Research Article

Mechanical Properties of Bacterial Cement Mortar Integrating Natural Banana Fibres

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Abstract
This investigation analyzes the usage of bacterial content and different lengths of banana fiber reinforced with variable percentages in cement mortar. Portland pozzolana cement (PPC) was combined with bacterial solutions (*Bacillus cereus*) at a concentration of 1.15×10^4 cells/ml to produce a mortar composite. By adding natural fibers like banana fiber to the composite components, the mechanical behavior of the bacterial mortar was enhanced. Mortar mixtures using banana fibers with different fiber concentrations (0.25, 0.5, 0.75, and 1%) and lengths (0.5, 1, 1.5, and 2 cm) were evaluated. Compressive and flexural strength was found to be greatly affected by the addition of banana fibers to concrete, but only at lower fiber levels of up to 0.25% for all fiber lengths. At lower fiber levels of up to 0.25%, the length of the fiber had no discernible effect on compressive strength; however, at larger dosages exceeding 0.25%, shorter fibers were shown to outperform longer ones. However, the mixing of bacterial content in the mortar is not only significant to the mechanical properties but also potentially lowers the carbon emissions, making it a more sustainable option for composite preparation. The stability of bacterial-based mortar and its compatibility with natural fibers further underscores the potential for eco-friendly construction materials. By exploring the chemical and physical properties of banana fibers treated with alkali chemicals and their compatibility with bacterial cultures, this study adds depth to our understanding of these composite materials. Overall, the proposed methodology for preparing these composites holds promise for future applications in the construction industry, offering a sustainable and efficient alternative to traditional materials.

Keywords: *Bacillus cereus*, Bacterial mortar, Banana fiber, Compatibility, Flexural strength

1 Introduction

In civil engineering, the most commonly used materials in construction are concrete and mortar because of their affordability, strength and durability when compared to construction materials. The major disadvantage of concrete is its poor tensile strength, which makes it susceptible to coalescence and formation of micro cracks, which lowers its durability and strength. The main features of cracks can allow such kind of harmful substances (salts, water, acids, gases and other agents) and lead to deterioration of concrete and corrosion of steel reinforcing materials [1]. Similarly, the presence of growing cracks due to corrosion reduces the stiffness and strength of concrete structures. Many attempts are currently in progress to reduce the spread of cracks and increase the durability of concrete [2].

Building materials that emit carbon dioxide (CO_2) during the manufacturing process include concrete, burnt clay brick and cement mortar. Cement serves as the traditional binding powder in the manufacturing of mortar and concrete. At the same time, burnt clay bricks are often used to construct masonry walls for buildings. Concrete is the world's second most extensively utilized material after water [3]. Concrete serves as the best construction material, with over 6 million tons produced globally every year, due to its casting, great compressive strength, and comparatively low cost. The main drawbacks include poor tensile strength, poor durability, brittleness and proneness to crack formation. The demand for crack resistant and high strength concrete led to the progression of fiber based concrete production. The maintenance of concrete highly impacts the environments and community budgets. The traditional types of repairing methods have some flaws like various thermal coefficients of matrix base, operation restrictions and environmental hazards [1]. Developing the concrete with natural fibers with biobased self-healing focuses on to reduce the cracking related issue.

Biobased cementitious materials with self-healing mortar use biological agents such as fungi or bacteria to repair cracks over time. The microorganisms secrete some minerals like $CaCO_3$, which fill the space and repair the cracks. In contrast with conventional healing agents, biological agents are permanent and can be reactivated, making them cost-efficient and sustainable. Although, natural fibers like bamboo, hemp, banana, sisal, and jute can be blended into mortar to increase resilience, durability, and strength, while reducing cracking. These fibers are renewable, environmentally friendly, and sustainable, adding both practical benefits and aesthetics to construction materials. Incorporation of bacterial cultures like *Bacillus* species, into cementitious materials further increases their self-healing properties by secreting the calcium carbonate formation inside the cracks. This directly improves the resistance property against environmental factors, lowers maintenance charges, and increases sustainable building practices [4].

The main aim of developing biobased (bacterial culture) self-healing is to achieve great healing performance during crack formation. Few studies reported that the treated samples have improved compressive strength along with decreased quality in control samples. Also found the restoration of mechanical strength after the addition of bacterial cultures like *B. subtilis* and *B. megaterium* into the mortar matrix [5]. In one study, researchers investigated the properties of *B. subtilis* in enhancing the strength of concrete and repairing cracks [6] in self-healing cracks in concrete and enhancing concrete strength through microbial induced calcium carbonate precipitation (MICP). The study evaluated the ability of the mortar to cover cracks within 28 days, taking into account the width of the crack, and observed the recovery of strength after self-healing. The use of microencapsulated endospores of *B. subtilis* was also examined for its impact on the strength of concrete. The compressive, splitting tensile, and flexural strengths of normal mortar were compared to those of biological mortar, and it was found that biological mortar had a higher strength capacity. Microstructure analysis using SEM and EDS showed that bacterial growth increased calcium production, contributing to the improved mechanical properties of the bio-mortar [6]. The bacteria produced calcium carbonate precipitation through microbial activity, effectively repairing cracks and improving concrete strength. Another study explored the concept of self-healing concrete as a composite material capable of autonomously repairing minor cracks without external diagnosis or human intervention. The result found that calcite precipitation played a significant role in self-healing concrete and crack repair with improved mechanical properties of the material. This innovation offers substantial benefits to the construction industry by reducing maintenance needs and enhancing durability [7]. Under the load deflection study, the treated samples showed low deformation when compared with control samples. The treated sample produced stiffer behavior during the same load. These studies suggest that the bacterial treated mortar confirms the durability enhancement [1].

