthetic fibers—such as steel, glass, polypropylene, carbon, and basalt—can be utilized, each offering distinct benefits suited to various structural requirements (1)(2). For instance, steel fibers enhance impact resistance and fatigue life (3), glass fibers contribute to chemical resistance and crack control (4), and polypropylene fibers improve fire resistance and reduce permeability (5). Carbon fibers are used in concrete for their exceptional tensile strength (6), while basalt fibers are noted for their high resistance to heat and chemical exposure (7). Although these synthetic fibers have demonstrated superior

performance, they often come with drawbacks such as higher production costs, non-biodegradability, and environmental concerns related to manufacturing and disposal.

As sustainability becomes a global priority, the construction sector has turned its focus toward materials that minimize ecological impact without sacrificing performance. In contrast, natural fibers such as coir, jute, bamboo, hemp, sisal, and banana offer eco-friendly, biodegradable reinforcement solutions. These materials are often chosen for their sustainability and cost-effectiveness. They are renewable in nature and can often be sourced from agricultural residues, making them a low-cost and energy-efficient alternative to synthetic fibers. However, they typically require surface treatments to reduce moisture absorption and enhance bonding with the cement matrix, which in turn improves their durability and mechanical properties (8)(9).

Among natural fibers, sisal and bamboo stand out due to their availability and mechanical performance (10). Sisal fibers, derived from the Agave plant, provide strong adhesion and tensile strength, while bamboo fibers improve flexibility and resistance to cracking. Using a combination of these fibers (hybridization) in concrete improves load distribution and enhances resistance to deformation and cracking. The hybrid approach allows the advantages of both fibers to complement each other, leading to improved performance across multiple strength parameters. Research indicates that treated natural fibers, particularly sisal and bamboo, can enhance the flexural strength, tensile strength and ductility of concrete while maintaining its compressive strength, thereby presenting a promising alternative for sustainable infrastructure development (11)(12).

Overall, the integration of natural fibers—individually or in hybrid form—offers a pathway toward greener, more resilient concrete systems. By utilizing locally available materials and reducing reliance on energy-intensive synthetic fibers, hybrid fiber-reinforced concrete can significantly contribute to sustainable construction practices. This growing interest highlights the potential of hybrid natural fiber systems as a viable and environmentally responsible

solution for future structural applications.

II. METHODOLOGY

This experimental study investigates the behavior of M40 grade concrete modified with hybrid natural fibers—sisal and bamboo. The main objectives of this study are to assess the mechanical properties of concrete reinforced with the hybrid fibers and to compare the results with those of Conventional concrete mix. Later the optimal proportion of fibers are used in combination to prepare RC beam specimens of 1.5m length and test the flexural performance with beams of RCC beams without any fiber content. The research methodology comprises systematic material acquisition, fiber treatment, initial testing of constituent materials, development of mix proportions, and casting and testing of concrete specimens in compliance with Indian Standards (IS) codes.

For this purpose, 53-grade Ordinary Portland Cement (OPC), adhering to IS 12269:1987, was selected as the primary binder. Manufactured sand, classified under Zone II as per IS 383:2016, served as the fine aggregate, while 20 mm nominal size angular crushed stones were used as coarse aggregates, also conforming to IS 383:2016. Clean potable water, fit for both mixing and curing, was used in accordance with IS 456:2000 guidelines.

The natural fibers were sourced and processed individually—sisal fibers were extracted from *Agave sisalana* leaves, cleaned, and naturally dried, whereas bamboo fibers were derived through mechanical processing of matured bamboo stalks. Based on research the optimal aspect ratio of fibers was 60-80 and the optimal length was found to be 15mm to 40mm based on various diameters (12)(13)(19). Therefore, both fiber types were trimmed to lengths between 12 mm and 15 mm to ensure consistent dispersion in the concrete matrix and to maintain an even aspect ratio as the fibers vary in diameter from 0.1mm to 0.2mm.

Before concrete preparation, all raw materials underwent preliminary testing to confirm their

suitability. Cement properties such as standard consistency, setting times, fineness and specific gravity were verified as per IS 4031. Both fine and coarse aggregates were evaluated for water absorption, specific gravity, and sieve analysis in line with IS 2386.

