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Research article

Enhancing mechanical properties of mortar with short and thin banana fibers: A sustainable alternative to synthetic fibers

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ABSTRACT

The use of fiber in mortar/concrete is now common for enhancing the flexural and ductility properties of structures. However, the utilization of synthetic fibers contributes to the emission of harmful greenhouse gases. Replacing these synthetic fibers with natural fibers derived from waste plants is imperative for sustainable development. The objective of this study was to evaluate the performance of short and thin banana fibers in enhancing the mechanical properties of fiber-reinforced mortar, specifically in terms of compressive, flexural, and splitting tensile strengths. The base mortar, with a water-cement ratio of 0.30 and a unit water content of 298 kg/m^3, was employed. The banana fibers were manually extracted from banana stalks, dried in an oven, and then cut into 10 mm fibers. The fibers were not treated with alkali. The fiber content was varied at 0 %, 0.125 %, 0.25 %, 0.5 %, and 0.75 % by weight of cement. Initially, the fibers were mixed into the viscous mortar along with the first portion of water and a superplasticizer. Subsequently, workability was improved by incorporating the second portion of water. The optimal content of banana fiber was determined to be 0.25 %, which increased the 28-day compressive, flexural, and splitting tensile strengths by 18.7 %, 29.9 %, and 41.1 %, respectively, compared to the base mortar. These findings suggest that the short and thin banana fiber has the potential to serve as a sustainable alternative to synthetic fibers. However, it is essential to conduct a thorough assessment of durability properties before implementing it in actual structures.

1. Introduction

Concrete is a widely used construction material composed of cement, water, and aggregate, mixed in specified proportions to achieve the desired strength, serviceability, and durability of reinforced concrete (RC) structures [1]. Its widespread availability, cost-effective production, flexibility for shaping into various forms and sizes, high compressive strength, rigidity, fire resistance, and durability are key characteristics of concrete [2]. However, its main shortcomings include low tensile strength, flexural strength, and brittle failure [3]. To address these shortcomings in RC structures, steel reinforcement bars have been utilized since the 20th century [4–7]. Moreover, the flexural and ductility behavior of RC structures and cement composites has been further enhanced with the use of short and discrete steel fibers, a practice that began as early as 1874 [8–11]. Nevertheless, a major drawback of using steel fiber in structures is its susceptibility to corrosion [12].

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Table 1
CO_2 emissions associated with the production of 1 ton of fibers.

Fiber types	CO_2 emission (ton)
Steel	1.4 [25]
Carbon	20 [26]
Glass	1.7–2.5 [27]
Polypropylene	1.34 [28]
Polyethylene	1.48 [28]
Polyvinyl alcohol	2.0 [29]

Various types of artificial synthetic fibers have been developed to replace steel fibers and address corrosion issues in structures [13]. The use of such synthetic fibers has not only resolved corrosion problems but has also significantly reduced the weight of composite structures, a major concern with steel fiber structures [14]. The inclusion of synthetic fibers in concrete, whether in small amounts to reduce plastic shrinkage cracking or in larger quantities to enhance flexural strength, toughness, ductility, and control crack width in the hardened state, yields several benefits [15]. Polypropylene (PP) fibers, glass fibers, and polyvinyl alcohol (PVA) fibers are frequently incorporated into concrete to enhance its mechanical and durability properties [16,17]. The use of these fibers is particularly advantageous in precast factories for producing tunnel segments, permanent formwork, wall and flooring panels, railway wind panels, bridge decks, slope stabilization, and more [18].

Their primary roles in concrete composites are increasing flexural strength, fracture toughness, ductility, and controlling crack width while reducing drying and autogenous shrinkage [19,20]. Guler and Akbulut [21] reported that both single and hybrid combinations of macro and micro basalt fibers increased the residual compressive and flexural strengths after 24, 48, and 72 cycles of freeze-thaw tests on mortar, despite a decrease in workability. Additionally, they found that hybrid basalt fibers outperformed single fibers in enhancing residual compressive and flexural strengths. In another experimental investigation utilizing polypropylene fibers, they also concluded that hybrid combinations of micro and macro fibers were superior to single macro fibers in enhancing the residual compressive and flexural strengths of concrete after 150 cycles of freeze-thaw tests [22].

In 2015, the United Nations adopted 17 sustainable goals, including "Climate Action" and "Life on Land" [23]. These goals have direct or indirect connections to the construction and production industries. The construction industry alone is responsible for 36 % of total energy consumption and 39 % of CO_2 emissions [24]. Despite the various advantages of steel fibers and artificial synthetic fibers in enhancing the mechanical and durability properties of concrete structures, they are not considered environmentally friendly materials. In 2018, the International Energy Agency estimated that CO_2 emissions accounted for 25 % of total global emissions [25]. Table 1 provides a summary of the CO_2 emissions associated with producing 1 ton of different fibers.

