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RESEARCH ARTICLE

Flexural Performance of HSC beams containing natural fibers

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Abstract
This research study investigates the structural performance of high-strength concrete (HSC) reinforced rectangular beam under flexure with the impact of banana fiber, coir fiber and alccofine for M70 grade concrete. In this research, natural banana fiber and coir fiber were employed for strengthening HSC at 0.5%, 1%, 1.5%, and 2% by volume, while the cement was partially substituted with a 15% alccofine content in weight. Nine rectangular reinforced concrete beams were fabricated and tested under flexure to assess the structural performance, including load-carrying capacity, load–deflection relationship, ductility index, load-strain relationship, failure mode, and crack patterns. The reinforcement was designed considering the under-reinforced section. The test results revealed that the inclusion of banana and coir fiber in high-strength concrete significantly enhances the ultimate load-carrying capacity of RC beam by 42.86% and 35.71%, respectively, attributed to synergistic action between fiber and aggregate interlink system of concrete.

Keywords Alccofine · Banana fiber · Coir fiber · Flexural performance · High strength concrete (HSC)

1 Introduction

Concrete is the widely used vital building material, valued for its various structural engineering applications, economic effectiveness, vast availability, and load carrying capacity [1, 2]. It is familiar that concrete is characterized by infirm behavior in tension but exhibits strength in compression [3, 4]. Moreover, after cracks, it behaves brittle and prevents stress transfer [5]. Research and technological advancements in materials science have demonstrated that fibers can be utilized in concrete production to sustain structural integrity, prevent crumbling, and improve structure ductility [6–9]. The development of fiber- reinforced concrete (FRC) has been one of the substantial developments in the construction sector [10, 11]. Fiber reinforced concrete is ordinary concrete that has been reinforced with fibers [12, 13]. According to the ACI standard [14], fiber has been classified into glass, steel, synthetic, and natural classes. The increasing focus on sustainable development in construction materials has led to a growing interest in replacing synthetic fibers with natural alternatives. Plant-based natural fibers, derived from renewable resources, offer a cost-effective and locally available alternative to synthetic fibers [15–17]. Natural fibers are also easily managed and do not cause a serious environmental risk [18]. Plant fibers have a rich history dating back to the inception of human civilization. Even during the Egyptian period, natural fibers like straw and horsehair were commonly combined to construct mud walls and roofs. Among the frequently utilized natural fibers are sisal, banana, bamboo, jute, coir, pine needle, hemp, and kenaf fibers [19–21]. Due to their superior qualities, banana and coir fibers are employed efficiently in construction materials [22, 23]. The main constituents of banana and coir fiber are lignin, cellulose, pectin, hemicellulose, and wax [24]. Most research on banana fiber and coir has primarily focused on ordinary concrete, with only limited studies reported on special concrete. Furthermore, there needs to be more research, particularly in the High-Strength Concrete (HSC) sector. The existing literature indicates that plant-based fibers can enhance the fundamental mechanical properties (including compressive, flexural, and tensile strength) and the ductility aspects (such as impact resistance, toughness, strain capacity and, post-peak cracking) of concrete [25]. Currently, the incorporation of natural fibers into High-Strength Concrete (HSC) for structural elements has garnered significant attention. Ismail Shah et al.

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[26] investigated on High-Strength Concrete (HSC) incorporating coconut fiber and sisal fiber at content levels of 0.5%, 1%, and 1.5% by mass of cement. The findings revealed that at a 1% content level, the inclusion of coconut fibers enhanced the compressive strength of HSC by 33%, while sisal fibers resulted in a 24% improvement. Amgad Elbehirya et al. [22] studied the flexural performance of RC beams utilizing banana fiber bars. The findings indicate that incorporating banana bars as a reinforcement material can substantially enhance the capacity to withstand spalling and cracking in concrete beams. Therefore, employing banana bars as the primary reinforcement in concrete results in a considerable increase in flexural strength, approximately 25% more than plain concrete. Wenli Quan et al. [27] fabricated an autoclaved aerated concrete (AAC) with natural bamboo and basalt fiber and investigated strength performance. The outcomes indicated that with the increase of fiber content, the area of hazardous pore, the slurry fluidity, the density, thermal conductivity and strength performance of AAC improved. Eswaramoorthi Palanisamy and Murugesan Ramasamy [28] investigated the mechanical and durability properties of Hybrid Fiber Concrete (HFC) incorporating polypropylene fiber (PP), sisal fiber (SF), and banana fiber (BF). The outcomes demonstrated that the combination of PP and SF yielded the highest strength performance compared to ordinary concrete. Hafsa Jamshaid et al. [29] investigated the strength characteristics of concrete reinforced with natural cellulosic fibers such as sisal, jute, coconut and sugarcane. The research revealed that integrating sisal and jute fibers led to significant enhancements, with a maximum improvement of 20% in compressive strength and 11% in split tensile strength discovered at a 2% fiber content by mass. Additionally, the insertion of fibers proved advantageous for the impact performance of the concrete. Lee and Choi [30] studied the impact of abaca fibers, ranging from 0 to 2% by cement weight, on high-performance cement composite. The findings indicated that the natural fiber exhibited inside curing performance. Abaca fibers proved beneficial in mitigating the hazard of cracking attributed to autogenous shrinkage in the cement composite. Taha A. El-Sayed et al. [31] observed that Hybrid Glass Fiber Reinforced Polymers (H-GFRP) bars exhibit a mechanical failure mechanism like reinforcement steel bars. They demonstrate a ductile failure mode upon reaching their maximum capacity, akin to steel bars. Moreover, the load–deflection curves for all H-GFRP beams show nearly complete model behavior, indicating an enhanced ductility with increasing load. Taha A. El-Sayed et al. [32] observed that Ultra-High-Performance (UHP) Geopolymer Reinforced Concrete (RC) beams employ GFRP bars as an alternative to conventional steel reinforcement. Utilizing UHP geopolymer concrete in RC beams enhanced ultimate load capacity and improved flexural performance compared to control beams made of High-Strength Concrete (HSC).Taha A. El-Sayed [33], accessed the impact of steel fibers obtained from industrial waste on reinforced concrete beams' flexural behavior. Concrete's strength and deformational properties are greatly enhanced when adding lathe waste. Compared to similar reinforced regular conventional concrete beams, reinforced lathe waste concrete beams exhibit less distortion. Abeer M. Erfan et al. [34] investigated the flexural behavior of nano-concrete beams. Furthermore, the HSC effect strengthened with GFRP. Compared to reinforced beams with steel bars, the failure loads of reinforced beams with GFRP bars increased. In the studied specimens, the ratio of failure load increases varies between 15.0% and 16.0%.Abeer M. Erfan et al. [35] examined the behavior of reinforced concrete (RC) beams under bending with the Basalt Fiber Reinforced Polymer (BFRP) reinforcement. Notably, incorporating BFRP bars led to a notable increase in the failure load of the beams, regardless of the concrete strength. On average, a remarkable enhancement of 93.0% was observed in specimens with a concrete strength of 30.0 MPa. Taha A. El-Sayed [36] reported that the incorporating lathe waste fibers into recycled concrete geopolymer beams resulted in substantial enhancements across various performance metrics, including loading carrying capacity, energy absorption, and displacement ductility. Notably, both steel and lathe fibers added to the geopolymer concrete beams demonstrated superior characteristics compared to the control group.

