

Experimental Investigation and Characterization Studies on Coconut Fibre Reinforced Bacterial Concrete Using *Bacillus Subtilis*

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Abstract: A common building material, concrete may fracture when subjected to mechanical loads and environmental pressure. These cracks can compromise its structural integrity and allow moisture to penetrate, which might cause the reinforcing steel to rust. Recent advancements in self-healing concrete investigated the application of microorganisms that can autonomously generate calcium carbonate (CaCO_3) for crack repair. This research determined an innovative approach to enriching concrete's strength and environmental sustainability by incorporating the coconut fibre (CF) and *Bacillus subtilis* bacteria. A 10% bacterial solution with a concentration of 10^7 CFU/ml, along with waste CF, was added to concrete mixtures in varying amounts (0, 1, 2, 3, 4, and 5%) to evaluate its effectiveness as a micro-reinforcement additive for crack control and mechanical performance enhancement. The prepared concrete specimens underwent curing, and their mechanical properties were evaluated at 7, 14, and 28 days. The blend that performed the best was subjected to microstructural examination. The concrete containing 1% CF showed better mechanical characteristics after 28 days of curing, with values of 46.66 MPa for compressive strength (CS), 6.88 MPa for splitting tensile strength (STS), and 9.33 MPa for flexural strength (FS). This mix's microstructural examination revealed calcium carbonate (CaCO_3) formation, confirming effective crack healing and enhanced durability. This method utilizes agricultural waste as a reinforcing material, promoting sustainable practices in construction and enhancing the durability and service life of concrete structures.

Keywords: *Bacillus subtilis*; Bacterial concrete; Coconut fibres; Eco-friendly; Sustainable concrete.

1. Introduction

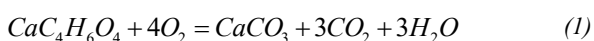
Concrete's strength, durability, and adaptability make it an essential component of contemporary construction, acting as the basis for skyscrapers, bridges, residential complexes, and commercial buildings¹. The standard ingredients for making concrete are water, aggregates, and cement; however, admixtures may enhance the material's properties. Additives are frequently used to enhance certain mechanical qualities and boost the endurance of a

material. Examples include superplasticizers, accelerators, retarders, air-entraining, and anti-corrosion agents². Despite these advantages, concrete remains inherently vulnerable to cracking due to its low tensile strength, shrinkage, thermal stresses, and sustained loading³⁻⁵. These cracks are not merely surface defects; they facilitate the ingress of aggressive agents such as moisture, chloride ions, and sulfates, which can accelerate reinforcement corrosion and compromise structural durability, ultimately reducing service life^{6,7}. Consequently, significant research

efforts have focused on developing strategies to mitigate crack formation and propagation in concrete structures.

The incorporation of supplementary cementitious materials such as silica fume (SF), rice husk ash (RHA), sugarcane bagasse ash (SBA), fly ash (FA), and ground granulated blast furnace slag (GGBS) has been shown to enhance concrete performance by reducing porosity and improving matrix densification through pozzolanic reactions⁸⁻¹⁰. More recently, self-healing concrete has emerged as a promising approach to autonomously repair cracks and extend the service life of concrete infrastructure^{11,12}.

Microbial-induced calcite precipitation (MICP) is one of the several self-healing techniques that has attracted much interest^{13,14}. This technique uses certain microbes that can precipitate calcium carbonate (CaCO_3) to fix fractures. Converting calcium salts into calcium carbonate, these microbes help repair fissures and restore the material's structural integrity^{15,16}. Bacteria from the *Bacillus* genus, especially *Bacillus sphaericus*, have demonstrated significant efficacy in decreasing moisture absorption and enhancing the compressive strength (CS) of concrete via microbial induced calcite precipitation (MICP)^{17,18}. Similarly, *Bacillus subtilis*, a closely related species, facilitates CaCO_3 precipitation due to its similar metabolic pathways. This microorganism is safe and widely available and thrives in the highly alkaline concrete environment^{19,20}. Additionally, *Bacillus subtilis* is a flexible choice for self-healing applications since it can adapt to aerobic and anaerobic environments. The supply of nutrients that help the bacteria produce calcium carbonates, such as calcium lactate, phosphorus, nitrogen, calcareous lactate, salts, tryptone, peptone, ammonium, and yeast extract, is essential for MICP to be successful^{21,22}. *Bacillus subtilis* was chosen for this study because of its remarkable capacity to endure extreme alkaline conditions and its resilience in aqueous environments. Furthermore, it can hydrolyze urea and participate in the nitrogen cycle, augmenting its adaptability. The potential longevity of up to 200 years significantly enhances its effectiveness in maintaining the enduring healing capabilities of concrete²³. The metabolic process entails the transformation of calcium acetate into calcium carbonate, water, and carbon dioxide, as shown in Equation (1).