Over the past three decades, researchers have explored the use of natural fibers in cementitious composites [30,31]. Natural fibers are generally considered eco-friendly construction materials with the potential to replace conventional steel and other artificial fibers, thereby contributing to sustainable development and reducing CO_2 emissions [32]. Natural fibers should be widely accepted as sustainable construction materials because they are not only readily available and cost-effective but also recyclable. They possess high tensile and flexural strength with low elongation at break [33]. Natural fibers can be sourced from minerals, animals, and plants. Mineral fibers are derived from sources such as asbestos, graphite, and glass, while animal fibers come from sources like hair, silk, and wool. Various types of plant cellulose fibers are extracted from materials such as grass, seeds, leaves, stalks, bast, wood, and more [34].

Previous research has employed natural fibers like sisal fiber [35], kenaf fiber [36], bamboo fiber [37], banana fiber [38], jute fiber [39], coconut fiber [40], hemp fiber [41], bagasse fiber [42], abaca fiber [43], and others. In recent years, efforts have been made to incorporate banana fiber (BF) into mortar/concrete. Bananas are fruit plants belonging to the Musaceae family [44]. After harvesting banana fruit, the entire banana stalk is typically left on the ground to decompose as agricultural waste [45,46] The banana stem contains fibers composed of approximately 50 % cellulose, 17 % lignin, along with hemicellulose and pectin, resulting in higher tensile and flexural strengths and low elongation at break [47–49]. Cellulose is the primary constituent of BF, which predominantly influences its mechanical properties [50]. BF is biodegradable, cost-effective, easily extracted, and eco-friendly as it emits oxygen (O_2) rather than carbon dioxide (CO_2) [51,52]. It is also lightweight, possesses low density, and exhibits resistance to water and fire [53]. Additionally, the inclusion of BF mitigates concrete cracking and spalling while enhancing flexural behavior [54].

BF can be manually or mechanically extracted from banana stalks [55]. They are used in the form of reinforcement bars [56] or as discrete fibers [46,48,52,55,57–61] in mortar/concrete. It has been reported that BF has a drawback related to weaker interfacial bond strength between the fiber and the matrix [62]. To address this issue, most researchers have treated BF with alkali to enhance its surface toughness and reduce its hydrophilic nature [46,52,56,57,61,62]. Nensok et al. [52] observed a decrease in BF diameter by 18.2 % and an increase in density by 7.4 % after treatment with a 6 % NaOH solution. They also reported an increase in single fiber flexural strength from 166 MPa to 487 MPa and a modulus of elasticity increase from 14.3 GPa to 28.7 GPa. Ernest and Peter [62] also reported improvements in tensile strength, flexural modulus, and elongation.

Nensok et al. [52] compared the mechanical properties of mortar using 0.4 % (by weight of mortar) of 30 mm BF treated with different NaOH solution concentrations. They found that using BF treated with a 6 % NaOH solution resulted in the highest compressive, flexural, and splitting tensile strengths of the mortar. Elbehiry et al. [54] conducted experimental investigations using BF as reinforcement bars in M25, M35, and M45 grade concrete beams, showing a 25 % enhancement in concrete flexural strength across all grades. Zhu et al. [46,56] reported an increase in flexural strength from approximately 12 MPa–25 MPa when using 14 % (by mass) of BF strands. Mouli et al. [58] achieved a 35 % enhancement in the 28-day compressive strength of M30 grade concrete by adding 3 %

Table 2
Fundamental and primary chemical constituents of 43-grade OPC.

Chemical components	
Components	Content (%, by weight)
Basic compounds:	
CaO	62.69
SiO_2	21.01
Al_2O_3	5.31
Fe_2O_3	3.78
SO_3	2.53
K_2O	0.57
MgO	1.81
Na_2O	0.31
Others	1.99
Major compounds:	
C_3S	45.1
C_2S	26.3
C_3A	9.30
C_4AF	8.58
Others	10.80

Table 3
Basic properties of cement.

Items	Values
Colour	grey
Fineness	5.53 %
Specific gravity	3.14
Normal consistency	28.0 %
Le-Chatelier	5 mm
Initial setting time	145 min
Final setting time	245 min
Compressive strength at 28-day	52.15 MPa

BF with a length of 40 mm. Similar enhancements of 18.6 % and 18.2 % were observed with 0.5 % BF content in the research of Keshavraman [60] and Ali et al. [61], respectively. Akinyemi and Dai [63] reported a 20 % increase in splitting tensile strength of mortar by using 1.5 % of 13 mm BF in addition to 10 % wood bottom ash and 0.3 % styrene-butadiene rubber.

Recently, Rajkohila et al. [38] conducted a detailed experimental investigation on the influence of banana fiber (BF) and coir fiber (CF) on the mechanical and microstructural properties of high-strength concrete. They observed notable improvements in the mechanical properties of concrete upon the incorporation of BF and CF. Their study revealed that the addition of 1 % BF notably enhanced the 28-day mechanical properties of high-strength concrete compared to CF, contributing to the early detection of potential failures due to its elastic behavior.