A significant quantity of agricultural residue is produced throughout the world, with a total capacity of 1000 million tonnes generated as garbage. Sometimes the plant wastes are left to decay, releasing a lot of methane or carbon dioxide gas. These wastes have severe impacts on the ozone layer, climate change, subsurface water and the global economy. In order to utilize them, few of these wastes have significant applications in the progression of green concrete, while the others end up with biomass for energy production [8]. The most commonly used fiber is the cellulose fibers, which develop chelate complex formation and prevent the cement hydration formation needed for strength development [9]. Hence, in this study, we used banana fibers with slight modifications reinforced with bacterial culture for the self-healing process. To produce a suitable sustainable material, this study mainly focuses on the use of banana fibers (BFs), as natural fibers (NBs) for various reasons like environmentally friendly and innovative in construction materials. Nowadays the BFs [10] are widely used in various fields.

The most probable solution for lowering the concrete crack can be achieved through the bio-cementation application. The bio-cementation is recognized as a green solution for the construction materials and their bonding. The microorganisms are used in this technique to generate calcium carbonate for construction purposes. Microbial induced calcite precipitation (MICP) with selected microorganisms can form calcite precipitation by various pathways [1]. The MICP generates carbon dioxide by microbial metabolism in the presence of water. This leads to carbonate ion formation, and the carbonate ion interacts with calcium ion to produce calcium carbonate under the right conditions [10]. The presence of MICP is attracted by the availability of water, ionic strength, bacterial concentration, the matrix's pH, nucleation sites, the presence of air space and nutrients. In one study, *B. subtilis* (Gram positive bacteria) showed extreme effects in MICP based concrete preparation. *B. subtilis* adheres to the surface of the cement particles and generates MICP nucleation sites. Many attempts of research provide a stable improvement in durability, mechanical properties and successful crack restoration [10]. The presence of microorganisms in cementitious materials is referred to as an eco-friendly and cost-effective method for repairing micro-cracks. This mode of self-healing is a suggestive technique for micro-crack healing, leading to significant improvement in the mechanical and physical properties of bio concrete [1], [5]. Hence, this approach can increase the life and durability of concrete structures without using time consuming and costly interventions [11], [12].

Although the metabolic activities of a few microorganisms in concrete material directly improve its behavior and it is known as an autogenous form of self-healing process. In bio-concrete, the microbial self-healing process uses two modes of metabolic pathways such as urea hydrolysis through urea bacteria and respiration by non-ureolytic bacteria [12]. Much attention has been gained to the use of *Bacillus* species. As it is a Gram-positive, rod-shaped bacteria, aerobic and pathogenic bacteria. This strain is common in the aquatic habitat and soil, and these bacteria are tolerant to alkalinity and are urease positive. Most of the *Bacillus* species bacteria can bio-transform urea into ammonium and calcite production. The presence of ammonia directly increases the level of pH, causing precipitation of calcite inside the presence of micro-cracks, thus sealing it properly [13]. In one study, the cracks healed faster in the presence of bacterial cultures than in non-bacterial specimens [14].

The present work focused on sustainable bio-concrete using banana fibers and ureolytic bacteria. This experiment primarily aimed to explore the fundamental characteristics of bacterial mortar enhanced with banana fiber composites. The focus was on examining how treating banana fibers with alkali chemicals impacts their chemical and physical traits. Additionally, the study sought to evaluate how well banana fibers integrate with bacterial cultures essential for producing bacterial mortar.

2 Materials and Methods

2.1 *Cement and M sand*

Portland pozzolana cement (PPC) was used in this work, which consists of ordinary cement and pozzolanic materials with a specific gravity of 2.9 and standard consistency of 31.9. M Sand was used as a fine aggregate, which helps to compact the cementitious materials. As per IS 2386:1963, Water absorption, Bulk density, specific gravity, fineness modulus and gradation of fine aggregates were calculated. From that calculation, Figure 1, a graph can be plotted of the particle size distribution curve, resulting in Zone II. The physical properties of fine aggregates tabulated in Table 1.

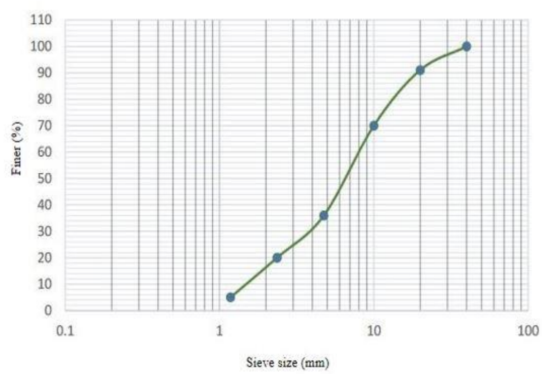


Figure 1: Particle Size Distribution of M sand indicates the range of size of particles in manufactured sand and graph drawn with values.

Table 1: Properties of fine aggregates.

Property	Value
Specific Gravity	2.6
Bulk Density (Compact) (kg/m^3)	1840
Bulk density (Loose) (kg/m^3)	1692
Absorption (%)	3.85
Fineness modulus	2.84

Figure 2: Preparation of microbial solution (*B. cereus*) (i) preparation of agar plate (ii) streaking culture (iii) prepared broth media (iv) inoculation in broth media (v) incubation (vi) microbial solution (vii) OD measurement.

2.2 *Water*

As per IS 456:2000, potable water can be used for mixing and curing purposes for control mix, bio-mix and fiber mixes. 0.45 as the water-cement ratio fixed for all the mixes.

2.3 *Bacterial culture*

The bacterial strain *Bacillus cereus* was introduced in this experiment sponsored by Dr. H.S. Lab, Madurai Kamaraj University. The strain was purchased from ATCC Bangalore. *Bacillus* is a gram-positive rod-shaped bacterium commonly found in soil, marine sponges, and food. According to Christensen's urea agar test, urease activity can be identified as positive. *B. cereus* can flourish at a temperature of up to 60 °C, but 35 °C is the optimum temperature for bacterial growth.