The reaction generates calcium carbonate, which efficiently plugs fissures and improves the concrete's strength, while the carbonated calcium hydroxide in the mixture facilitates the healing process²⁴⁻²⁷. Concrete devoid of fibres is prone to cracking for reasons like plastic shrinkage, drying shrinkage, and volumetric changes, which may lead to elastic deformation. Fibres are added to

conventional concrete to improve flexural strength (FS) and mitigate cracking associated with shrinkage. Fibre-reinforced concrete integrates short, discrete fibres composed of steel, plastic, glass, or natural sources like vegetable fibres, coconut fibre, leaves, and twigs, randomly orientated and uniformly dispersed throughout the mixture. Numerous factors influence the characteristics of fibre-reinforced concrete, including the kind of cement used, the fibres composition and shape, and their distribution, concentration, and orientation within the mixture. Natural fibres provide an affordable alternative to synthetic ones, and a fibre composition of 0.1 to 3% by volume is often advised. These locally sourced fibres require minimal energy and labor, making fibre-reinforced especially advantageous in developing areas where conventional materials may be limited or costly. Coconut and sisal fibres, recognized for their strength and lightweight nature, find use in products such as pipes, roof tiles, silos, corrugated sheets, and tanks. CF are the strongest among natural fibres, capable of withstanding 4 to 6 times the load compared to other types. Therefore, CF are economical, readily available, and contribute to increased concrete strength while lowering thermal conductivity²⁸⁻³⁰. In addition to being lightweight and readily available, CF improves tensile resistance, reduces crack width, and contributes to enhanced durability, making it an attractive reinforcement material for sustainable construction applications.

Although numerous studies have investigated bacterial self-healing concrete and fibre-reinforced concrete independently, limited research has explored the combined application of bacterial technology and natural fibre reinforcement, particularly using *Bacillus subtilis* and coconut fibre. Existing studies on bacterial concrete predominantly focus on compressive strength and healing efficiency, with insufficient attention to the role of fibres in crack-bridging and their influence on bacterial mineralization. Likewise, research on coconut fibre-reinforced concrete largely emphasizes mechanical enhancement but rarely considers its compatibility with bacterial self-healing systems. Therefore, the synergistic interaction between coconut fibre and bacterial activity and its effect on mechanical and microstructural performance remains insufficiently understood.

The present study introduces a novel bio-fibre concrete system by integrating *Bacillus subtilis* with eco-friendly coconut fibre to achieve dual functionality, namely mechanical crack control through fibre reinforcement and autonomous crack healing through microbial mineralization. The novelty of this work lies in demonstrating the synergistic enhancement of mechanical performance, microstructural densification, and sustainability resulting from the combined application of natural fibre reinforcement and bacterial concrete technology. Accordingly, this study investigates the

influence of varying dosages of coconut fibre and Bacillus subtilis on the mechanical behaviour of concrete, evaluates performance in terms of compressive strength, splitting tensile strength, and flexural strength, examines microstructural modifications using XRD, FTIR, SEM, and EDS techniques, and assesses the feasibility of coconut fibre-based bacterial concrete as a durable, sustainable, and high-performance construction material.

2. Experimental work

2.1. Materials used

The cement used in this study was obtained locally. Ordinary Portland Cement (OPC) Grade 43, conforming to IS 8112:2013, with a specific gravity of 3.10, was employed³¹⁾. The chemical composition of OPC 43, as provided by the Ultra Tech Cement manufacturer, is presented in Table 1.