When using BF in mortar/concrete, most researchers have varied their length from 30 to 60 mm. Mugume et al. [57] demonstrated that 40 mm BF yielded better performance than 50 mm and 60 mm in terms of mechanical properties of mortar and concrete. They also noted that the optimal content increased with longer BF lengths. Furthermore, previous research has shown that the use of thinner and shorter polyvinyl alcohol (PVA) fibers enhances the flexural properties of mortar [64]. In the work of Akinyemi and Dai [63], shorter banana fiber (13 mm) was employed, albeit with a single content of banana fiber (1.5 % by weight of the mortar). Thus, this paper investigates the impact of different content levels of short BF on the mechanical properties of mortar, with a fixed length of 10 mm for the BF.

2. Materials and method

2.1. Materials and mixture proportions

Ordinary Portland Cement (OPC) of 43 grade, conforming to NS 49:2053 [65], was utilized in this series of experiments. The fundamental constituents of the cement were tested in the laboratory according to IS: 4032-1985 [66], and the primary constituents were determined using Bogue's equations. The fundamental and primary constituents are outlined in Table 2.

The specific gravity, consistency, soundness, setting time, and compressive strength tests were conducted following the guidelines provided in IS 2720 (Part III) [67], IS 4031 (Part IV) [68], IS 4031 (Part III) [69], IS 4031 (Part V) [70], and IS 4031 (Part VI) [71], respectively. The test results are presented in Table 3.

The fine aggregate was sourced from a nearby aggregate crushing industry in Kotre, Tanahun, Nepal. The sieve analysis of the fine aggregate was conducted in accordance with IS2386 (Part I) [72]. Specific gravity, density, and water absorption tests were carried out

Table 4
Physical properties of fine aggregate.

Properties	Values obtained
Maximum aggregate size (mm)	4.75
Specific Gravity	2.6
Bulk density (kg/m^3)	1647
Fineness Modulus	2.8
Grade Zone	I
Water Absorption (%)	0.20
Silk content (%)	2.36

Fig. 1. Image of BF after extraction and dried in oven.

Table 5
Mixture proportions of mortar.

Mixture condition		Unit content (kg/m^3)			
W/C	BF (%)	Water	Cement	Fine aggregate	BF
0.30	0.000	298	993	1006	0
	0.125			1005	0.3725
	0.250			1004	0.7450
	0.500			1003	1.4900
	0.750			1002	2.235

following the guidelines provided in IS2386 (Part III) [73]. Table 4 displays the essential properties of the fine aggregate utilized in the experiment.

The superplasticizer used was categorized as type F according to the ASTMC 490-10 specification, and it had a pH level of 6.2, a specific gravity of 1.12, and exhibited a pale yellow colour. The water used was potable, with a measured pH value of 7.0.

Banana pseudo-stems were gathered from a local banana farm, washed to remove mud and debris, and subsequently cut into small pieces to allow for the separation of the leaf sheaths. The fiber was manually extracted and dried in an oven at 60 °C for 4 h. Fig. 1 depicts images of the extracted BF after the drying process. Once the BF was completely dry, it was chopped into approximately 10 mm pieces for use in the experiment. The fiber had a grey/creamy color, was odorless, and had an average measured diameter and density of 0.208 mm and 1325 kg/m^3, respectively. It is worth noting that previous research has demonstrated that alkali treatment of BF enhances the mechanical properties of mortar/concrete. However, for this series of experiments, the aim was to determine the optimal BF content for the given mortar mixture proportions. As a result, alkali treatment of the banana fiber was intentionally omitted.

The mixture proportions of the mortar closely resembled those used in the development of high ductile mortar [64]. They were slightly adjusted to accommodate the specific characteristics of the ingredients and the need for adequate workability during the compaction process while casting the test specimens. BF content varied from 0 % to 0.125 %, 0.25 %, 0.5 %, and 0.75 % by weight of cement. To account for the volume occupied by BF in one cubic meter (m^3) of the total mixture, the volume of fine aggregate was adjusted accordingly. The specifics of the mixture proportions are outlined in Table 5. It is worth noting that a uniform 1.0 % by weight of cement of superplasticizer was utilized in each mix.

Fig. 2. Visual observation and hand touching checks of BM mortar.

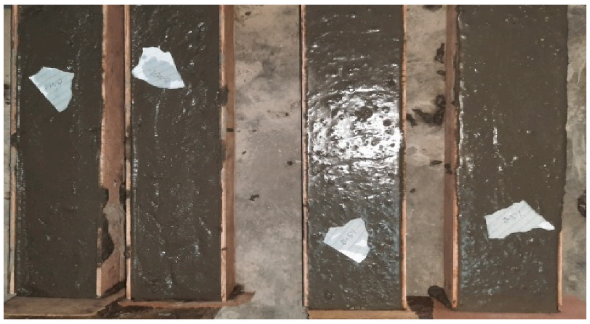

Fig. 3. Finishing condition of the beam specimens.

2.2. Mixing method

The laboratory was maintained at a temperature of 20 ± 2 °C and a relative humidity of 65 %. A J-type mortar mixer with a 5-L capacity was used for the experiments. Each batch had a volume of 4 L. The mixing procedure closely followed the method employed for mixing high ductile mortar using PVA fiber [74].