To enhance fiber performance in the cementitious matrix, an alkali treatment process was conducted. Bamboo fibers were immersed in a 2% sodium hydroxide (NaOH) solution and Sisal fibers were immersed in a 10% sodium hydroxide (NaOH) solution at room temperature (14)(15). Later, both the fibers were thoroughly rinsed in clean water and left to air dry. Later heat treatment was done in an oven at 90°C for a period of 6 hours (16). This chemical modification improves surface texture, eliminates unwanted lignin and hemicellulose, and increases the interfacial bonding strength with the concrete matrix.

An M40 grade mix was designed based on the recommendations of IS 10262:2019 and IS 456:2000, targeting a workability slump of approximately 100 mm. The concrete was modified with varying proportions of sisal and bamboo fibers (0.25%, 0.5% and 0.75% each by weight of Cement) to study their influence on mechanical behavior. The increase in proportion of fibers showed good improvement in the tensile strength of concrete (17).

The increase in fiber content also reduced the flowability, therefore a superplasticizer was incorporated to compensate for any loss in workability and increased water absorption caused by the fibers. (18)(19).

The HFRC mix was prepared and poured into standard moulds to produce specimens for testing. The specimen types included 150 mm cubes for compressive strength (IS 516:2018), 150 mm × 300

mm cylinders for split tensile strength (IS 5816:1999), and 100 mm × 100 mm × 500 mm prisms for flexural strength evaluation (IS 516:2018). Vibratory compaction was applied to each mould, and specimens were covered immediately to prevent premature moisture loss.

A total of 24 specimens of each HFRC mix and Conventional mix were casted for each of the tests. To test the performance of the HFRC mix, 1.5m RC beams were also casted, after initial tests, using the optimal proportion of fibers so that they can be compared with Conventional mix. After 24 hours, the specimens were demoulded and transferred to a curing tank maintained at $27 \pm 2^\circ\text{C}$. They were cured for 7, 14, and 28 days. Upon completion of each curing period, the specimens were tested for their respective mechanical strengths—compressive, tensile, and flexural—following the prescribed procedures outlined in the relevant IS codes.

III. MATERIALS AND PRELIMINARY TESTS

This investigation utilized Ordinary Portland Cement (OPC) of 53 grade, natural river sand as fine aggregate, and crushed stone as coarse aggregate. To ensure their applicability in concrete production, basic tests were carried out on all materials.

The cement showed a specific gravity of 3.15, a fineness of 5%, with a standard consistency of 27%, and an initial setting time recorded at 30 minutes. The fine aggregates were classified under Zone II as per the gradation requirements and had a specific gravity of 2.63, a fineness modulus of 4.17, and a water absorption rate of 3.2%. For the **coarse** aggregates, a specific gravity of 2.54 and water absorption of 1.5% were recorded. All test results comply with the criteria necessary for designing M40 grade concrete as per the Indian Standards.