While the traditional coarse aggregate of 20 mm size was used following IS 383: 2016, the fine aggregate used in this study was natural river sand conforming to IS 383:2016, with a particle size distribution ranging from 0 to 4.75 mm³²⁾. The preparation's fine and coarse aggregates had specific gravities of 2.72 and 3.0, respectively. The CF used in this study were employed in their raw (untreated) form to preserve sustainability, reduce processing cost, and maintain practical applicability. Untreated CF possess a naturally rough surface and high lignin content, which promote adequate fibre–matrix bonding and effective crack-bridging in cementitious composites. Several studies have reported satisfactory mechanical performance of concrete incorporating raw coconut fibres without chemical treatment. The fibres used were approximately 50 mm in length and 0.5–1 mm in diameter, with their physical properties presented in Table 2. The raw CF used in the experimental study is shown in Figure 1. The purified tap water was used for concrete mixing, specimen curing, and preparation of the bacterial solution, ensuring uniformity and reproducibility. The water had a neutral pH of approximately 7, which is suitable for both concrete hydration and maintaining bacterial viability during culture preparation. The bacterial solution was separated with the preferred ideal concentration of 10^7 (CFU/ml).

Table 1: OPC Chemical composition

Compounds	OPC (%)
Al ₂ O ₃	8.27
CaO	46.58
Fe ₂ O ₃	5.12
Na ₂ O	0.12
SiO ₂	26.3
K ₂ O	0.03
MgO	1.12
LOI	2.99

Table 2: Physical properties of the CF

Physical properties	Results
Diameter (mm)	0.5-1.0
Length (mm)	8-10
Density (g/c.c)	1.3
Elongation (%)	25
Young's modulus (GPa)	4.4



Fig. 1: Coconut Fibre

The lab cultured bacterial solutions were blended while the concrete preparations were mixed, with 10% of the water replaced by the bacterial condition.

2.2. Preparation of Bacillus subtilis bacteria

Bacillus subtilis was the bacterium employed in this experiment. Bacteria-related research was carried out in two separate labs and periods. Production of the solution with precise chemical quantification, preparation of the mother culture using bacterium strips, autoclave, chilling the solution, and incubating the bacteria³³⁾. The Chemicals used to prepare the media were soybean medium, L-alanine (C₃H₇NO₂) manganese sulphate (MnSO₄). The bacteria Bacillus subtilis for use in this self-healing project concrete can endure a pH range of 6.5 to 8.5. The optimal pH was recorded at 7.5. The pH range of the concrete produced with MnSO₄ is 7.3 to 7.5. The chemicals used to manufacture 2 liters of media were as follows: Soybean - 60 grams, L-alanine - 0.4 grams, and manganese sulfate - 0.2 grams, combined with 200 milliliters of water. The autoclave was used to sterilize the prepared medium for 15 minutes at 121°C and 15 psi pressure. After sterilization, the medium was injected with Bacillus subtilis spore strips and cultured in a shaking incubator for four days³⁴⁾. Following the incubation time, bacterial concentration was evaluated by the usual plate count technique, leading to a cell concentration of 10^7 cells/mL. After 10 minutes of spinning at 6,000 rpm, the bacterial cells were removed from the growth media. The separated bacteria were directly added to the sterile water. After that, it was taken for the concrete sample preparation.

2.3. Mix Proportion

Table 3: Concrete mix preparation

Mix constituents	CF in a bacterial control mix					
	0%	1%	2%	3%	4%	5%
Cement (kg/m ³)	385	385	385	385	385	385
Fine aggregates (kg/m ³)	850	850	850	850	850	850
Coarse aggregates (kg/m ³)	937	937	937	937	937	937
Water/cement ratio	0.45	0.45	0.45	0.45	0.45	0.45
Bacterial solution (%)	-	10	10	10	10	10
Tec-mix 550 (%)	-	1	1	1	1	1

Note: CF percentages are expressed as weight fraction of cement.

According to the recommendations of the IS 10262:2019, Table 3 includes the M30 grade concrete mix proportions. The mixture of control was cast with 0% coconut fibre and the rest cast with 1 to 5% coconut fibre. In the case of the fibre reinforced mixes, 10% bacterial solution was added instead of the water content where the control mix contained no bacteria solution. Minimum amount of calcium acetate was added to bacterial solution in coconut fibre mixes to serve as supplement to the bacterial activity.