Based on the existing literature, most research studies have primarily focused on testing reinforced concrete (RC) beams with normal-strength concrete. Consequently, there needs to be more information regarding the influence of natural fibers in high-strength concrete (HSC) on the behavior of RC beams. Despite the growing interest in using natural fibers in HSC, more research is needed to investigate the flexural performance of HSC incorporating natural fibers. The present study aims to bridge this gap by exploring the flexural behavior of RC beams constructed using HSC containing banana and coir fibers as concrete material.

This research investigates the structural performance of RC beams made with HSC under flexure. The study explores the influence of banana and coir fibers in HSC reinforced beam. The structural behavior including load-carrying capacity, load–deflection relationship, ductility index, load-strain relationship, failure mode, and crack patterns were analyzed under flexure.

2 Research significance

In light of the colossal advancements in concrete technology, there is a growing need to fabricate sustainable high-strength concrete (HSC). High-strength concrete is susceptible to crumbly behavior and does not allow the transfer of stress after fissures, which can impact its long-term performance. An attempt was made in this research to add natural fibers

Table 1 Oxide composition of cement and alccofine

Oxide (%)	OPC	Alccofine
SiO_2	18.60	35.30
Al_2O_3	5.60	21.40
CaO	63.90	32.23
Fe_2O_3	4.10	1.20
MgO	1.92	8.20
SO_3	2.40	0.13
K_2O	0.82	-
Na_2O	0.44	-
LOI	1.35	-

Table 2 Physical characteristics of cement and alccofine

Properties	Specific gravity	Standard consistency	Initial setting time	Final setting time
Cement	3.14	28.9%	38 Minutes	612 Minutes
Alccofine	2.71	-	-	-

to HSC mixes. This study involved extensive experimental work, utilizing banana and coir fibers in various proportions in combination with supplementary cementitious materials (SCMs) such as alccofine. The flexural performance of natural fiber HSC was studied for the M70 grade of concrete.

3 Methodology

3.1 Materials

The binding material used for this experiment was Ordinary Portland Cement (OPC) of grade 53, conforming to IS 12269: 2013 standards[37]. Table 1 exhibits the chemical composition of the binder material. The cement's properties were assessed in line with IS 4031(Part 4): 1988 [38] and IS 4031 (Part 5): 1988 [39], as outlined in Table 2. As per IS 383: 2016 [40], the fine aggregate of Zone III grading was used. The fine aggregate of 4.75 mm and coarse aggregate of 10 mm were used in concrete manufacturing. The fine aggregate had a specific gravity of 2.78, a 1662 kg/m^3 bulk density, and a fineness modulus of 2.81. The coarse aggregate had a specific gravity of 2.60, a 1585 kg/m^3 bulk density, and a fineness modulus of 2.72. This study employs finer materials, including alccofine-1203, as SCM to achieve optimal slump and strength. Alccofine is obtained from blast furnace slag and is characterized by its micro-fine nature, low calcium silicate content and a distinctive distribution of particle size. Water with a pH range of 7.0 to 8.5 was used for mixing the concrete. In addition, a high-performance chemical water-reducing agent was utilized to enhance the concrete's workability. As seen in Figs. 1 and 2, two distinct types of natural fibers were selected for this investigation: banana and coir fibers with densities of 1.10 g/cm^3 and 1.30 g/cm^3, respectively, obtained from a nearby factory. These fibers were chopped into 40 mm length and 1 mm diameter. Tables 3 and 4 show pertinent physical and chemical characteristics of the banana and coir fibers.

Fig. 1 Banana fiber

Fig. 2 Coir fiber

Table 3 Physical characteristics of natural fibers

Properties	Length	Diameter	Density	Elastic Modulus
Banana fiber	40 mm	1 mm	1.30 g/cm^3	9 -16 GPa
Coir fiber	40 mm	1 mm	1.10 g/cm^3	6 GPa

Table 4 Chemical characteristics of natural fibers

Properties	Lignin	Cellulose	Pectin	Hemicelluloses	Extractives	Moisture
Banana fiber (%)	18	55	3.50	15.90	8	
Coir fiber (%)	40–45	32–43	1.80	-	-	8

3.2 Mix proportions

The concrete mix was designed per IS 10262: 2019 [41], specifically targeting the M70 grade. In the controlled mix, 15% of alccofine was partially included to substitute cement content. To maintain a consistent water-cement ratio of 0.29 across all mixtures. Table 5 provides the detailed mixture proportions for High-Strength Concrete (HSC). A water-reducing admixture of the polycarboxylate ether type was incorporated to ensure the desired workability. Moreover, the concrete mixes were enriched with banana and coir fibers at 0.5%, 1%, 1.5%, and 2% based on the volume of the concrete mixture. The nomenclature for the concrete mixes was established as follows: 'NFC' signifies natural fiber concrete, 'BF' and 'CF' represent the type of fiber (banana and coir in this case), and the numeral indicates the percentage of fiber content.

4 Experimental program

4.1 Compressive strength

According to IS 516: 2018 [42], the compressive strength properties of concrete were tested at ages 3, 7, and 28 days using varying amounts of banana and coir fiber with alccofine.

4.2 The beam specifications

The flexural beam was created as per IS 456: 2000 [43] standards. The dimensions of the designed beam were 2100 mm × 150 mm × 230 mm. The beams were designed as singly reinforced beams, featuring three numbers of 10 mm diameter bars in the tension zone and two numbers of 10 mm diameter bars serving as hanger bars. Two-legged stirrups with a diameter of 8 mm were positioned in the beam at a spacing of 150 mm to hamper shear failure. Figure 3 displays the beam cross-section.

4.3 Casting of beam

In this study, nine RC beams were cast for flexural testing. Four banana fiber and four coir fiber infused RC beams with varying percentages of strengthening and one control RC beam. Wood plates were used to prepare the mould following the size of the beam. The 5 mm strain gauge was mounted to the tensile rebar. Before fixing the strain gauge, the tension bar surface needs to be ground smoothly. The concrete was properly mixed in accordance with the desired mix proportions. The mould was carefully filled with concrete and leveled. After demolding, the beam underwent a water-curing process for 28 days, facilitated using gunny bags. Figure 4 displays the fabrication process of beam.