2.4 *Preparation of bacterial solution*

Bacterial cultures were obtained from glycerol stocks. A freshly prepared LB (Luria Bertani) broth medium containing peptone, yeast extract, and NaCl was sterilized by autoclaving at 120 °C for 20 min. After cooling to room temperature, 10 µL of glycerol stock culture was inoculated into 10 mL of LB broth for overnight cultivation in a shaking incubator at 37 °C for 12 h. For large-scale cultivation, the overnight culture was transferred to 500 mL of LB broth and incubated in a shaking incubator at 37 °C for 24 h. Subsequently, the culture density was measured using a UV spectrophotometer to achieve an OD of 0.15, adjusted by adding sterilized distilled water according to McFarland standards. A schematic representation of the bacterial preparation process is shown in Figure 2.

2.5 *Carrier material*

Untreated banana fibers (BF) were purchased from ECO GREEN UNIT, Coimbatore, as a carrier material for this work. A chemical treatment was performed on the raw banana fibers to reduce their stiffness and enhance the matrixes of other materials [15]. Elbehiry and Mostafa experimented with the alkaline treatment of NaOH for the modification of physical and mechanical properties. Cleaned and dried raw fiber has been taken for the treatment process. This experiment followed the modified protocol which gave high tensile strength from the published work [16], immersed the untreated banana fiber in 0.5% NaOH for 10 h, cleaned it thoroughly, dried it in an oven for 24 h, and then cut it into suitable sizes for further work. Physical, mechanical and biological properties have been analyzed by treated BF fibers (Figure 3).

Figure 3: Process of banana fiber (BF) (a) raw banana fiber (b) 0.5% NaOH (c) immersing BF in NaOH solution for 10 h (d) wash the BF with tap water (e) treated BF (f) cut the treated fiber into suitable sizes.

2.6 *Banana fiber properties*

2.6.1 Physical properties

According to ASTM C 127, the physical properties of banana fiber, such as absorption, bulk density, and apparent specific gravity, were assessed [17]. A sample of BF was taken, weighed, and recorded as (Wr), and then Wr was kept in an oven at 110 °C until the same weight was obtained, and the weight was recorded as oven-dried weight (Wo). Immersed the sample (Wo) in water for 24 h to check the water absorption rate, weighed, and noted as an immersed weight (Wi). Taken out of the water and sponged the fiber by cloth, then weighed as saturated surface dry (WSSD). The following equations are bulk density Equation (1), apparent specific gravity Equation (2) and Absorption Equation (3).

$$Bulk\ Density = \frac{W_o}{W_{SSD} - W_i} * 997.5 \quad (1)$$

$$Apparent\ specific\ gravity = \frac{W_o}{W_o - W_i} \quad (2)$$

$$Absorption\ (\%) = \frac{W_{SSD} - W_o}{W_o} * 100 \quad (3)$$

2.6.2 Mechanical properties

According to ASTM C-1557, a tensile test of banana fibers was conducted with an applied load of 10 kg at a speed of 3.5 mm/min on a SHIMADZU Universal Testing machine. Fiber failure happens within 30 s after starting the machine as per standard. For this test, 140 mm fiber length was taken and 80 mm was the gauge length. The fiber was fixed in the center of the machine and tightened the screws as shown in the Figure 4. As the load is applied fiber tends to break at a particular point that was noted.

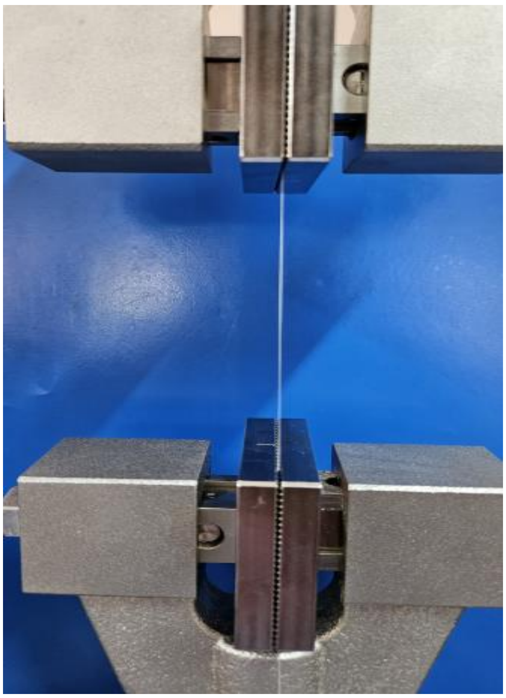


Figure 4: An experiment setup in which a single strand of BF is fit to the universal testing machine to measure the mechanical properties.

2.7 *Compatibility of BF with bacterial strain*

A protocol was outlined to assess the performance of *B. cereus* with BF to check its compatibility [18]. The agar plate was prepared by mixing nutrient agar and agar powder with distilled water. *B. cereus* was streaked on the plate by using a cotton swab, then sprinkle the fiber over the streaked area and parafilm the plate. Compatibility was confirmed after 24 h of incubation by growth pattern. The compatibility result shows that BF does not baffle the growth of bacterial strains (Figure 5).

Figure 5: Compatibility test between the bacterial strain *B. cereus* and banana fiber by agar plate method.

2.8 *Mix proportion and mortar cube preparation*

A total of three mixed proportions of different mortar recipes were formulated as control mix, *B.cereus* mix and *B. cereus* banana fiber (BCBF) mix. The specific mix proportion could vary based on factors including desired strength, workability of the mortar and intended application of the mortar. Table 2 represents the mortar mix design for this experiment. Portland pozzolana cement (PPC) the blended type of cement comprising the Portland clinker, gypsum and the pozzolana particles in specific proportions was utilized as a basic binding ingredient of mortar for the cube preparation with a ratio of mortar as 1:3. A water cement ratio comprising of 0.45 as the specific proportion for all mixes in addition to the introducing the microbial solution of *B. cereus*, non-pathogenic bacteria to the mortar mix concerning with weight of water for bio mixes. The calcium salt of acidic acid was appended as the nutrient for *B. cereus*. Banana fiber as a carrier material for this mix taken in different ratios varies with length and percentages.