2.4. Strength test

In order to assess the mechanical properties of bacterial concrete incorporating coconut fibre (CF) at different percentages ranging from 0% to 5%, specimens were systematically prepared and subjected to testing at curing intervals of 7, 14, and 28 days shown in Figure 2. Cubic specimens measuring 150 mm × 150 mm × 150 mm were produced for the purpose of evaluating compressive strength (CS), whereas cylindrical specimens with a diameter of 100 mm and a height of 200 mm were fabricated for the assessment of split tensile strength (STS)³⁵. Furthermore, prism specimens with dimensions of 500 mm × 100 mm × 100 mm were prepared for the assessment of flexural strength (FS). All bacterial concrete specimens underwent testing utilizing a compression testing machine (CTM) with a capacity of 2000 kN, in alignment with the guidelines set forth in IS 456:2000.

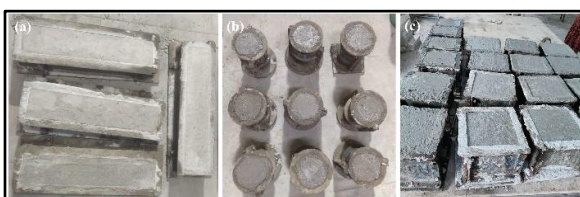


Fig. 2: CF concrete samples (a) Prism, (b) Cylinder, (c) Cube

2.5. Characterization studies

Microstructural characteristics, such as Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD), are what primarily defines the behaviour of concrete.

3. Results and Discussion

Both the fresh and hardened concrete properties were tested and the results given below. The slump test results show that the workability of the bacterial concrete decreases gradually with increase in the content of coconut fibre. This was because the control mix without fibre had the best slump which is indicative of good workability and as the 1% coconut fibre was added there was only a slight decrease and it still produced a workable mix that would be suitable to be compacted appropriately. With further increase in fibre content past 2 the slump was noticeably reduced because of the fibre interlocking, the surface area and internal friction within the mix. Blends with 4-5% coconut fibre had very low slump values and this signifies high stiff and less workable concrete and this can negatively influence the compaction and uniformity. The findings in general show that the addition of coconut fibre has negative effects on the workability at the higher dosages and the fibre content of 1 % offers the right balance of workability and performance in bacterial concrete.

3.1. Compressive strength (CS)

The mechanical properties of ordinary concrete and concrete enhanced with CF and *Bacillus subtilis* were compared in this research. For testing, CF and bacterial additions were included into specific samples at different percentages (0% to 5%) using OPC 43 as the binder. A CTM capable of holding 2000 kN of load at a rate of 4.5 kN/s was used to assess the concrete specimens' strength properties. The rate of strength growth can be measured in concrete samples after 7, 14, and 28 days of curing.

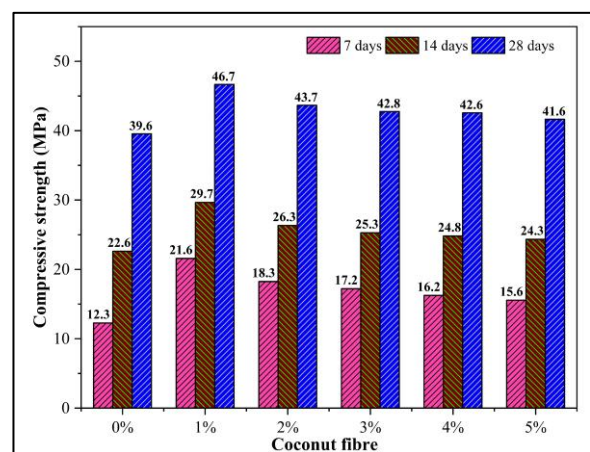


Fig. 3: CS results of CF-reinforced bacterial concrete

Samples are submerged in a curing tank throughout the process to ensure continuous hydration. Compression testing was used to determine load-bearing capacity and investigate failure mechanisms after extracted samples were collected at predetermined intervals and allowed to air-dry for 24 hours under ambient settings. The hydration process, which enhances the chemical interaction between water and cement and defines the concrete's strength. Each raw material particle must be adequately hydrated to achieve the required strength, including cement, CF, and aggregates. This requires maintaining the proper water-to-cement ratio; too little water prevents hydration, and too much water increases porosity, which reduces strength. Figure 3 displays the CF and CS in the bacterial concrete at 7, 14, and 28 days.