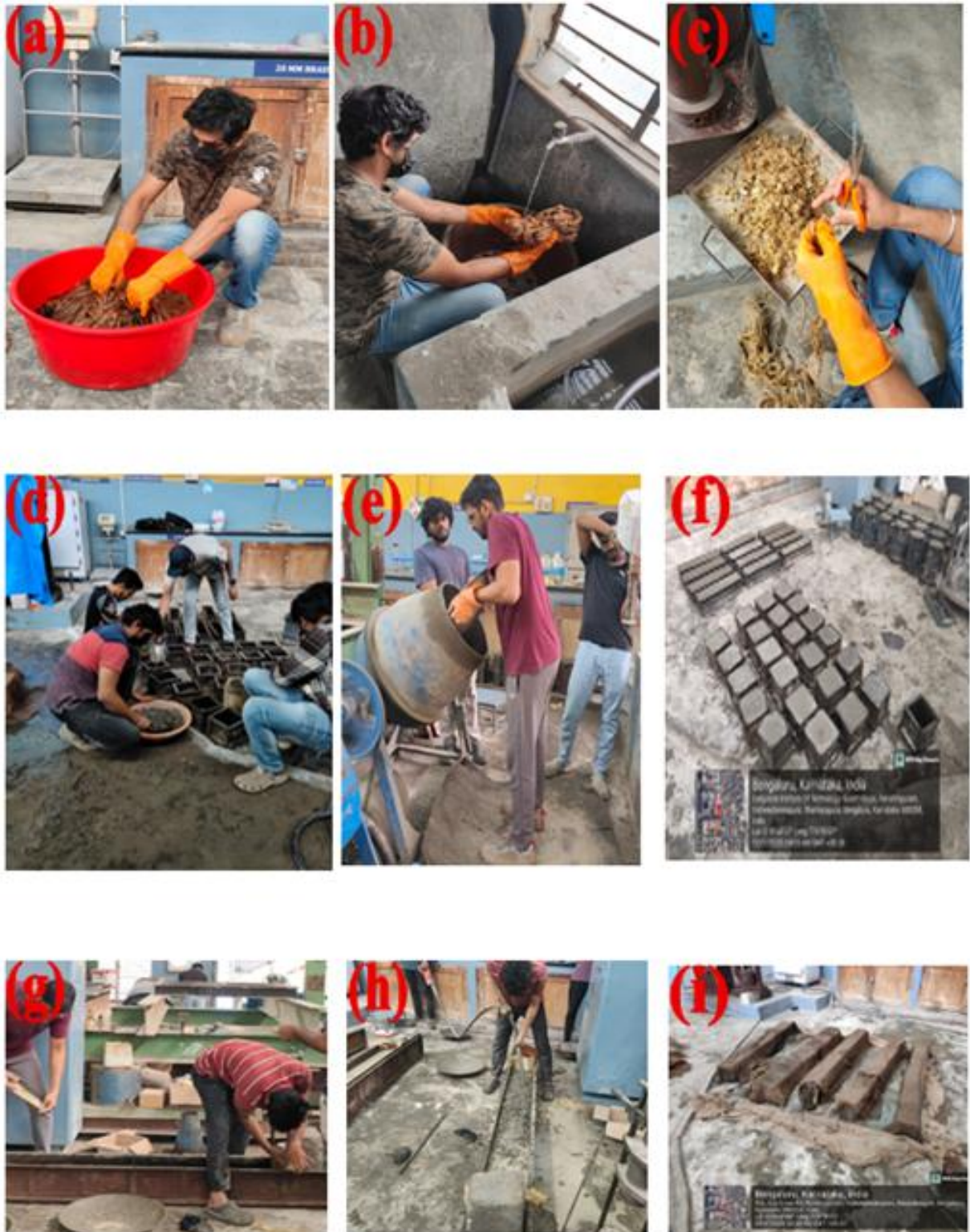


Figure 1: Preparation of Fibers & Casting of Specimens. (a) Treatment of Fibers in NaOH solution. (b) Rinsing Fibers in fresh water. (c) Shredding of fibers as per required aspect ratio. (d) Preparation of Specimen moulds. (e) Preparation of M40 Concrete. (f) Basic Test Specimens. (g) Preparation of shuttering for RC beams. (h) Casting of RC beams. (i) RC beams curing using gunny bags.

IV. EXPERIMENTAL INVESTIGATION

Concrete mixes were modified with natural fibers (sisal and bamboo) to study their effect on mechanical properties. Tests were conducted as per IS 516:2018, including compressive strength on cubes, split tensile strength on cylinders, and flexural strength on prisms, with a total of 24 cubes, 24 cylinders, and 24 prisms tested. The experimental program compared conventional concrete with fiber-reinforced concrete to evaluate improvements in strength, ductility, and crack resistance.

In M40 concrete, the strong matrix resists cracking, while fibers enhance crack control and ductility. Superplasticizers ensured workability and uniform fiber dispersion, while the low water-cement ratio provided durability, reduced permeability, and better resistance against fatigue and environmental effects. Fiber contents of 0.5%, 1%, and 1.5% (by weight of cement) were used, with equal proportions of bamboo and sisal fibers.

As validation 1.5m Reinforced concrete beams were also casted with the optimal proportion of fibers and compared with 1.5m Reinforced concrete beams of conventional concrete mix.

Compressive strength test of HFRC showed that 0.5% addition of each fiber constituting a total of 1% Hybrid fibers showed good early strength and was found to be optimal. After 28 day curing period, it showed similar compressive strength compared to conventional M40 concrete.