The superplasticizer was premixed with the first part of water (75 %) in a bucket using a spoon. First, half of the fine aggregate was added to the mixer, followed by the entire amount of cement, and then the remaining fine aggregate, creating a sandwich-like arrangement. Dry mixing of the solid ingredients was carried out for half a minute. Subsequently, the first part of the water (containing superplasticizer) was poured and mixed for 2 min to achieve a viscous mixture. The banana fiber (BF) was added gradually, in portions, to prevent agglomeration, with a mixing time of one and a half minutes. Finally, additional mixing was conducted for 2 more minutes with the addition of the second part of the water to achieve a workable BF mortar. It is important to note that the time taken for adding the BF (one and a half minutes) was subtracted when preparing the control mortar without BF.

A few minutes after mixing, ambient and mortar temperatures were recorded to ensure there was no significant difference. Visual and tactile checks were performed to confirm the uniform distribution and coating of BF, as well as to assess the workability of the BF mortar for casting (refer to Fig. 2).

Before casting the specimens, each mold was thoroughly cleaned, and the inner surface was coated with grease. From each parameter batch, 6 cubes of dimensions 70.6 mm × 70.6 mm × 70.6 mm were cast for the 7-day and 28-day compressive strength tests. Likewise, 6 beams with dimensions of 400 mm (length) × 50 mm (breadth) × 100 mm (depth) and 6 cylinders with dimensions of 100 mm (diameter) × 200 mm (depth) were cast for flexural and splitting tensile strength tests, respectively. The cubes and cylinders were cast in three layers, with 20 tamping strokes at each layer. The beam specimens were also cast in three layers, but with 40 tamping strokes at each layer. Careful attention was given to the finishing of the upper surface to ensure an even surface and prevent voids.

Fig. 4. Wet curing condition of the test specimens.

Fig. 3 illustrates the finishing condition of the upper surface of the test specimens.

Following the completion of specimen casting, initial curing was carried out for 24 h by covering the upper surface with clean, damp cloths in a controlled environment. After this initial period, all specimens were demoulded and placed inside a water curing tank, where they remained until the testing day. The water temperature was maintained at 20 ± 2 °C during the entire curing process. The wet curing of the specimens is depicted in Fig. 4.

Strength tests were conducted at both 7 days and 28 days. Before the tests, the specimens were removed from the curing tank, and their surfaces were wiped clean with cloths. Subsequently, they were placed on the floor to allow their surfaces to dry. The dimensions and weights of all specimens were recorded to calculate their respective densities. The strength tests were carried out using a universal testing machine with a capacity of 1000 kN, and Indian standard procedures were rigorously followed for specimen setup and loading. Compressive, flexural, and splitting strength tests were performed in accordance with the guidelines outlined in IS: 516 [75]. Following the recording of the maximum load for all test specimens, the respective strengths were calculated using Equations (1)–(3) for compressive, flexural, and splitting tensile strengths, respectively.

$$f_c = \frac{P}{a^2} \tag{1}$$

$$f_b = \frac{3Pl}{2bd^2} \tag{2}$$

$$f_{st} = \frac{2P}{\pi LD} \tag{3}$$

In the equations above, f_c, f_b, and f_{st} represent the compressive, flexural and splitting tensile strengths of the cube, beam, and cylinder, respectively. a is one dimension of the cube. l, b and d denote the effective span, width and depth of the beam, respectively. D and L stand for the diameter and depth of the cylinder specimen, respectively.

3. Results and discussion

3.1. Density

Based on visual observation and tactile examination, it was evident that the BF was uniformly distributed and well-coated throughout the mixed mortar. No agglomeration of BF was detected within the mortar mix. Notably, despite varying levels of BF content, the mortar exhibited the necessary workability essential for casting cubes, cylinders, and beams. The density results measured from all test specimens at 7 and 28 days are depicted in Fig. 5.

The densities at both 7 and 28 days were nearly identical, regardless of the varying percentages of BF. This similarity can be

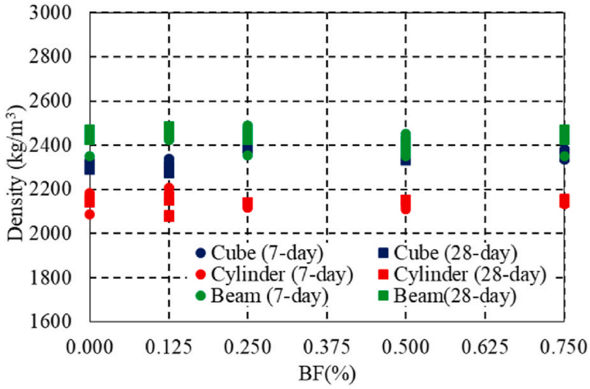

Fig. 5. Densities of test specimen in 7 and 28-days.