4.4 Testing of beam

The experimental setup of a beam is illustrated in Fig. 5. Three dial gauges were affixed at strategic locations to measure the deflection of the beam at both its midpoint and the applied load point. Three strain gauges were mounted to measure the strain. Precisely, 5 mm strain gauges were meticulously positioned along the length of the tensile rebar. Additionally, a 10 mm strain gauge was adhered to the top

Table 5 Mixture proportions (kg/m^3)

Mix ID	Cement	Alccofine	Water	Sand	CA	SP	Fiber (%)	
							BF	CF
CC	435.36	76.83	149	692.76	1120.34	5.08	-	-
NFCBF0.5	435.36	76.83	149	692.76	1120.34	5.08	0.50	-
NFCBF1	435.36	76.83	149	692.76	1120.34	5.08	1.00	-
NFCBF1.5	435.36	76.83	149	692.76	1120.34	5.08	1.50	-
NFCBF2	435.36	76.83	149	692.76	1120.34	5.08	2.00	-
NFCCF0.5	435.36	76.83	149	692.76	1120.34	5.08	-	0.50
NFCCF1	435.36	76.83	149	692.76	1120.34	5.08	-	1.00
NFCCF1.5	435.36	76.83	149	692.76	1120.34	5.08	-	1.50
NFCCF2	435.36	76.83	149	692.76	1120.34	5.08	-	2.00

CA – Coarse Aggregate and SP – Super plasticizer

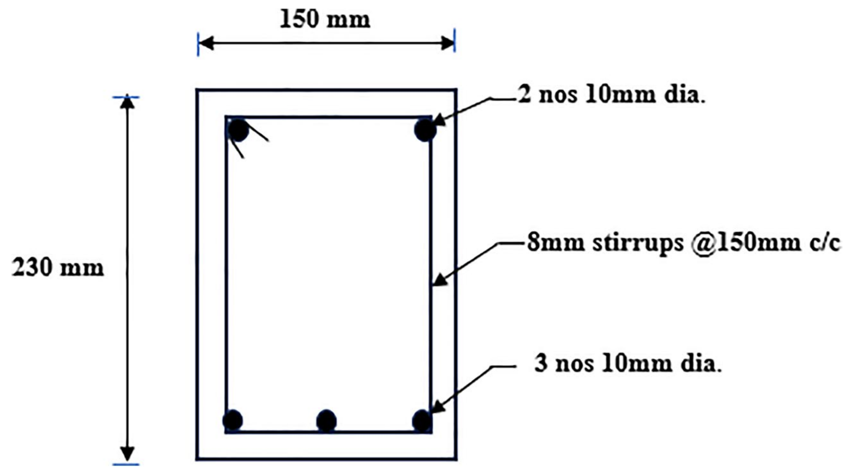


Fig. 3 Beam cross sectional view

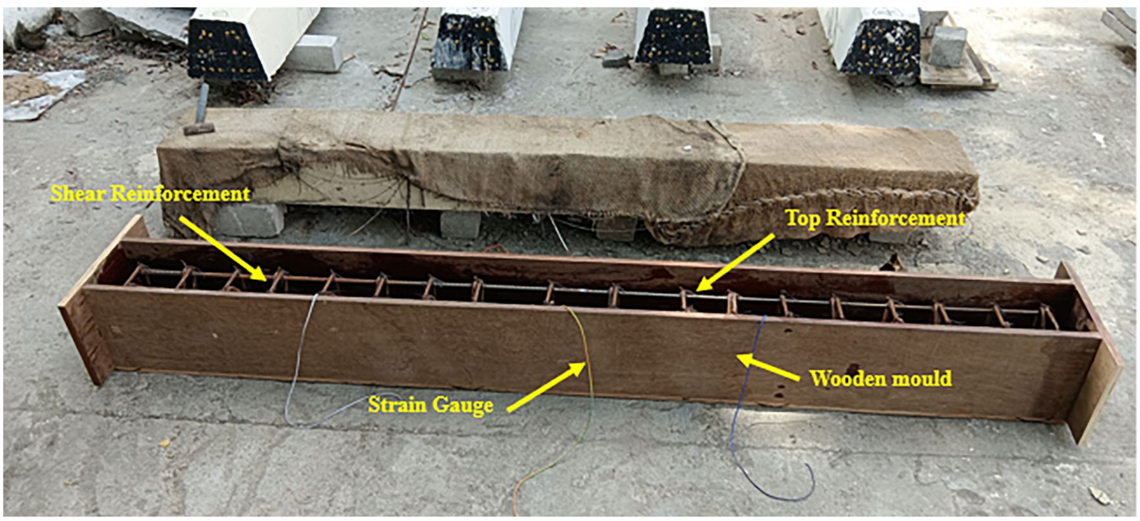


Fig. 4 Fabrication process of Beam

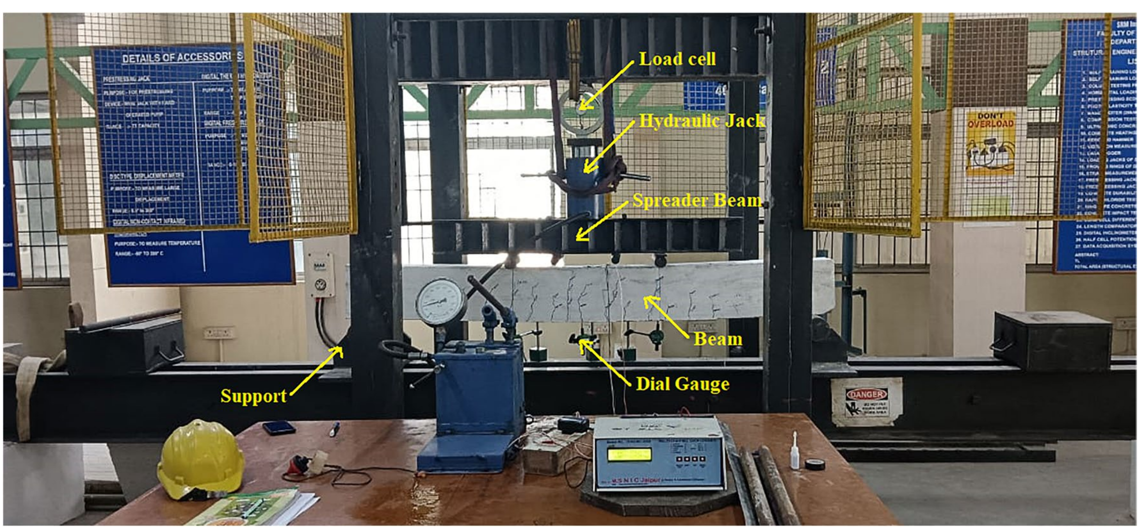


Fig. 5 Beam experimental test setup

section of the span to capture the compressive strain exhibited by the concrete component. After confirming the safety of personnel and instruments, the beams underwent a four-point bending test, and the schematic depiction of the beam specimen experiment arrangements is shown in Fig. 6. Two concentrated loads were delivered to the test beam using a hydraulic boom and spreader beam. The beam specimen was initially loaded in 5kN, 10kN, and 15kN increments. The strain, load data, and deflection were observed and documented. An optical microscope held by hand, featuring a magnification of 40 and a sensitivity of 0.01 mm, was employed to evaluate the width of the crack.