Table 1: Compressive Strength (MPa)			
Fiber content	7 days	14 days	28 days
0%	36.6 7	39.1	50.2 1
0.5% (0.25%+0.25%)	26.6	25.3	38.5 1
1% (0.5%+0.5%)	41.3 3	45.8	50
1.5% (0.75%+0.75%)	23	29.8	38.3 1

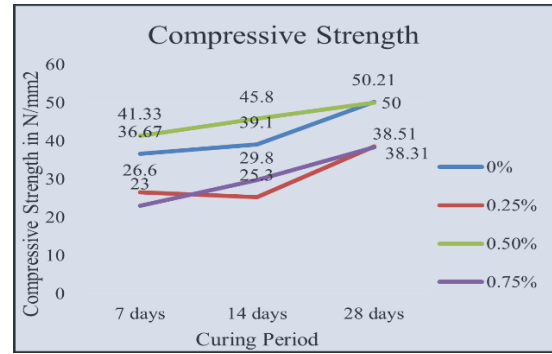


Figure 2: Compressive strength graph

Split tensile test of HFRC showed that 0.5% addition of each fiber constituting a total of 1% Hybrid fibers showed a good improvement in Tensile strength and was found to be optimal. After 28 day curing period, the tensile strength of 0.5% Hybrid Fiber Reinforced concrete showed 12% improvement over conventional concrete. Other Fiber concentrations showed reduced strength compared to conventional concrete.

Table 2: Tensile Strength (MPa)			
Fiber Content	7 days	14 days	28 days
0%	2.35	2.45	2.78
0.5% (0.25%+0.25%)	2.08	2.48	2.5
1% (0.5%+0.5%)	2.7	3.1	3.15
1.5% (0.75%+0.75%)	1.86	2.4	2.35

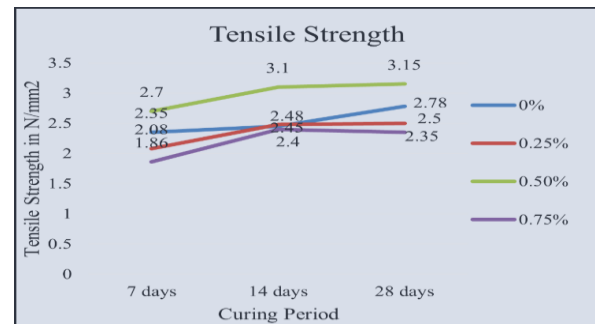


Figure 3: Tensile strength graph

Flexural Strength test of HFRC showed that 0.5% addition of each fiber constituting a total of 1% Hybrid fibers showed a good improvement in the flexural strength and was found to be optimal percentage. After 28 day curing period, the flexural strength of 0.5% Hybrid Fiber Reinforced concrete showed 6.4% improvement when compared to conventional concrete. 0.25% fiber concentration

showed slightly reduced flexural strength compared to the optimal concentration but was on par with the control mix.

Table 3: Flexural Strength (MPa)			
Fiber Content	7 days	14 days	28 days
0%	4.32	4.87	5.16
0.5% (0.25%+0.25%)	4.67	4.8	5
1% (0.5%+0.5%)	4.93	5.2	5.49
1.5% (0.75%+0.75%)	2.47	3.825	4.07

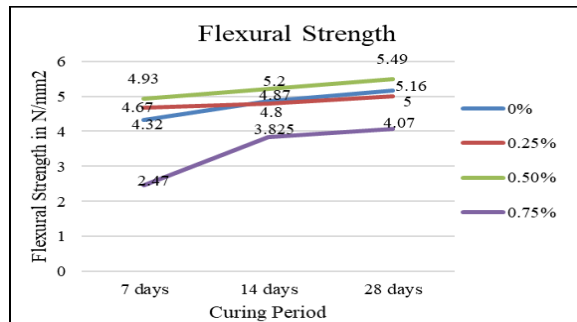


Figure 4: Flexural strength graph

After testing 1.5m RC beams, the deflection of the beams was measured at 2kN increments and the crack widths and crack patterns were also noted.