Table 2: Mortar mix design.

Material	CM	BCM	BCBFM
Cement (kg/m^3)	478.8	478.8	478.8
Fine aggregate (kg/m^3)	1596	1596	1596
Water (L/m^3)	215.46	209	209
B.cereus (L/m^3)	-	6.46	6.46
Calcium acetate (wt%)	-	1.078	1.078
Banana Fiber (wt%)	-	-	BF

In this recipe, materials such as cement, sand, calcium acetate and banana fibers of 0.25, 0.5, 0.75, and 1% and lengths of 0.5, 1, 1.5, and 2 cm were mixed in the dry condition in a mortar mixer for 2 min with different formulations (Table 3). Optimized three percent of bacterial solution BC was blended to the mix at the particular intervals for the water weight in the proportion for homogeneity. Freshly prepared mortar is poured into the specific molds as cubes, cylinders, and beams and compacted by a vibrating table. After 24 h, the demolded specimens were kept in a curing tank for testing the strength for 3, 7, and 28 days.

2.9 *Mechanical property test*

2.9.1 Compressive strength test

The compression strength, the capacity of concrete to withstand loads before it fails, or calculated from the failure load divided by the area of cross-section resisting the provided load, is the maximum strength of the hardened concrete deliberated by the compression test. The compression strength of the concrete could be a measure of the concrete's ability to resist loads, which tend to compress it. Initially curing of samples is done under controlled conditions, typically in a humid environment to stimulate the present environmental conditions which allows the concrete to gain strength over a range of time.

The cured samples of cubes were placed in a compression testing machine that had been properly calibrated. By applying the load that gradually increases until the specimen fails. The data have been recorded for specific intervals like 3, 7, and 28 days of curing of 5×5 cm^2 concrete specimens that were cracked by testing the compressive strength of the specimens or cubes. Compressive strength is calculated by dividing the maximum applied load to the sample by the area of a cross-section of the considered sample which came in mega Pascals (MPa). Figure 6 demonstrates the procedure of casting the specimen.

Figure 6: Specimen casting (a) raw materials such as cement, M sand and banana fiber (b) mortar mixer machine (c) mix the ingredients in dry form (d) water and bacterial solution (e) add required water in the dry mix to make a wet mix (f) cast the specimens using molds (g) curing process in water (h) after 28 days of curing.

Table 3: Mixture proportion of BCBF mortars.

Material	BF (%)	BF Length (cm)	BC (%)	Calcium acetate (g/L)	w/c	Cement /sand
CM (control)	-	-	-	-	0.45	1/3
F0.25L0.5	0.25	0.50	3	5	0.45	1/3
F0.50L0.50	0.50	0.50	3	5	0.45	1/3
F0.75L0.50	0.75	0.50	3	5	0.45	1/3
F01L0.50	1	0.50	3	5	0.45	1/3
F0.25L01	0.25	01	3	5	0.45	1/3
F0.50L01	0.50	01	3	5	0.45	1/3
F0.75L01	0.75	01	3	5	0.45	1/3
F01L01	1	01	3	5	0.45	1/3
F0.25L1.50	0.25	1.50	3	5	0.45	1/3
F0.50L1.50	0.50	1.50	3	5	0.45	1/3
F0.75L1.50	0.75	1.50	3	5	0.45	1/3
F01L1.50	1	1.50	3	5	0.45	1/3
F0.25L02	0.25	02	3	5	0.45	1/3
F0.50L02	0.50	02	3	5	0.45	1/3
F0.75L02	0.75	02	3	5	0.45	1/3
F01L02	1	02	3	5	0.45	1/3

2.9.2 Split tensile strength test

The sample has been modified in the form of a cylinder with dimensions 100×200 mm [19]. Generally designed as the diameter is twice its height (2:1) ratio. It has been ensured that the samples that have to follow the split tensile strength testing were cured properly under controlled conditions similar to the compressive strength unlike the test conducted after 28 days of curing to achieve adequate strength. The sample was placed on the testing machine, ensuring it was centered and aligned properly as the machine was applying compressive load diametrical manner to the cylinder sample. The compressive load was applied gradually and uniformly along the length part of the cylinder until the sample was fractured at consistent testing conditions as per ASTM C 496 [20] for concrete. There is no separate codal provision for the split tensile strength of mortar so followed the concrete codal procedure for this study. As the sample eventually split along its length, the maximum load or the split tensile strength of the cylindrical sample has been determined using the Equation (4),

$$Split\ Tensile\ strength = \frac{2P}{\pi DL} \quad (4)$$

Where, P - Maximum applied load
D - Cylindrical sample's diameter
L - Cylindrical sample's length

After recording the split tensile strength of the samples, the results from every sample have been analyzed for consistent and accurate results.

2.9.3 Flexural test

For conducting the flexural strength test in the beam-shaped samples of size 160 × 40 × 40 mm, typically the three-point bending test has been done and checked for any defects or irregularities. As per the ASTM C 348, the controlled curing is done for 28 days to attain sufficient strength.

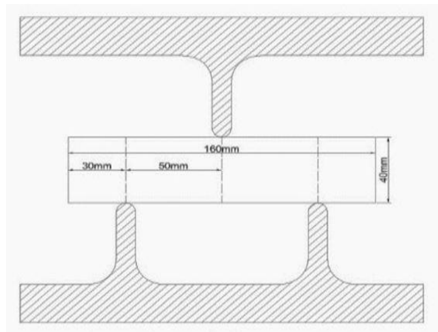


Figure 7: A sketch showing the fixation of the sample (a beam size of 160×40×40mm) in a three-point flexural test set-up. In which a sample is fixed at two supports called the span and the load is given at a center point.