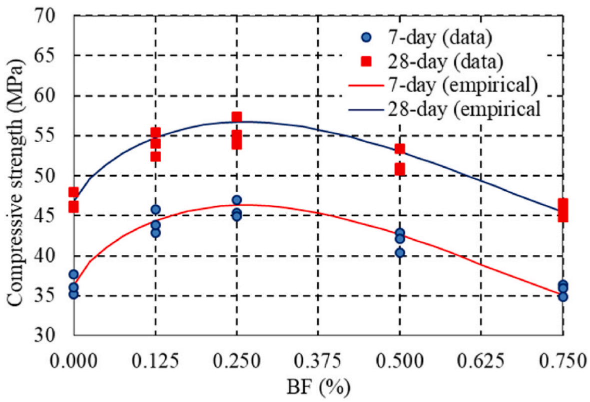

Fig. 6. Relation of compressive strength with BF content.

attributed to the relatively low BF content, which had a minimal impact on the density. Interestingly, the densities of the beams were recorded as higher, while the densities of the cylinders were lower than those of the cubes. This discrepancy was a result of the compaction method employed during specimen preparation.

In the case of beams, compaction was achieved by using a hand trowel at each layer in addition to tamping. However, for cubes and cylinders, the mortar was only compacted from the upper surface. The lower density in cylinders can be attributed to the greater thickness of the layers compared to cubes and beams. It is important to note that no vibration was used during the compaction process.

3.2. *Compressive strength*

7-day and 28-day compressive strength test data verses BF (%) are presented in Fig. 6.

When introducing 0.125 % of BF to the control mortar, both 7-day and 28-day compressive strengths exhibited a significant increase. This increase was gradual as the BF content ranged from 0.125 % to 0.25 %. At 0.25 % BF content, the optimum compressive strength was achieved, beyond which the compressive strength began to decline with higher BF content. Notably, at 0.75 % BF content, the compressive strength was lower than that of the control mortar.

Nensok et al. [52] used 30 mm length BF and determined that the highest compressive, flexural, and splitting tensile strengths were attained at the optimum content of 1.2 % by weight of cement, both for untreated and those treated with 6 % NaOH. Mugume et al. [57] found the optimum compressive strengths for M20 and M25 grade concrete with 0.1 % of 40 mm BF, while the flexural and splitting tensile strengths were maximized at 0.25 % of 60 mm BF. Mouli et al. [58] achieved the maximum compressive strength for M30 grade concrete with 3 % of 40 mm BF and flexural strength with 4 % BF. Ali et al. [61] obtained the maximum compressive, flexural, and splitting tensile strengths for M30 grade concrete at 0.5 % (by weight of concrete) of treated BF with 6 % NaOH.

Based on the analysis of the trend of increasing compressive strength of the mortar with BF content up to the optimum and then decreasing, an empirical model was developed as shown in Equation (4).

$$f_c = f_{cm} + k\sin\left[4(BF)^{0.7}\right] \quad (4)$$

In the above equation, f_c represents the compressive strength of mortar with varying BF content, and f_{cm} signifies the compressive

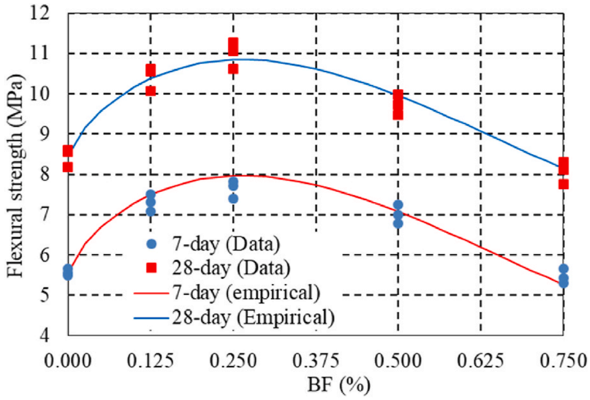

Fig. 7. Relation of flexural strength of mortar with ranging content of BF.

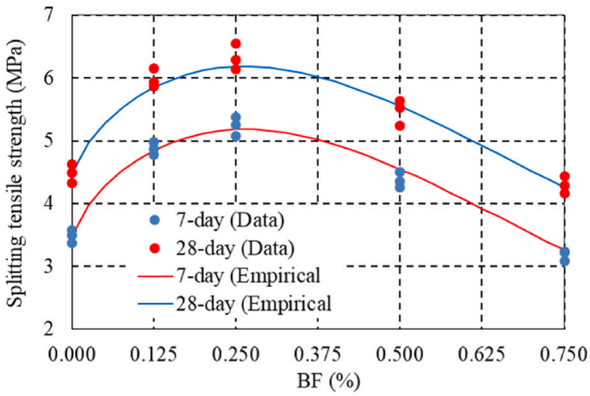

Fig. 8. Relation of splitting tensile strength with ranging content of BF.

strength of the control mortar. *BF* denote the percentage of BF by weight of cement, and *k* stands for the material constant, which set to a value of 10 to align with the experimental data.