5 Results and discussion

5.1 Compressive performance of HSC

The findings of experiments on the compressive strength of High-Strength Concrete (HSC) mixtures, incorporating different combinations of banana and coir fibers and subjected to various curing durations, are illustrated in Figs. 7 and 8. Incorporating banana and coir fibers and a specific amount of alccofine enhances compressive strength. The results from each series indicate that, following 28 days of water curing, the compressive strength surpassed that of other mixtures, especially when incorporating 1% banana fiber and 1% coir fiber. The preferable physicochemical characteristics of the fibers and binders could be the reason for this enhancement. Compared to traditional concrete, the NFCBF0.5, NFCBF1.5, and NFCCF0.5 mixtures exhibited marginal enhancements in compressive strength, with increases of 1.79%, 0.81%, and 0.87%, respectively. Conversely, the NFCBF2, NFCCF1.5, and NFCCF2 mixtures resulted in a decline in compressive strength, showing decreases of 1.60%, 1.67%, and 2.64%, respectively. The study findings revealed that when compared to source mixtures of HSC after a 28-day curing period, NFCBF1 and NFCCF1 blends at 1% fiber dosage enhanced compressive behavior at 3.84% and 2.05%, respectively. In contrast, banana fiber concrete strengthened structures better than coir fiber concrete. The influence of the natural fiber and aggregate integrate structure was strengthened, preventing, and delaying the significant growth of micro-fissures.

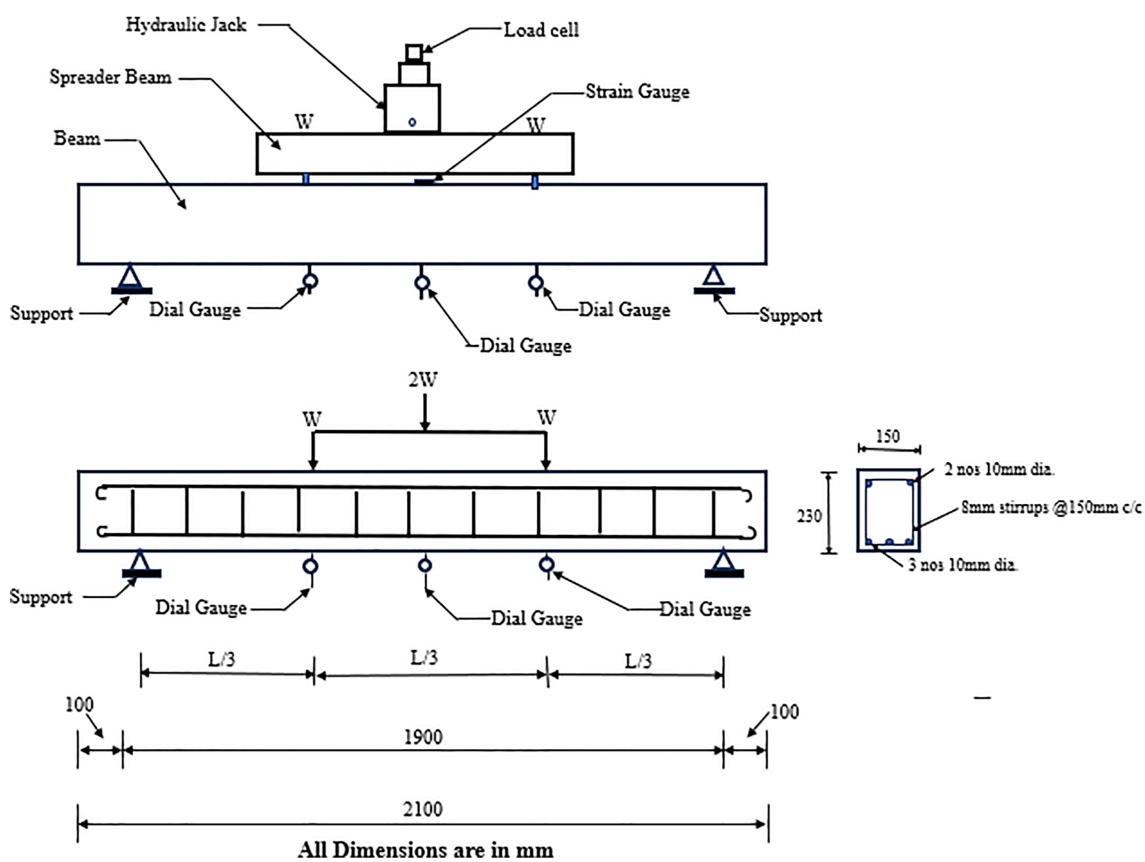


Fig. 6 Schematic view of flexural beam test setup

5.2 Load carrying capacity

Tables 6 and 7 present the theoretical and experimental values for the load-carrying capacity and moment of a RC beam using varying proportions of banana fiber and coir fiber and a certain quantity of alccofine. These values are assessed at both the service and final (ultimate) stages. Notably, the RC beams containing banana and coir fiber demonstrated greater load-carrying capacity and moment than conventional RC beams. In all the experiments, it becomes apparent that the load-carrying capacity of the beams, particularly when incorporating 1% banana fiber and 1% coir fiber with certain amount of alccofine, exhibited outstanding performance compared to the remaining specimens. According to the results, the load-carrying capacity of the BF-induced RC beam at 1% dosage

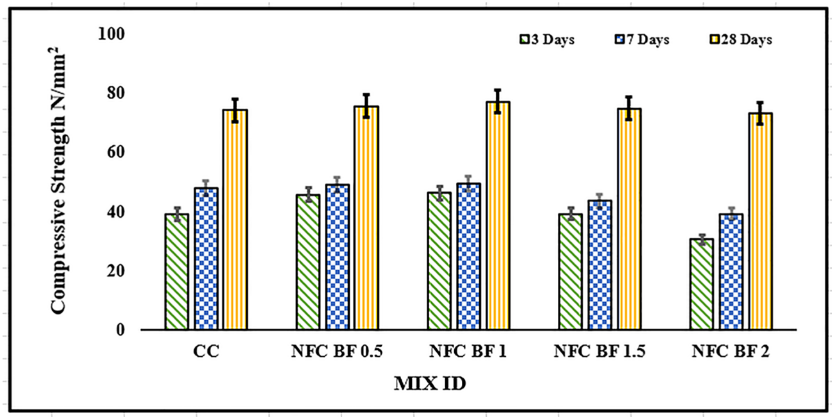


Fig. 7 Compressive strength experiment results of NFCBF

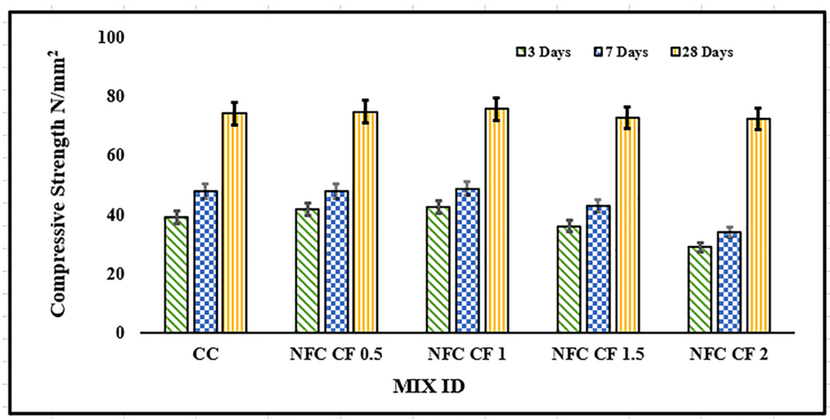


Fig. 8 Compressive strength experiment results of NFCCF

Table 6 Load and moment values at the service phase

Mix ID	Depth of neutral axis (mm)	Experimental data		Theoretical data		Capacity ratio (Exp / Theo)
		Load (kN)	Moment (kN.m)	Load (kN)	Moment (kN.m)	
CC	25.55	46.67	14.78	41.95	13.29	1.11
NFCBF0.5	25.10	60.00	19.00	41.99	13.30	1.43
NFCBF1	24.61	66.67	21.11	42.04	13.31	1.59
NFCBF1.5	25.34	56.67	17.94	41.97	13.29	1.35
NFCBF2	25.97	53.33	16.89	41.92	13.27	1.27
NFCCF0.5	25.33	56.67	17.94	41.97	13.29	1.35
NFCCF1	25.10	63.33	20.06	41.99	13.30	1.51
NFCCF1.5	25.98	53.33	16.89	41.91	13.27	1.27
NFCCF2	26.24	50.00	15.83	41.89	13.27	1.19