The testing machine consisting of the appropriate fixtures for the three-point bending test (Figure 7) has been set up, which involves two supports put down a fixed distance apart with a loading point between them by ensuring the loading point is centered on the sample. The load was applied at a constant rate that was uniform in the testing machine until the sample fractured which denoted the specific limit. The maximum applied load to the sample before it is dismantled is recorded using the formula Equation (5),

$$Flexural\ Strength = \frac{3PL}{2bd\hat{}2} \quad (5)$$

Where, P - Maximum applied load
b - Sample's width, d - Sample's depth
L - Span length between the supports

After recording the flexural strength values with relevant standards of the samples, the results from every sample have been analyzed for consistent and accurate results.

2.9.4 Abrasion test

Abrasion resistance is evaluated as per the guidelines given in IS 15658 2006 [21]. The samples were cast in the cube molds with the specific dimensions of

70.5×70.5×70.5 cm^3, and the testing standard was conducted by considering the defined testing standard parameters, which include the type of abrasive material, the rotational speed, the test duration, and other relevant factors. The changes [22] were made in the specimen dimensions of 67.5×67.5×67.5 cm^3 according to the machine standards by filing. As per IS 1237, the abrasive sand was used in the abrasion testing machine to find the resistance of the mortar. The specimen was kept in the oven for 24 h before the experiment and the weight was the initial reading. It was ensured that the testing machine was calibrated and operating efficiently and one of the surfaces was mounted into the grinding disc in the mold holder as a testing surface. 20.00 gms of abrasive sand was taken and sprinkled around the grinding disc. The testing machine runs at 30 to 34 rpm speed and 22 revolutions per cycle. Discarded the abrasive sand in the disc after each cycle. The specimen moved around 90° in a clockwise direction for every cycle but the testing surface was kept constant, the same up to 16 cycles and measured the weight as final reading.

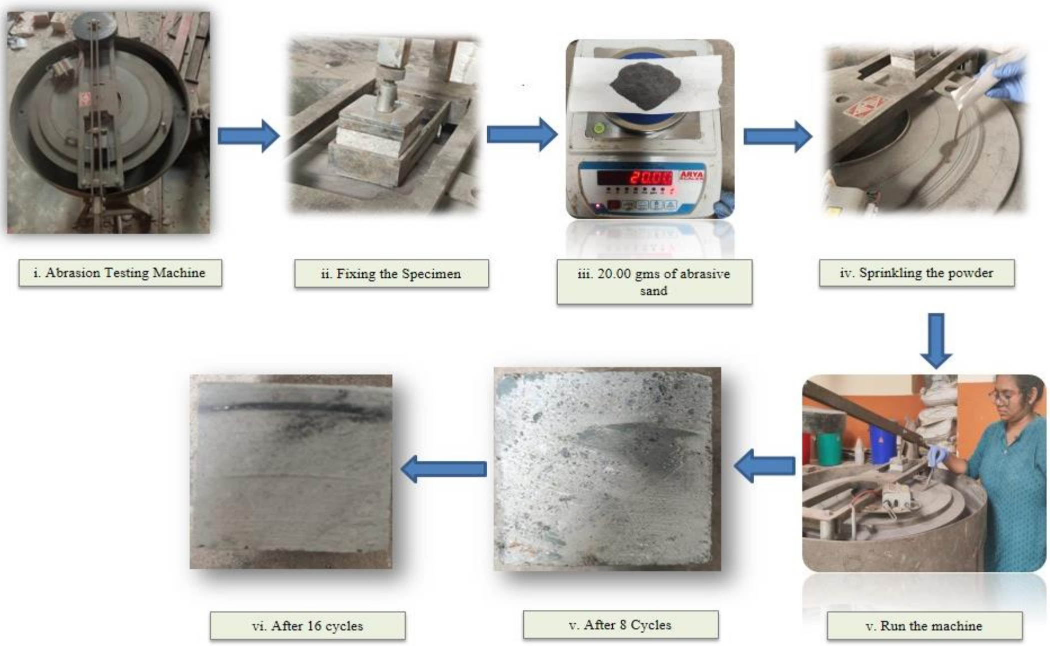


Figure 8: Abrasion test (i) abrasion testing machine (ii) fix the specimen in the machine (iii) weigh the abrasive sand as 20.00 gms (iv) sprinkle the powder in the disc (v) start the machine to run (vi) picture captured after 8 cycles (vii) picture captured after 18 cycles.

This test helped us to measure the mass loss sample by the difference between the initial value (before abrasion) and the final value (after abrasion). Figure 8 explains the procedure of the abrasion test and the abrasion resistance was formulated by Equation (6),

$$\Delta V = \frac{\Delta m}{PR} \quad (6)$$

ΔV – Loss in volume after 16 cycles mm^3
Δm – Loss in mass after 16 cycles g
PR – Density of the specimen g/mm^3

2.9.5 Water absorption

The water absorption test was conducted under the specified conditions and adhered to relevant testing standards (BS 1881: Part 122: 1983). In this work, followed this code to find the absorption of water capacity in percentage by the specimen as mortar. The water curing process was done for all the mortar cubes of 50×50×50 mm in all 16 mixes, along with the control mortar, for 28 days. After taking out the specimen from the curing tank, then maintained the specimen in an oven at 105 °C for 72 h [23] and cooled down at room temperature then each of the samples was weighed to calculate its initial dry weight (W_i). The specimens were kept for immersion in the water for around 24 h at room temperature. After that immersion period, gently remove the excess surface water from the specimen by wiping without compacting the surface. Weighed again individually after surface drying to ascertain the saturated weight of the sample as wet weight (W_o). The water absorption can be calculated by using the formula Equation (7) as per codal provisions [24] and expressed in terms of the percentage.

$$W_a = \frac{W_o - W_i}{W_i} \quad (7)$$

Where, W_a – Water absorption; W_i – Dry weight; W_o – Wet weight

3 Results and Discussion

3.1 *Physical and mechanical properties of fibers*

The purpose of the study was to determine the water absorption, specific gravity, and bulk density of banana fibers. The measurements were conducted three times using an empirical formula. The results revealed that the bulk density of banana fibers is 1367 kg/m^3 mentioned in Table 4, which classifies them as harder fibers. Additionally, the water absorption capacity of banana fibers is 31%, which is relatively low when compared to other natural fibers, such as jute, sisal, kemp, and kenaf.