3.3. Flexural strength

The relationship between flexural strength and BF content is illustrated in Fig. 7. It is evident from the graph that the pattern of increase and decrease in both 7-day and 28-day flexural strengths with varying BF content mirrors that of compressive strengths. The empirical model presented in Equation (4) also applies to flexural strength, as demonstrated in Equation (5).

$$f_b = f_{bm} + l\sin\left[4(BF)^{0.7}\right] \tag{5}$$

Only f_b and f_{bm} denote the flexural strengths of BF mortar and the control mortar, respectively. The value of *l* was set at 2.4 to match the experimental data.

3.4. Splitting tensile strength

The trend in the relationship between the splitting tensile strength of the mortar and varying BF content was also observed to be similar to that of the compressive and flexural strengths (refer to Fig. 8).

The empirical model presented in Equation (6) closely resembles those for compressive and flexural strength, with the change of the respective symbols. In this case, the value of *m* was set at 1.7 to align with the experimental data.

$$f_{st} = f_{stm} + m\sin\left[4(BF)^{0.7}\right] \tag{6}$$

3.5. Summary of data

Table 6 presents a summary of all the tested data, including the averages of three test results and the standard deviations for the

Table 6
Summary of test data.

BF (%)	Age	Densities (kg/m^3)			Strengths (MPa)		
		cubes	cylinder	beams	f_c	f_b	f_{st}
0.000	7-day	2323 ± 7	2142 ± 41	2409 ± 41	36.32 ± 1.01	5.57 ± 0.07	3.48 ± 0.09
	28-day	2297 ± 9	2148 ± 5	2447 ± 19	46.73 ± 0.86	8.45 ± 0.19	4.48 ± 0.12
0.125	7-day	2316 ± 23	2190 ± 11	2450 ± 26	44.18 ± 1.21	7.31 ± 0.17	4.87 ± 0.09
	28-day	2284 ± 13	2103 ± 33	2469 ± 15	53.91 ± 1.22	10.41 ± 0.24	5.98 ± 0.12
0.250	7-day	2387 ± 10	2124 ± 7	2426 ± 56	45.72 ± 0.87	7.65 ± 0.18	5.23 ± 0.06
	28-day	2401 ± 10	2141 ± 1	2442 ± 17	55.45 ± 1.41	10.98 ± 0.28	6.32 ± 0.17
0.500	7-day	2365 ± 9	2121 ± 9	2396 ± 41	41.82 ± 1.03	7.01 ± 0.19	4.38 ± 0.10
	28-day	2366 ± 27	2152 ± 2	2400 ± 20	51.65 ± 1.19	9.73 ± 0.21	5.47 ± 0.17
0.750	7-day	2366 ± 21	2136 ± 1	2409 ± 41	35.74 ± 0.67	5.47 ± 0.14	3.18 ± 0.07
	28-day	2357 ± 7	2151 ± 6	2448 ± 19	45.62 ± 0.70	8.07 ± 0.23	4.30 ± 0.11

f_c: Compressive strength; f_b: Flexural strength; f_{st}: Splitting tensile strength.

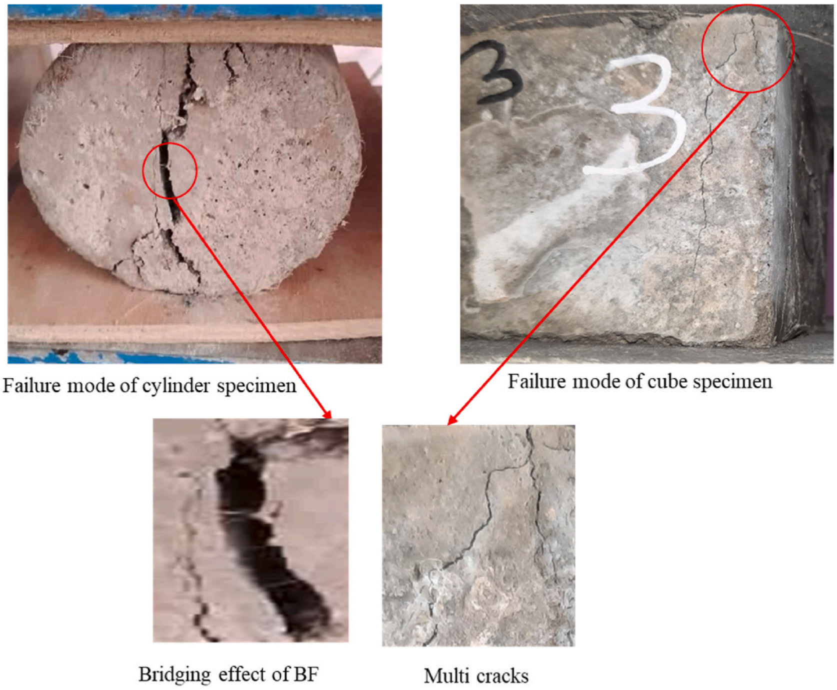

Fig. 9. Failure modes of the specimens during testing.

densities and strengths at both 7 days and 28 days. It is noteworthy that all the test data fell within the margin of error.