Table 7 Load and moment values at the ultimate phase

Mix ID	Depth of neutral axis (mm)	Experimental data		Theoretical data		Capacity ratio (Exp / Theo)
		Load (kN)	Moment (kN.m)	Load (kN)	Moment (kN.m)	
CC	25.55	70	22.17	62.93	19.93	1.11
NFCBF0.5	25.10	90	28.50	62.99	19.95	1.43
NFCBF1	24.61	100	31.67	63.06	19.97	1.59
NFCBF1.5	25.34	85	26.92	62.96	19.94	1.35
NFCBF2	25.97	80	25.33	62.87	19.91	1.27
NFCCF0.5	25.33	85	26.92	62.96	19.94	1.35
NFCCF1	25.10	95	30.08	62.99	19.95	1.51
NFCCF1.5	25.98	80	25.33	62.87	19.91	1.27
NFCCF2	26.24	75	23.75	62.84	19.90	1.19

increased by 42.86%. In comparison, the load-carrying capacity of the CF at 1% increased by 35.71%. In this case, banana fiber and coir fiber were found to be effective in preventing cracks from growing. Fibers must be used in the cement matrix to prevent microcracks from expanding. Natural fibers offer good tug-out capacity; more energy is lost when significant cracks emerge. As a result, the crack's expansion is postponed, and load carrying capability is increased. The load-carrying capacity of the beam is effectively increased by the complementary failure processes of the banana and coir fibers. As a result, prior to flexure failure, the deflection is significant and able to withstand a greater load. Additionally, it might issue a failure alert. Using IS456:2000 [43]standards, the experimentally obtained moment was compared to the theoretical moment. The experimental ultimate moment for the conventional reinforced concrete beam was 11.24% greater than the theoretical values, while for the banana fiber and coir fiber RC beams; it ranged from 19.36% to 58.89% higher. The strength enhancement shows banana and coir fiber integration in the matrix. The capacity ratio serves as a parameter to gauge the discrepancy between experimental and theoretical results. It represents the experimental values to theoretical values ratio. In the context of RC beams, the addition of natural fiber enhances the capacity ratio. Specifically, the capacity ratio for the NFCBF0.5, NFCBF1, NFCBF1.5, and NFCBF2 beams exceeded that of the conventional RC beam by 28.83%, 43.24%, 21.62%, and 14.41%, respectively. Similarly, for the NFCCF0.5, NFCCF1, NFCCF1.5, and NFCCF2 beams, the capacity ratio surpassed that of the CC beams by 21.62%, 36.04%, 14.41%, and 7.21%, respectively. Across all the series, it is evident that the capacity ratio, especially when incorporating 1% BF and 1% CF with certain amount of alccofine, exhibited exceptional performance contrast to the other test specimens. Several researchers revealed a similar trend of improving load carrying capacity with the incorporation of fibers in concrete [22, 44, 45]

5.3 Deflections behaviour

The beam deflection was measured at the load point and midpoint along the beam span. Figures 9 and 10 show the load–deflection behavior of the beam at its midpoint. It was discovered that the same load–deflection pattern could be seen in all the tested beams. Due to the enhanced cohesiveness between the fiber and concrete at the earlier phase, there is no confluence slide. After the initial crack appeared, all the beams displayed nonlinear behavior. Compared to a conventional RC beam, the natural-fiber incorporated RC beam specimens were able to resist more significant deflections at the final stage. It was shown that banana fibers provide a superior fiber anchorage mechanism to coir fiber, increasing the beam's flexural strength and post-fissures bridging performance. Additionally, coir and banana fiber make concrete more potent and flexible, slowing the breaking process. Therefore, adding banana and coir fiber strengthens the concrete's flexural properties, as seen in the deflection curve. The NFCBF1 and NFCCF1 specimen exhibit superior deflection resistance compared to other specimens during their final stages. In the ultimate stage, the NFCBF1 specimen can endure a mid-span deflection of 26.00 mm, representing an impressive 88.13% increase over the control sample. Similarly, the NFCCF1 specimen can sustain a mid-span deflection of 22.58 mm, showcasing a remarkable 63.39% improvement over CC. However, the allowed maximum of span/250 is required by IS 456:2000[43] standards to meet the requirements for structural safety and appearance. It was determined that including banana fiber and coir fiber with alccofine considerably enhanced the load deflection of the beam through a synergetic effect.

5.4 Ductility behaviour

Ductility was assessed by analyzing the beam's deflection, with the ductility ratio (μ) calculated as $\mu = \Delta u / \Delta y$, where Δu represents the beam's ultimate (maximum) deflection,