Control beams with 0% fibers had a yield point at around 84 kN and Beams with 1% (0.5% Bamboo + 0.5% Sisal) Fibers yielded at around 76 kN. The average ultimate load of Control beams was 99kN and the average ultimate load of HFRC beams was 106kN, which is a 7% increase in the ultimate load carrying capacity.

The ductility index of the beams is shown in Table 4. The average ductility index of HFRC beams is higher compared to the conventional RC beams which shows good energy absorption even after yielding and takes load even after a considerable amount of deflection.

The crack widths measured at failure are shown in table 5. These results show that there is a good crack bridging at the early stages of loading and crack propagation is also limited due to the fibers.

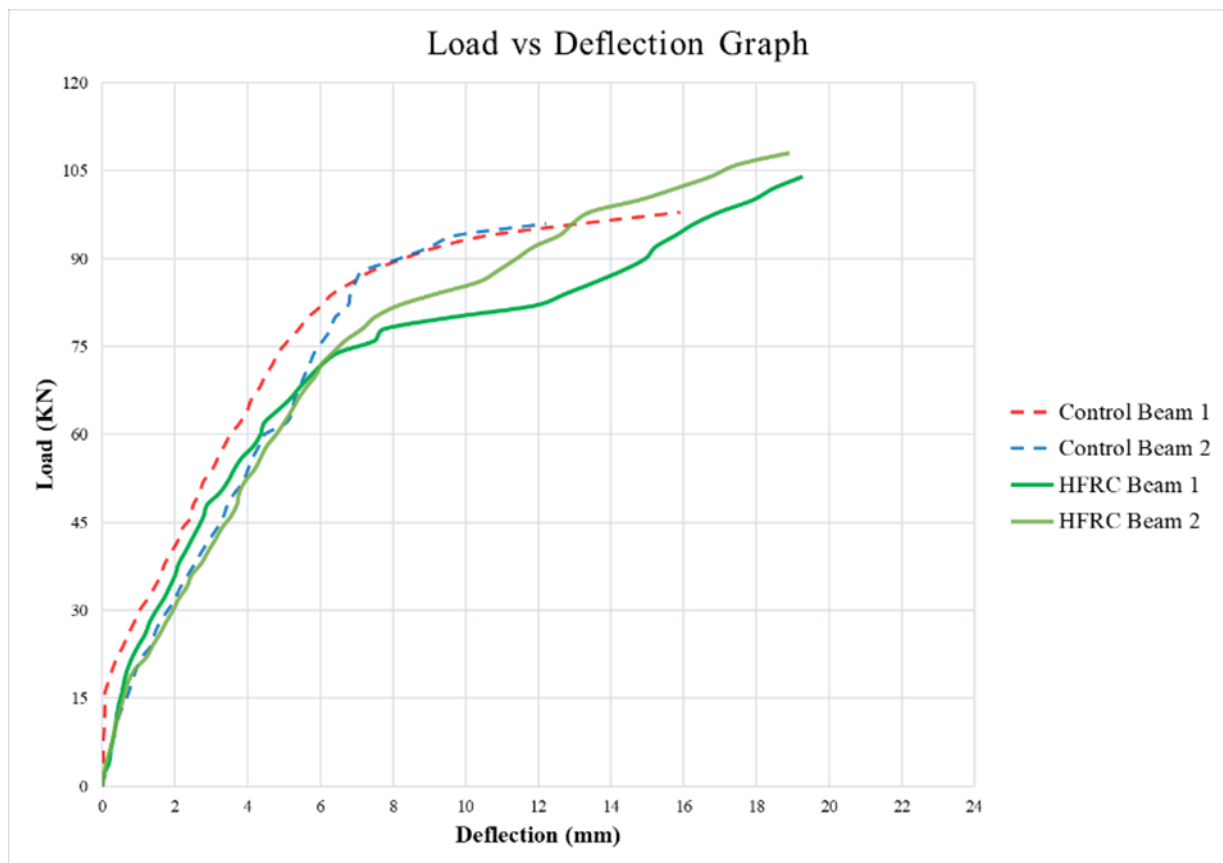


Figure 5: Load v/s Deflection Graph of RC beams



Figure 6: Crack Patterns of RC beams at Ultimate load (CB: Control Beam, NF: Hybrid Natural Fiber RC beam)
(a) CB 01 (b) CB 02 (c) NF 01 (d) NF 02