Average density data revealed that there was no significant difference between the age of specimens and the varying percentages of BF. The overall average density of the cylinders was 8.7 % lower, while that of the beams was 3.5 % higher than that of the cube specimens. This discrepancy can be attributed to differences in compaction methods and the very low percentage of BF used. Ernest and Peter [62] reported a decrease in density with an increase in BF content, which can be attributed to their use of higher BF content, ranging from 5 % to 20 % by volume in cement composites. Zhu et al. [56] also obtained similar results, with a decrease in density of polyester composites as the weight percentage of BF strands increased.

In terms of compressive strength, the 28-day values increased by 15.4 %, 18.7 %, and 10.5 % compared to the control mortar for BF percentages of 0.125 %, 0.25 %, and 0.5 %, respectively. However, there was a 2.4 % decrease in compressive strength for 0.75 % BF. The 28-day flexural strength saw increases of 23.2 %, 29.9 %, and 15.1 % for 0.125 %, 0.25 %, and 0.5 % BF, with a 4.5 % decrease for 0.75 % BF. For 28-day splitting tensile strength, there was an increase of 33.5 %, 41.1 %, and 22.1 % for 0.125 %, 0.25 %, and 0.5 % BF, respectively, but a 4.0 % decrease for 0.75 % BF. These results validate that the optimum BF content was 0.25 %, resulting in an 18.7 %, 29.9 %, and 41.1 % increase in compressive, flexural, and splitting tensile strength, respectively.

Nensok et al. [52] reported a 13.7 %, 32.7 %, and 45.3 % increase in compressive, flexural, and splitting tensile strength, respectively, with the use of 1.2 % of 30 mm untreated BF. They also reported increases of 59.8 %, 117.4 %, and 157 % with the use of 6 % NaOH treated BF. It is worth noting that their results were for very low-strength cellular lightweight concrete, with 28-day compressive, flexural, and splitting tensile strengths of the control concrete measuring only 5.20 MPa, 0.98 MPa, and 0.64 MPa,

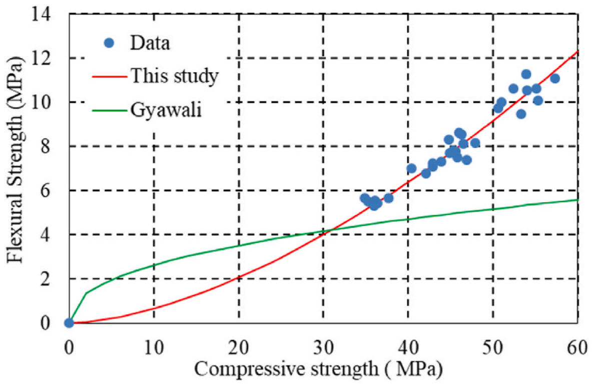

Fig. 10. Relation of flexural strength with compressive strength.

respectively.

Mugume et al. [57] employed 40 mm, 50 mm, and 60 mm of 5 % NaOH treated BF in M20 grade concrete and reported a 14 % increase in compressive strength at 0.1 % of 40 mm BF, which decreased with higher BF content. Flexural strength and splitting tensile strengths increased by 10.4 % and 4 % at 0.25 % of 60 mm and 40 mm BF, respectively. Mouli et al. [58] achieved a 35 % and 47.4 % increase in compressive and flexural strengths of M30 grade concrete with the use of 3 % and 4 % of 40 mm BF, respectively. Ali et al. [61] reported an 18.2 %, 16.7 %, and 9.2 % increase in compressive, flexural, and splitting tensile strengths of M30 grade concrete with 0.5 % of 50 mm BF treated with 6 % NaOH. Akinyemi and Dai [63] reported a 3.64 % and 20 % increase in flexural and splitting strengths of C: S = 1:3 mortar with 1.5 % of 13 mm BF. Elbehiry et al. [54] obtained a 25 % enhancement in flexural strength when using BF as reinforcement bars in concrete. In contrast, Afraj and Ali [59] found a 40 % decrease in flexural strength of concrete with 5 % of 50 mm BF.

Comparing all the aforementioned previous results, two major points can be drawn from this study. First, shorter fibers are more effective for enhancing mortar strength and can lead to a lower optimum content to achieve maximum strengths. Another significant point is that the use of the High Ductile Mortar (HDM) mixing method likely had a positive effect on the strength results, as previously verified in a separate study [64]. While BF was not treated with alkali in this study, it can be inferred from other researchers' results that strengths can be further enhanced with the alkali treatment of BF.

3.6. Failure modes

During testing, it was observed that the control mortar specimens failed with a single crack, resulting in complete brittleness. However, the inclusion of BF minimized the brittle failure of the test specimens (refer to Fig. 9). Multiple cracks were observed in the mortar specimens containing BF. The bridging effect of BF was clearly noticeable in the early stages of micro-cracking. In the cube and cylinder specimens, initial multiple cracks appeared in the middle region of the depth. In the beam specimen, multiple cracks emerged at the bottom of the mid-span, and the single crack widened and extended to the top as the load increased until the specimens failed. In all cases, the beam specimens exhibited flexural failure.