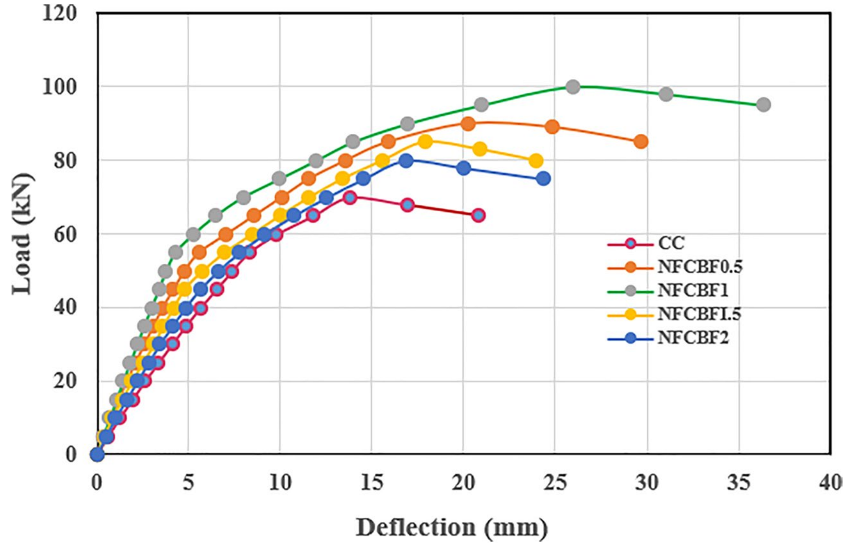


Fig. 9 Mid span load—deflection curve of banana fiber RC beam

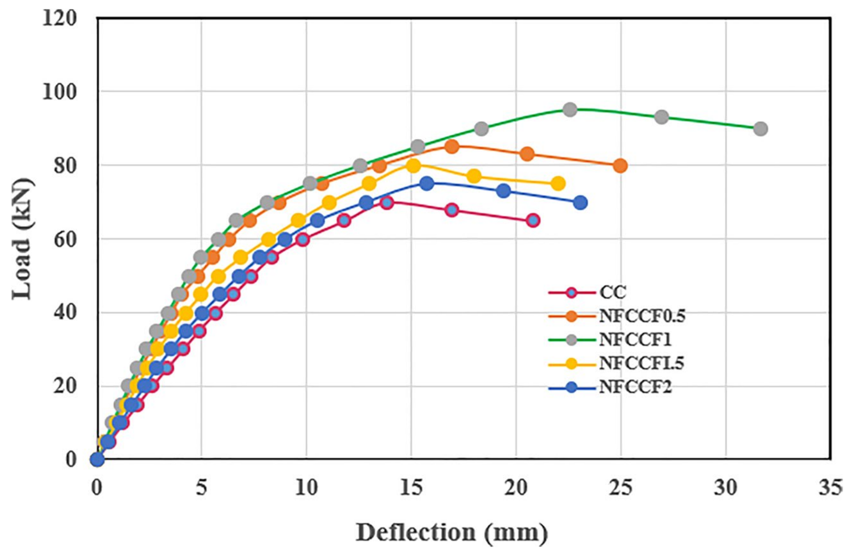


Fig. 10 Mid span load—deflection curve of coir fiber RC beam

and Δy is the deflection when the rebar reaches its yield point. The ductility ratios for all beams are depicted in Table 8. Generally, an excellent ductility ratio (μ) indicates an RC beam can endure significant deflections prior to failure. The ductility ratios of all beam specimens surpass 4, indicating a notably favorable level of ductility. Notably, the banana and coir fiber integrated RC beam shows a significantly greater ductility ratio than the conventional RC beam. Adding 1% each of coir and banana fiber resulted in the most tremendous increase in ductility. The NFCBF1 and NFCCF1 beam specimens' ductility ratios were 87.56% and 62.93% greater, respectively than those of the conventional RC beam specimens. Including banana and coir fibers in the RC beam led to a remarkable rise in the ductility ratio. The fiber added to the concrete prevents cracks from forming and helps to bridge them, reducing the cracks. As a result, the crack's propagation

Table 8 Deflection and ductility behavior

Mix ID	Yield phase deflection (Δ y)		Ultimate phase deflection (Δ u)		Ductility ratio ($\mu = \Delta$ u/Δ y)
	Load (kN)	Deflection (mm)	load (kN)	Deflection (mm)	
CC	25	3.37	70	13.82	4.10
NFCBF0.5	35	3.08	90	20.22	6.56
NFCBF1	46	3.38	100	26.00	7.69
NFCBF1.5	32	3.12	85	17.89	5.73
NFCBF2	30	3.44	80	16.85	4.90
NFCCF0.5	33	3.06	85	16.91	5.53
NFCCF1	42	3.38	95	22.58	6.68
NFCCF1.5	30	2.94	80	15.11	5.14
NFCCF2	27	3.54	75	15.78	4.46

diminished, increasing the post-cracking region's ability to support greater loads.

5.5 Load-strain relationship

Figures 8 and 9 show the load-strain correlation at the middle span of the beams. The top layer of the concrete in the compression region and the tension in the rebar strains are depicted in the figure, respectively. The load-strain curves in Figs. 11 and 12 can be separated into the elastic and yield phases. In the elastic stage, the curves are nearly identical. At this level, the strain on concrete and rebar is not dramatically changing trends. Because the banana fiber and coir fiber-reinforced beam may continue to support some of the load even after the concrete begins to crack, the rate at which rebar and concrete underwent strain increase has decreased. When rebar and concrete's load-strain curves are compared, the rebar has already reached the yield region prior to the concrete's maximal compression strain, demonstrating that its distinctive characteristics have been completely utilized. The beam develops microcracks because of the loading process; however, even a cracked beam can support loads owing to the bridging effect of fibers.

5.6 Cracking characteristics

Figure 13 displays the crack pattern of the tested beams. There were two forms of failures seen in the beam specimens. The initial failure occurred due to the concrete crushing at the upper section of the beam, while the subsequent failure resulted from the yielding of the tension reinforcement. Table 9 lists all the beam specimens' different cracking properties. The surface of the beam has vertical cracks, which indicate that flexure is the cause of the failure. The