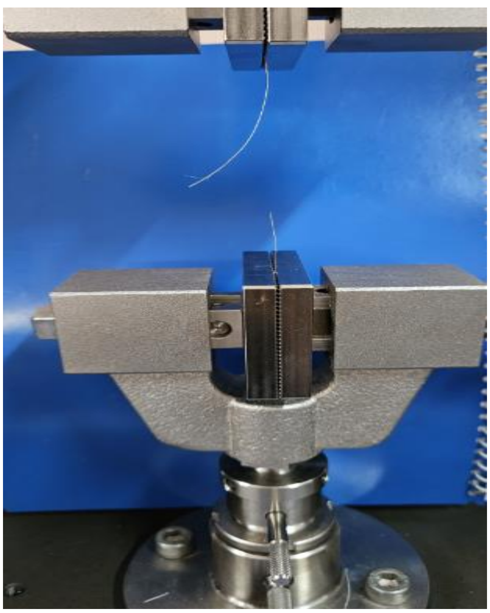


Figure 9: Banana fiber sample broke at a particular point when the load was applied.

Figure 10: Microscopic images of broken fiber (100X magnification).

Table 4: Physical Properties of banana fiber.

BF Property	Value
Bulk Density	1360g/m^3
Water Absorption	31%
Specific gravity	1.3

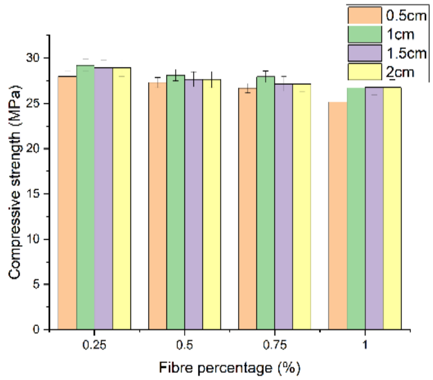
Table 5: Mechanical properties of banana fiber.

Property	Treated BF	Untreated BF
Max Load (N)	4.00543	3.0628
Tensile strength (Mpa)	400.893	253.255
Young’s modulus (Mpa)	186.72	113.856
Elongation (%)	4.15	2.1538

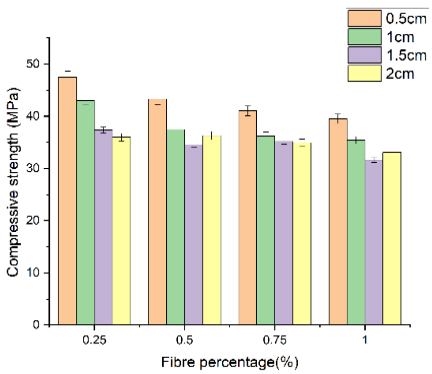
During testing in the machine, a broken fiber was captured (Figure 9). The comparative result has been tabulated in Table 5. The average tensile strength of the treated banana fiber is 400.893 MPa, with a standard deviation of 168.49 while the tensile strength of untreated banana fibre is 253.255 MPa. 58% increase in tensile strength after an alkaline treatment was found. The percentage elongation of treated banana fiber 4.15% relates to the plastic behavior of the material. A microscopic image of the broken fiber was captured in Figure 10.

3.2 *Compressive strength*

Figure 11 displays banana fiber compressive strengths with the bacterial mix at varied fiber lengths and percentages on the 28th day of testing and made it very evident that, for all fiber lengths, compressive strength values increased as fiber content increased except that length of 0.5 cm. Figure 12 explains the testing of mortar cubes in the machine. According to Xiong *et al.* [25], when the fiber percentage was raised from 0.5 to 1.5%, the compressive strength of concrete containing recycled carbon fiber-reinforced polymer (RCFRP) fibers dropped from 54.89 to 49.09 MPa.



(a)



(b)

Figure 11: Effect on compressive strength of banana fibers (a) on 7 days (b) on 28 days.

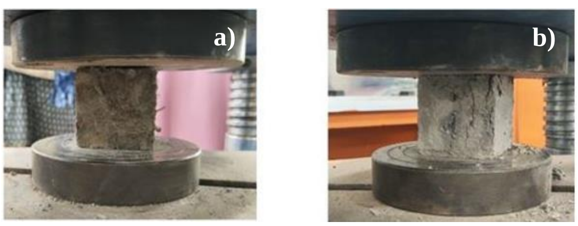


Figure 12: Compression testing (a) compression test setup (b) crack occurs on the specimen while testing.

The inclusion of fibers causes the mortar's porosity to rise, resulting in a significant number of pores and microcracks at the matrix-fiber interface and a decrease in compressive strength. It is anticipated that when fiber content increases, more ITZs will be formed in the mortar, which will reduce its compressive strength. Incorporating banana fibers in concrete changes its failure mode from brittle to plastic, and reduces crack formation and propagation. Other researchers noticed similar results, reporting that fibers greatly contribute to the load-carrying capability of the post-peak phase and limit micro-crack formation, which delays failure and increases ultimate strength [26]–[28]. It has also been proposed that the addition of fibers to concrete allows it to withstand increased compressive stress by rerouting and obstructing cracks [29].