Bacterial concrete with CF added at a concentration of 1% shows an increase in CS compared to the control mix, and its strength has improved. Various percentages of CF samples were substituted for the weight of cement to assess the impact on strength. After 28 days of cure, the fibre-reinforced bacterial concrete reached its maximal CS with a 1% cement weight replacement, demonstrating a significant increase in strength. After adding 1% CF to the control mixture, the CS increased by 15.41% after 28 days. According to earlier studies, adding fibres to concrete may increase its CS by up to 2.0%^{36,37}. Using bamboo fibres at a 2.0% ratio optimizes CS in comparison to the control combination after 28 days of curing³⁸. Incorporating CF significantly enhances CS³⁹. The advantageous impact of CF is ascribed to their confinement around cylindrical specimens, which mitigates lateral expansion induced by compressive pressures, hence augmenting CS. However, this resistance may diminish due to reduced workability at higher dosages. Increased dosage complicates compaction, leading to porous concrete and a subsequent reduction in CS. Research demonstrates that using 1.5% fibres by volume may enhance the fresh density of concrete by around 15%⁴⁰. The findings demonstrate higher density and hardness, resulting in improved CS. Including fibres at a volumetric percentage of 1.0% yields a notable initial enhancement and a prolonged rise in the concrete's CS. This modified concrete demonstrated a significant enhancement in CS relative to the reference concrete, with a measured gain of 15%. Consequently, it is essential to ascertain the ideal quantity of CF for fabricating fibre-reinforced bacterial concrete. The findings suggest that substituting 1% by weight of cement with CF is the most effective approach to achieve improved CS.

3.2. Flexural strength (FS)

Four-point bending equipment tests a rectangular beam, with the carrying span being a third of the support span. The following connection was used to calculate the strength characteristics. FS is calculated as PL/bd^2 . In this context, L denotes the external principal span, b represents

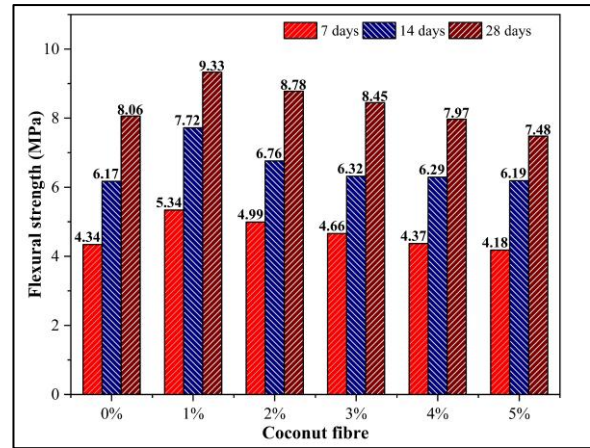


Fig. 4: FS of CF in Bacterial Concrete

the beam's breadth, d indicates its thickness, and P signifies the stress at the fracture point. Figure 4 illustrates the FS of incorporating CF in bacterial concrete.

The graph depicts the progression of FS in bacterial concrete enhanced with varying percentages of CF (0%, 1%, 2%, 3%, 4%, and 5%) throughout curing durations of 7, 14, and 28 days. Bacterial concrete with one percent CF in it produces a maximum FS of 9.33 MPa. Compared to the control mix and other mixtures, 1% CF in bacterial concrete results in a 15.75% enhancement in FS. Analogous to compressive capacity, FS augmented the number of CF by up to 1% by the weight of cement, after which it diminished relative to traditional concrete. Prior studies demonstrate that including up to 1% of fibres enhances FS relative to the control group^{41,42}. After the specified curing duration, the optimal FS was attained with a 1% replacement of CF in bacterial concrete relative to the control. FS decreased gradually with each 1% increment in CF replacement. All CF-reinforced concrete mixtures demonstrate enhanced FS relative to traditional mixtures. The advantageous impact of CF on FS is ascribed to their function in fracture mitigation. Using CF in a concrete mixture enhances the transmission of external loads to the fibres via interfacial interactions among the concrete constituents and the CF. CF impede crack propagation and redirect stress around cracks, facilitating load transfer within the concrete matrix. Integrating CF with the concrete enhances overall load resistance, improving FS. The compaction process becomes increasingly challenging with a higher percentage of fibres. Workability decreased at a higher dosage of 2%, resulting in porous concrete and a subsequent reduction in FS.

3.3. Splitting tensile strength (STS)

Cylinders were loaded into the CTM. STS was computed based on the data up to the last split in the cylinder. Utilizing the formula $2P/\pi DL$, cylinders are calculated. Where P = weight, L = clear span length, and D = specimen diameter. The maximum tensile strength was determined at 1% of the CF, slightly above conventional concrete. The

STS was assessed for 45 cylinders (100 x 200 mm) with fibre concentrations from 0% to 5%. As the quantity of CF increases, the cylinder's tensile strength will decrease.