Rehman and Sudheer [76] observed that nearly 70 % of the BF were pulled out, while the remaining 30 % were broken at the failure surface. They concluded that the bridging effect of BF prevented shrinkage cracks during loading. Afraj and Ali [59] revealed that BF enhances the bridging effect and the bond between the concrete matrix and fibers, leading to increased energy absorption and toughness index. Zhu et al. [46] also reported that shorter fibers disperse more uniformly without clumping, effectively resisting initial micro-cracks. This effect was even more significant in this study due to the use of short BF and the HDM mixing procedure. According to Jagadeesh et al. [77], BF possesses an elliptical cross-section, which enhances tensile strength.

3.7. Relation of strengths

Different types of concrete strength can be estimated from its compressive strength. Fig. 10 illustrates the relationship between the flexural strength and compressive strength of mortar with varying contents of BF. Equation (7) provides the empirical model for the relationship between flexural strength and compressive strength:

$$f_b = 0.01 a f_c^{\,a} \tag{7}$$

In the equation f_b and f_c represent flexural strength and the compressive strength, respectively. The material constant is denoted by a. The values of a was chosen to 1.62 to best fit the experimental data. The figure also displays the empirical model of Gyawali [78], which significantly differs from the data of this study and follows a different trend. This disparity is because the model of Gyawali was developed for lightweight mortar using EPS beads.

The relationship between the splitting tensile strength and the compressive strength is depicted in Fig. 11. The empirical model

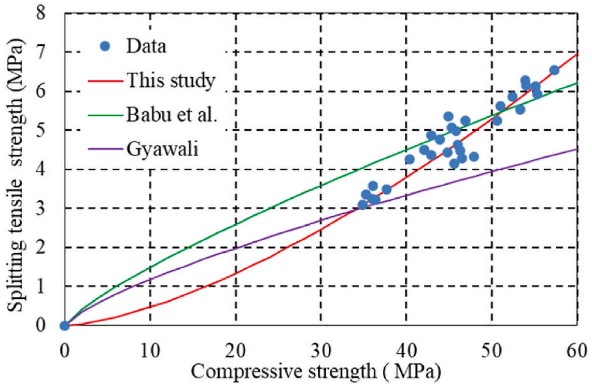

Fig. 11. Relation of splitting strength with compressive strength.

follows the same form as Equation (7), with a value of 1.5 chosen for *a* in the case of splitting strength. The figure also includes the empirical models of two other researchers. The trend of their models differs from that of this study. The model of Gyawali [78] falls below the experimental data, while Babu et al.'s model [79] is higher and only covers the middle range of the data. Their model is based on experimental data from EPS concrete.

This study has confirmed that a very low content (0.25 %) of short BF fibers (10 mm) is suitable for mortar applications. The HDM mixing method has played a significant role in enhancing the strengths of mortar, even when using untreated BF fibers. However, it is important to note that many researchers have emphasized the necessity of alkali treatment for BF to further enhance strength and improve durability. Akinawande et al. [80] reported that alkali treatment reduces the hydrophilic nature of BF and, consequently, its water absorption capacity. Additionally, Ernest and Peter [62] have suggested various chemical treatment options for natural fibers. Therefore, future research efforts should focus on evaluating the effectiveness of alkali treatment and assessing durability properties before considering the practical application of thin and short BF mortar composites in real structures.

4. Conclusion

BF was manually extracted from banana stalk waste and then dried in an oven at 60 °C for 4 h. It was subsequently chopped into 10 mm fibers. The mortar was mixed using the high ductile mortar mixing method, with varying fiber contents of 0 %, 0.125 %, 0.25 %, 0.5 %, and 0.75 % by weight of cement. The following key findings were obtained from this experimental investigation.

✓ The high ductile mortar mixing method facilitated uniform distribution and firm coating of the thin and short BF fibers.
✓ Introducing different contents of BF had no significant impact on the density of the mortar, primarily due to the small volume of BF relative to the total mortar volume.
✓ The optimum content of BF was found to be 0.25 %, resulting in an 18.7 % increase in compressive strength, a 29.9 % increase in flexural strength, and a 41.1 % increase in splitting tensile strength compared to the base mortar.
✓ The lower content optimum (0.25 %) was attributed to the use of very short BF fibers (10 mm).
✓ The brittle failure mode of specimens was notably reduced due to the formation of multiple micro-cracks, a result of BF's bridging performance.
✓ Empirical models were proposed to fit the respective experimental data.

Future work should focus on assessing the performance of alkali-treated BF and investigating the durability properties of BF mortar.

CRediT authorship contribution statement

Niroj Lamichhane: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Aadarsha Lamichhane:** Writing – original draft, Methodology, Investigation, Data curation. **Tek Raj Gyawali:** Writing – review & editing, Supervision, Investigation, Formal analysis, Conceptualization.

Declaration of 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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