The use of pozzolanic materials such as volcanic ash, fly ash, or calcined clay in Portland pozzolanic cement (PPC) offers advantages over ordinary Portland cement (OPC). PPC demonstrates improved resistance to aggressive environments, including sulfate attack and chloride ingress. Additionally, PPC produces less heat of hydration during the mixing process, which enhances durability and reduces the risk of water penetration due to its denser concrete microstructure.

Furthermore, the production of PPC incorporates industrial by-products like fly ash, which helps reduce the carbon footprint associated with cement production [30]. For BF mortar mix with fiber concentration > 0.25%, shorter fibers showed greater values of compressive strength about length than longer fibers when compared to control mix. Based on experimental results, it was observed banana fiber content of about 1% was suitable when compared with other lengths of fibers used except the shorter fiber of 0.5 cm. For BCBF mix, with the impact of fiber length respect to percentage as 0.25, 0.50, 0.75, and 1%. Compressive strength gradually decreases for shorter fibers. In other cases, the effect has completely reversed while increasing fiber length, decrement in compressive strength for percentage wise, as longer 2 cm fibers had somewhat lower compressive strength values than remain all the lengths of fibers including plain concrete. This study unequivocally demonstrates that when lower fiber contents are applied, the amount of fibers used is more important than the fiber dimension/length, and when higher fiber contents are applied, the amount of fibers is more important than the fiber dimension/length.

3.3 *Split tensile strength*

The split tensile strength of varying percentages of fibers with different lengths was plotted in Figure 13. It was observed that the addition of fiber content of 1% resulted in an increment of split tensile strength except for longer fibers 2 cm length fibers with a percentage of 0.25% to 1% have a dramatic decrease in tensile strength. Wu *et al*. tried different fibers, such as polypropylene, basalt and glass fibers, the use of an apricot shell in concrete resulted in an enhancement in tensile strength at a percentage of 0.25 to 0.50% then a sudden decrease in remaining percentages [31]. Figure 14 shows that testing the cylinder specimen in the machine.

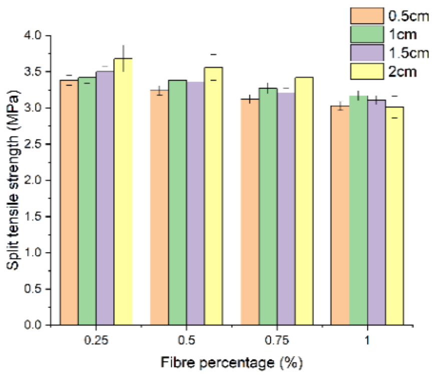


Figure 13: Effect on split tensile strength of mixing of banana fiber with bacteria with varying percentages and different lengths.

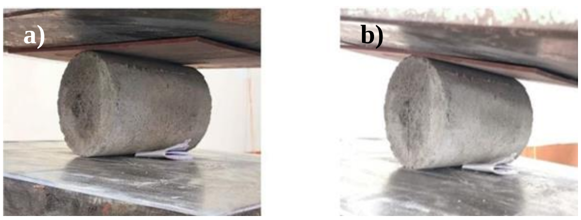


Figure 14: Split tensile strength (a) cylindrical specimen was positioned in the testing machine for testing (b) a crack formed on the surface after the load was applied.

Some studies reported that fiber addition into concrete gives a good result in tensile strength. Tensile strength improvement leads to a reduction in the propagation of cracks and a better impact on mechanical properties [26], [32], [33]. In this study, the fiber to the bacterial mortar was mixed in different lengths and percentage content. Concerning the length of fibers, longer fibers of 1.5 cm and 2 cm of 0.25% showed higher tensile strength compared with the control mortar. It was observed that based on the results obtained, the value after 28 days of curing implied a gradual decrease in ascending order for all varying lengths and for 0.25% of 2 cm shows higher tensile strength, further the value reduces gradually for 1.5, 1, and 0.5 cm. 1% compared to plain mortar. The outcome of this study showed that longer fibers gave a better result on tensile strength than shorter fibers up to 1%.

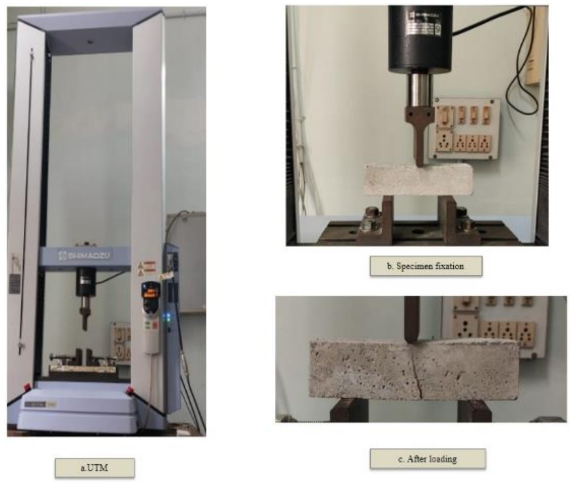


Figure 15: Experimental setup for testing the flexural strength of specimen (a) image of universal testing machine (UTM) (b) labeling the prism specimens as required and attaching the marked specimens to UTM (c) the prism broke at the point of loading.

3.4 *Flexural strength*

The empirical formula for the relationship between compressive strength and flexural strength was developed by IS 456: 2000, when shorter fibers were employed at lower fiber dosages, the addition of banana fibers to concrete generally had only a negligible effect on the material's flexural strength. With an increase in fiber content, longer fibers of length 2 cm declined in a range of 0.25% to 1%. On the other hand, as the amount of fiber increased, the flexural strength of all the BCBF mixes with shorter fibers increased in ascending order. A shorter fiber of 0.5 cm was inclined with percentages and a longer fiber declined from a lower percentage to a higher percentage. Inclination and declination have a little variation with particular percentages hiking at one value and then decreasing. From this study, banana fiber does not provide a significant impact on flexural strength. Figure 15 demonstrates the testing of a flexural test by UTM and Figure 16 illustrates that flexural strength BCBF mix varying in percentage and length.