Adding CF to bacterial concrete improves its fracture tensile characteristics, as seen in Figure 5. After 7,14, and 28 days of curing, the tensile strength of bacterial concrete varies for different concentrations of CF samples. A longer curing time increases the splitting tensile strength, which peaks at 28 days for all fibre percentages. This demonstrates how bacterially-induced calcite precipitation and progressive hydration reinforce concrete's structural integrity over time. After seven days, adding 1% CF to concrete resulted in a noticeable increase in its tensile strength, demonstrating their role in the early enhancement of concrete properties. The fact that concrete without CF had the lowest tensile strength throughout all curing times highlights how important fibres are to improving the functionality of bacterial concrete.

The STS was 1% higher in the CF-added mixture compared to the control mix, consistent with the higher CS. After the designated curing time, a 1% addition of CF to the mixture produced the best tensile strength. Adding 1% CF to bacterial concrete increases its tensile strength by 26.7% when contrasted with the controls. Earlier research found that compared to the reference mix, the STS increased by around 40% when 1% fibres were added, suggesting that fibres significantly increase tensile strength over CS^{43,44}. Nonetheless, the STS progressively diminishes with each replacement of CF above 1% due to a decline in workability. Incorporating CF augments concrete's flexibility by inhibiting crack development, enhancing the material's tensile strength capability. Bacteria-infused reinforced concrete has enhanced characteristics relative to traditional concrete mixtures. CF integrated with *Bacillus subtilis* serve mainly as crack stoppers rather than preventers, augment tensile strength more efficiently than CS, and are recognized for boosting the post-cracking performance of concrete⁴⁵. Fibres constituting 0.5 to 1% by volume significantly enhance the

tensile strength of concrete⁴⁶. As previously stated, the tensile capacity of concrete has behavior similar to that of CS.

3.4. Water absorption

Results of the experimental study of concrete with different proportions of coconut fibre and *Bacillus subtilis* indicated a marked difference as compared to the control mix 0% fibre content. The control sample recorded the highest measures of water absorption at all ages of curing period with a maximum of 2.10% at 28 days and 2.28% at 90 days implying highest porosity and poor impedance to water intrusion in the case of ordinary concrete. That addition of coconut fibres greatly decreased the water absorption, with the samples reinforced by fibres (1-5%) exhibiting a uniformly low water absorption as compared to the control mix. Fibre-reinforced mixes displayed the highest absorption values with a 1% fibre content recording the lowest absorption values of 1.68 at 28 days and 1.63 at 90 days shown in Figure 6, which was an assurance of its high level of reducing water uptake levels. This aligns with recent studies that reported coconut fibre reinforcement significantly improves durability and lowers water absorption in cement composites by refining pore distribution⁴⁷. The trend across all mixes further showed a steady reduction in absorption with curing age, attributed to progressive matrix densification aided by microbial activity, in line with microbial concrete studies using natural fibres⁴⁸. At higher fibre contents (4–5%), absorption values were slightly greater than at lower contents, though still improved over the control, highlighting the positive yet dosage-sensitive effect of fibres. Similar observations have been made, where excessive fibre content reduced homogeneity and led to micro-defects⁴⁹. At 3 percent fibre the absorbency was 1.60 percent at 90 days indicating an adequate balance between dose of fibre and the action of the microbes. However, 1% fibre made the most desirable mix recording