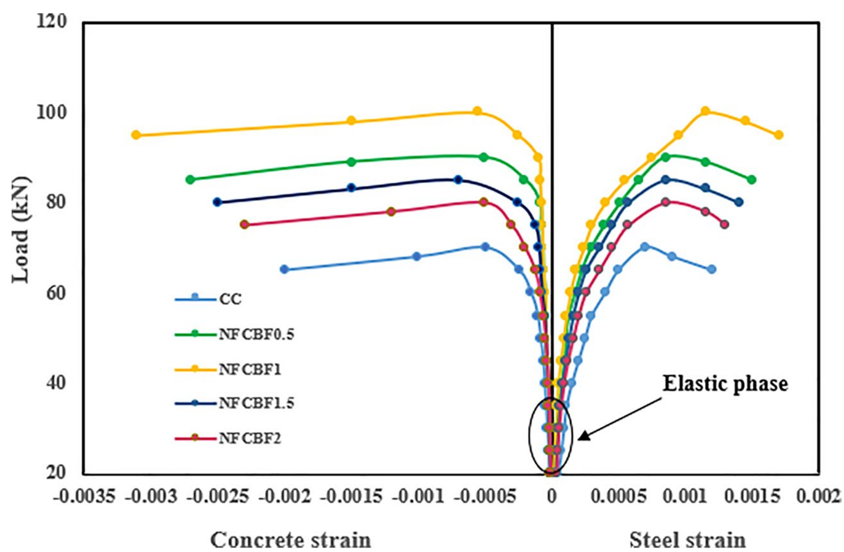


Fig. 11 Load-strain correlation of steel and banana fiber concrete

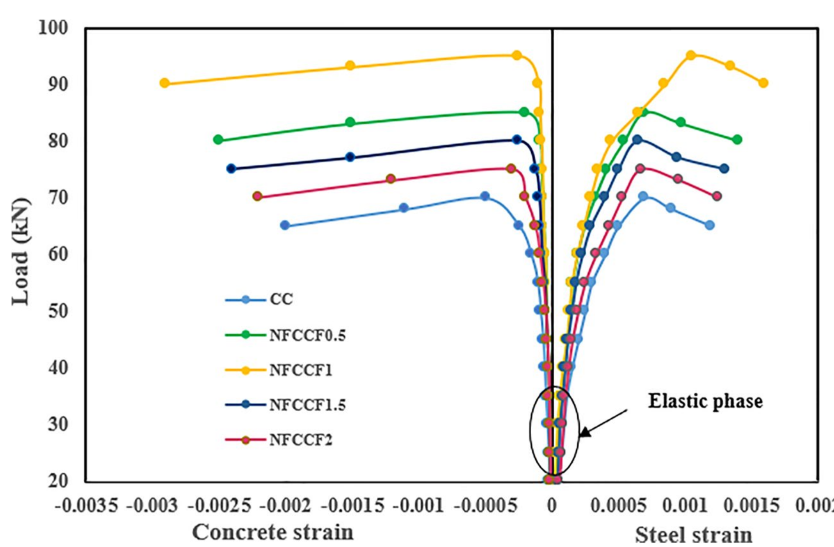
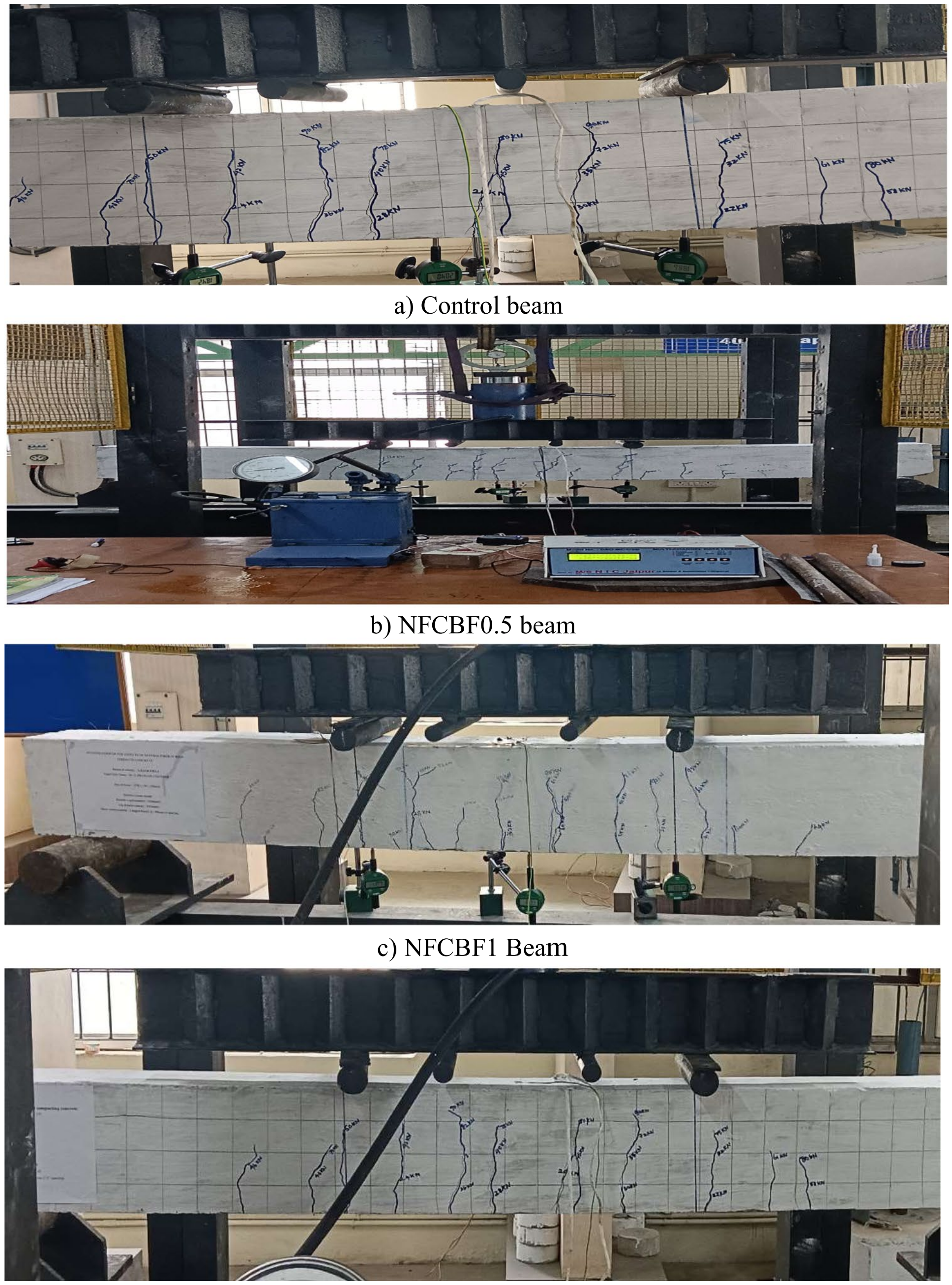


Fig.12 Load-strain correlation of steel and coir fiber concrete



a) Control beam

b) NFCBF0.5 beam

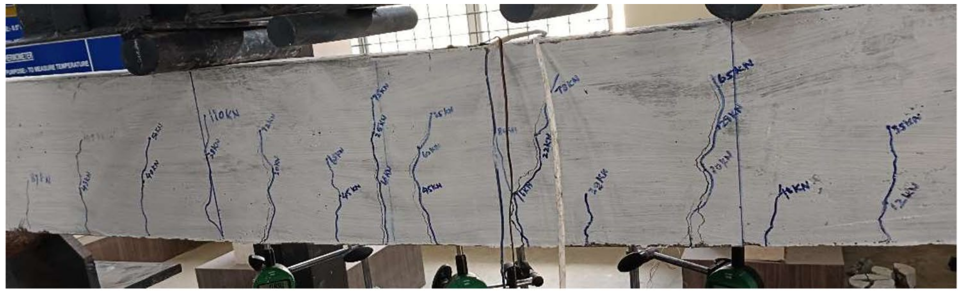
c) NFCBF1 Beam

d) NFCBF1.5 Beam

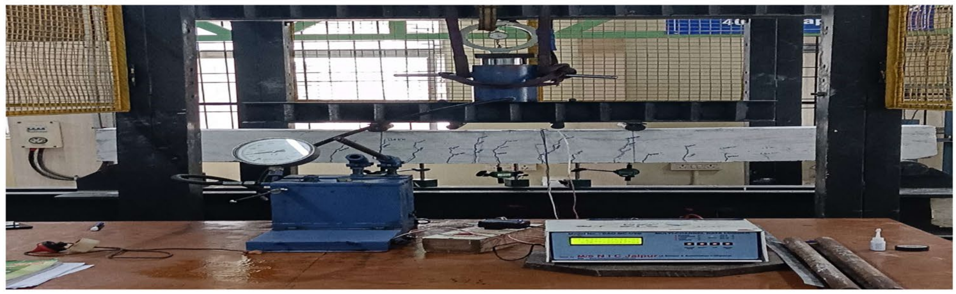
Fig. 13 Cracks patterns of all tested beams

first crack loads of CC, NFCBF0.5, NFCBF1, NFCBF1.5, NFCBF2, NFCCF0.5, NFCCF1, NFCCF1.5, and NFCCF2 were 25 kN, 35 kN, 46 kN, 32 kN, 30 kN, 33 kN, 42 kN, 30 kN, and 27 kN, respectively. Compared to the control beam, every beam with fiber incorporation displayed greater first cracking loads. The beam's deflection significantly increased when more cracks appeared and spread closer to the neutral axis because of the externally applied load increase. Compared to the conventional RC beam, the banana and coir fiber incorporated RC beam had a denser crack network, smaller crack spacing, more cracks, and were finer and narrower. The reason for the delayed creation of cracks is the fiber's capacity to transmit stress to the concrete through the crack. The specimen's uniform fiber dispersion provides better stress distribution, which creates reinforcement. The total number of cracks of CC, NFCBF0.5, NFCBF1, NFCBF1.5, NFCBF2, NFCCF0.5, NFCCF1, NFCCF1.5 and NFCCF2 were 8,11,13,10,9,10,12, 9 and 9, respectively, and the respective crack spacings of all beams were 109.25 mm, 84.91 mm, 69.62 mm, 89.80 mm,92.89 mm,87.20 mm, 74 mm, 95.89 mm, and 99.78 mm. In contrast to the conventional RC beam, entire strengthened RC beams had lower