Beam ID	First Tension Crack Load (kN)	First Shear Crack Load (kN)	Ultimate Load (kN)	Crack Pattern Observations
CB1 (Conventional RC)	24	40	98	Fewer but wider cracks concentrated near mid-span, with some inclined cracks near supports. Cracks were longer, with larger spacing.
CB2 (Conventional RC)	22	44	96	Similar to CB1 – flexural cracks in bending zone, shear cracks appeared earlier, wider propagation, fewer secondary cracks.
NF1 (Hybrid fiber RC)	26	56	104	Multiple fine cracks distributed along span, shorter in length, with delayed shear cracks. Fibers bridged cracks and reduced crack widths.
NF2 (Hybrid fiber RC)	26	62	108	Crack propagation controlled with many finer cracks, improved ductility. Higher shear resistance and delayed crack widening compared to CB beams.

The comparison between the conventional reinforced concrete beams (CB1 and CB2) and the hybrid fiber-reinforced beams (NF1 and NF2) highlights the positive influence of bamboo and sisal fibers in enhancing structural performance. In the control specimens (CB beams), the first visible flexural cracks developed at relatively lower loads of 22–24 kN, whereas in the fiber-reinforced specimens, this was postponed to 26 kN. Similarly, shear cracks appeared much earlier in the control beams (40–44 kN) than in the fiber-reinforced beams (56–62 kN), indicating that the fibers improved the shear resistance of the concrete matrix.

The maximum load-carrying capacity also showed improvement, with conventional beams sustaining about 96–98 kN, while the fiber-reinforced beams carried higher loads in the range of 104–108 kN—an increase of nearly 8–12%. The crack development pattern further confirms these improvements: the CB beams exhibited fewer but longer and wider cracks, particularly in the central span and near the supports. In contrast, the NF beams displayed a larger number of fine, shorter cracks distributed along the beam length. This indicates better stress distribution, effective crack control, and reduced crack opening due to the fiber-bridging mechanism.

In summary, the integration of bamboo and sisal fibers significantly improved the ductility, crack resistance, and overall load capacity of the reinforced beams, demonstrating the effectiveness of hybrid fiber reinforcement in enhancing the flexural behavior of concrete structures.

V. CONCLUSIONS

The integration of sisal and bamboo fibers significantly improves the overall mechanical characteristics of concrete in comparison to conventional M40 concrete; sisal enhances tensile strength and crack control, whereas bamboo contributes to flexibility and ductility, creating a complementary effect.

The most effective fiber dosage was determined to be 1% of cement weight (0.5% sisal + 0.5% bamboo), which provided a well-balanced improvement in compressive, tensile, and flexural properties while

retaining adequate workability.

After 28 days of curing, the compressive strength of HFRC containing 1% hybrid fibers was on par with that of normal M40 concrete, while mixes with lower or higher fiber contents displayed strength reductions due to clumping and poor dispersion.

The split tensile strength of HFRC showed an increase of nearly 12%, and flexural strength improved by approximately 6.4% at 28 days compared to the control mix, confirming the efficiency of hybrid fibers under tensile and flexural loading.

Reinforced concrete beams made with HFRC demonstrated superior structural behavior, including a 7% rise in ultimate load capacity, smaller crack widths, finer crack patterns, and higher ductility indices, indicating greater energy absorption and better post-yield load retention.

Although fiber addition reduced workability due to higher water absorption, the application of a superplasticizer successfully restored slump values and ensured uniform fiber distribution within the mix.

The incorporation of natural fibers such as sisal and bamboo presents a sustainable, economical, and environmentally friendly alternative to synthetic fibers and steel, aligning with green construction principles while maintaining strong structural performance.

The investigation confirms that incorporating a hybrid blend of sisal and bamboo fibers into concrete is an effective approach to improve flexural strength, ductility, and crack control in reinforced concrete members. An optimum dosage of 1% fiber content provides the most favourable balance between strength and serviceability without reducing compressive capacity. Overall, the results highlight both the structural benefits and the environmental advantages of using hybrid natural fibers, making them a practical and sustainable alternative to conventional reinforcement methods in modern construction.

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