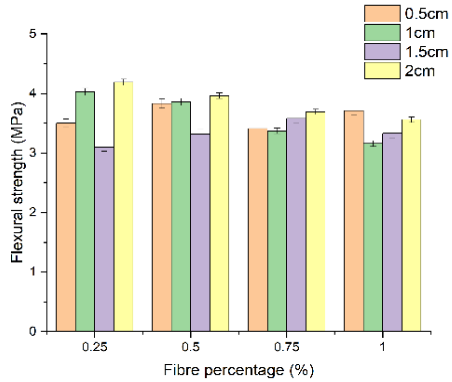


Figure 16: Effect on flexural strength due to the variation of percentages and lengths of banana fiber in bacterial mortar.

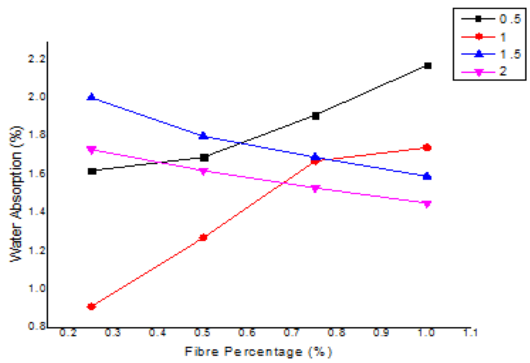


Figure 17: Effect on water absorption.

3.5 *Water Absorption*

Figure 17 illustrates the water absorption effect on the banana fiber-mixed mortar. After 28 days of water curing, a water absorption test was performed and calculated using the empirical formula. Short fibers of length 0.5 cm and 1 cm followed a trend in an increasing manner with respect to percentage. The reverse effect happened in the longer fibers of 1.5 cm and 2 cm, and the absorption value dropped. All the values are within the limit as per standards.

3.6 *Abrasion test*

Figure 18 quantifies the abrasion resistance of the mortar, the result resembles the water absorption. Elevated value was found for the short fiber lengths of 0.5 and 1 cm. Longer fiber was decreased from 0.25 to 1%.

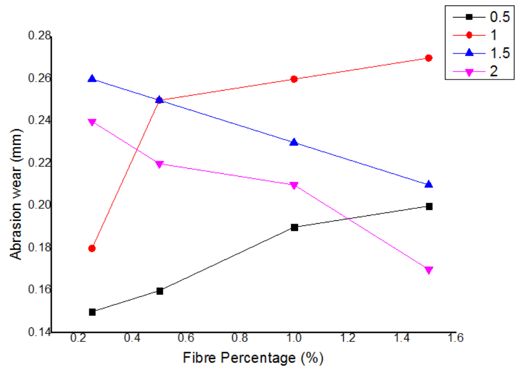


Figure 18: Abrasion resistance effect on mortar.

4 Conclusions

The experimental investigation focused on enhancing the mechanical properties of bacterial mortar by adding banana fiber at varying percentages and lengths. The study explored a modified protocol alkaline treatment on raw banana fiber, resulting in a significant 58% increase in tensile strength. Compatibility between bacterial strains and banana fiber was confirmed prior to the experiment, indicating that the bacterial strain did not impede the incorporation of banana fiber and tended to integrate well with the carrier material. Compression tests were conducted on mortar cubes on the 3rd, 7th, and 28th days. The use of shorter fibers (0.5 cm) resulted in decreased strength except for 0.25% to 1% fiber content. Optimal strength was achieved with 1% fiber content, especially with longer fibers. Longer fibers up to 1% showed superior performance in split tensile strength of mortar. Flexural strength was minimally affected by banana fiber in the mortar mix. Longer fibers showed a decrease with increasing fiber content. Further research is recommended to enhance flexural strength through the addition of natural fibers. Microstructural properties will be further investigated to understand the incorporation of banana fiber into the mortar mix, the interaction between bacteria and fiber within the cement mortar mix, matrix porosity, and the bond between the matrix and fiber in the Interfacial Transition Zone (ITZ).

The incorporation of banana fiber-reinforced bacterial mortar composites represents a significant advancement in construction materials by combining inherent structural strength with self-healing capabilities from natural fibers. This composite material is crucial for the maintenance and repair of infrastructure such as roads, bridges, and buildings. Although, banana fibers improved the mechanical properties, physical properties and thermal stability of polymeric materials compared with other natural fibers. Future research should aim to optimize performance and material properties under different environmental conditions. This includes exploring different combinations of fiber content, matric compositions and bacterial species to enhance the mechanical strength and self-healing capabilities of the construction materials [34].

This study investigated the properties of bacterial mortar reinforced with banana fiber composites. The banana fibers were treated with alkali for analysis of the modification of chemical and physical properties. Three types of analysis (physical, mechanical and biological) were done by using chemical treated BF fiber. The study also analyzed the compatibility of banana fibers with bacterial culture. This was analyzed by sprinkling the fiber over the bacterial culture and found that banana fiber does not baffle the growth of bacterial strains. The major findings observed in this study revealed that the levels of 0.25% fiber length had no observable. By exploring the chemical and physical properties of banana fibers treated with alkali chemicals and their compatibility with bacterial cultures, this study adds depth to our understanding of these composite materials. The emphasis on environmental friendliness and efficiency in utilizing natural resources and bacteria highlights the importance of sustainable practices in construction engineering.

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Author Contributions

S.B: conceptualization, investigation, experiment work, writing an original draft, methodology, review and editing; J.S.: supervision; P.S.: validation, visualization, data curation; A.C.R.: experiment work, data curation; S.T.V.: investigation, methodology, visualization, supervision: B.S.T.: project administration, funding acquisition, methodology design, supervision.

Conflicts of Interest

The authors declare no conflict of interest.

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