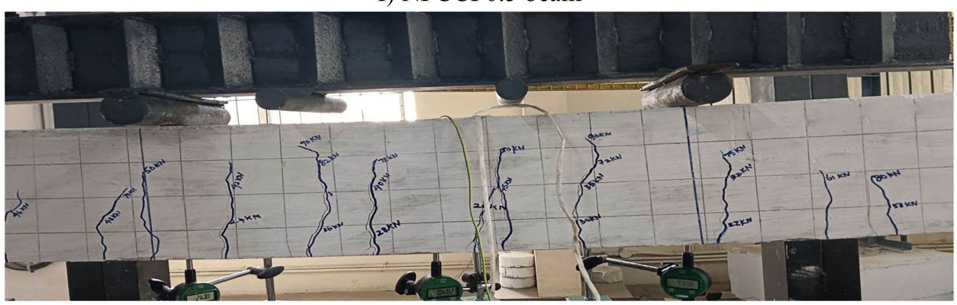
Fig. 13 (continued)



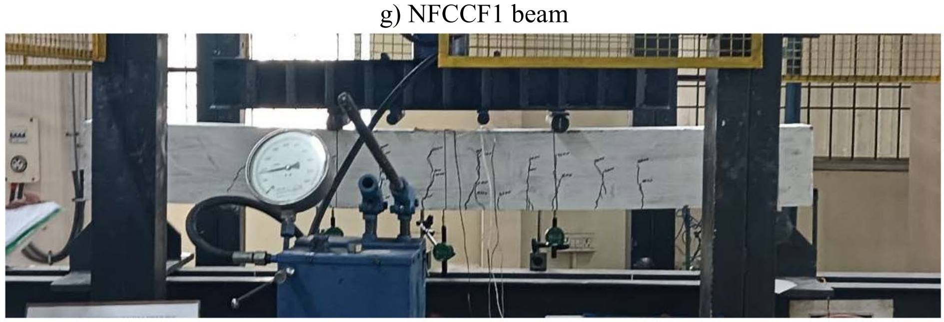
e) NFCBF2 beam



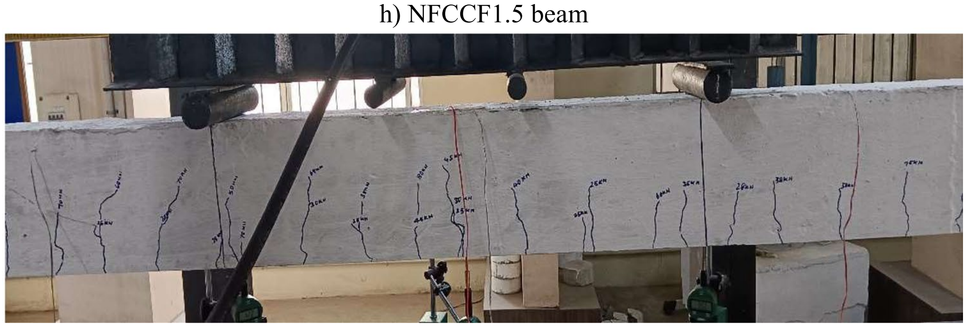
f) NFCCF0.5 beam



g) NFCCF1 beam



h) NFCCF1.5 beam



i) NFCCF2 beam

Table 9 Crack performance of specimen

Mix ID	First crack load (kN)	Crack width @ First crack load (mm)	Crack width @ ultimate load (mm)	Average crack spacing (mm)	No. of cracks
CC	25	0.1	1.48	109.25	8
NFCBF0.5	35	0.03	0.53	84.91	11
NFCBF1	46	0.02	0.36	69.62	13
NFCBF1.5	32	0.05	0.72	89.80	10
NFCBF2	30	0.07	1.04	92.89	9
NFCCF0.5	33	0.04	0.61	87.20	10
NFCCF1	42	0.03	0.59	74.00	12
NFCCF1.5	30	0.06	0.9	95.89	9
NFCCF2	27	0.08	1.2	99.78	9

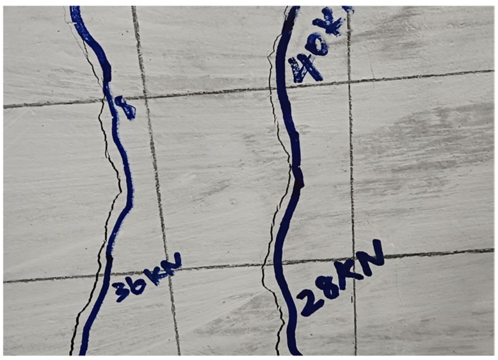


Fig. 14 Bridging crack by fibers

crack spacing. The fibers provide effective anchorages, which reduces the crack spacing. The post-crack behavior of the beam drastically improves with the inclusion of banana and coir fibers. The results are like the previous studies [23] that usage of fiber in concrete limiting the crack openings and deformations. As seen in Fig. 14, instantly, as the first crack developed, the fibers bridged it, resisted the load, and stopped the crack from spreading. The tested beams are placed in the yard, as seen in Fig. 15. Depending on exposure circumstances, the surface crack width cannot be greater than 0.3 mm, according to the IS 456:2000 [43]. Following these requirements, the study's examined beams all had crack widths at the service stage that were less than 0.3 mm.

6 Conclusions

This study investigated the influence of banana and coir fiber at different combinations on the high-strength RC beam. The test outcomes were analyzed regarding load-carrying capacity, load–deflection relationship, ductility, strain, failure mode, and crack patterns. The following conclusions can be drawn from the results and the presented discussion.

- Using natural fiber in HSC in the tested RC beams improved the ultimate load and increased the flexural performance regarding control HSC beams.
- The optimum content of 1% banana fiber showed an increase in the ultimate load-carrying capacity of 42.86% of the high-strength RC beam relative to the reference beam.
- The inclusion of banana and Coir fiber in HSC beams made with an alccofine ductility index improved them compared with conventional beams.

Fig. 15 Tested specimens

- The load–deflection curves for all fiber-incorporated RC beams demonstrated nearly complete model behaviour with increased ductility.
- Inculcation of banana and coir fibres into the high-strength RC beams increased the failure load, ultimate displacement, and crack propagation more than the HSC one.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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