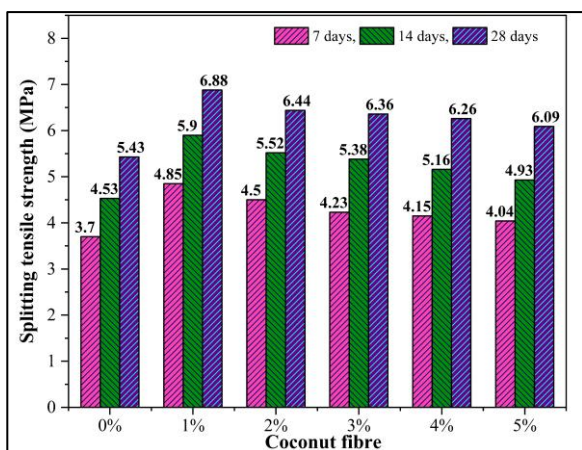


Fig. 5: STS of CF in bacterial concrete

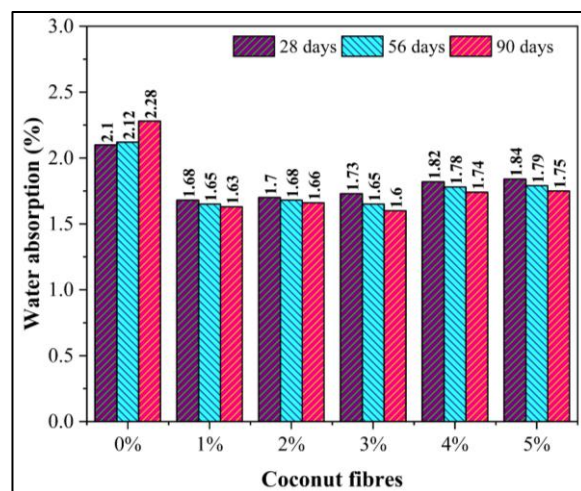


Fig. 6: Water absorption of CF in bacterial concrete

the most outstanding values in all ages. The 90-day findings on all fibre reinforced concretes showed the least absorption on overall basis reinforcing the long-term implications of microbial and fibre incorporation as also substantiated by self-healing concrete research based on bacteria⁵⁰). Therefore, fibre in combination with microbial treatment was effective in enhancing concrete durability and decreasing permeability at controlled doses where 1% fibre addition at 90 days was the most effective one, which led to the production of sustainable eco-friendly concrete.

3.5. SEM and EDS Analysis

SEM analysis of the optimized CF in bacterial concrete is shown in Figure 7. CF, composed of many circular cells, facilitates the transport of water and nutrients. The mechanical properties are affected by cellulose fibres organized in a helical spiral at a microfibril angle of 30 to 51 degrees. Under tensile stress, fibrous proteins transition from an off-axis orientation to a longitudinal alignment, leading to increased strength. When used with SEM, EDS makes it possible to measure the chemical makeup. on surfaces by examining X-ray signals produced during interactions with the electron beam. SEM images depict the microstructural features of bacterial concrete incorporating CF. Figure 7(a) show that the rough and varied surface shows the interaction between the cement matrix and the natural fibres at a magnification of 300µm. At a magnification of 100 µm, concentrated areas of hydration byproducts, such as C-S-H, are seen in Figure 7(b) Further magnification to the 30 µm highlights fibrous C-S-H gel and microbial deposits that enhance matrix bonding, as shown in Figure 7(c). The maximum magnification of 20µm reveals elongated ettringite crystals, calcium hydroxide (CH), and partially

occupied pores, where microbial-induced calcite precipitation decreases porosity. It increases material density, as shown in Figure 7(d). The use of CaCO₃ in the optimum mixture improves the performance of concrete. Using CF markedly increases tensile strength, while microbial activity fosters self-healing and durability⁵¹), thereby improving the overall efficacy of bacterial concrete. The SEM images validate ettringite formation, linking it to bacterial culture and CF through microbial calcite precipitation (MICP) induced by Bacillus subtilis. This process enhances the matrix's density by filling voids with CaCO₃, altering the chemical environment, increasing the availability of calcium ions (Ca²⁺), and indirectly facilitating ettringite formation. The concrete matrix is improved by CF because they act as places where hydration products may form, impacting water retention and ettringite kinetics. Their interaction with cementitious materials enhances adhesion, reduces porosity, and strengthens microstructural integrity; nevertheless, an excess of CF may hinder workability, affecting hydration processes and the development of ettringite crystals. Therefore, bacterial activity that promotes calcite precipitation and the addition of CF alters hydration dynamics, ultimately improving structural integrity and durability, and they collaborate to generate ettringite in bacterial concrete. Figure 8 shows the EDS analysis of the CF in the bacterial concrete. The result of Energy Dispersive Spectroscopy (EDS) spectrum expresses an elemental analysis of bacterial concrete, including CF. The notable peaks indicate the existence of elements such as calcium (Ca), silicon (Si), oxygen (O), aluminum (Al), sodium (Na), and iron (Fe), which are vital constituents of the cementitious matrix. Calcium and silicon are predominant, demonstrating the existence of hydration

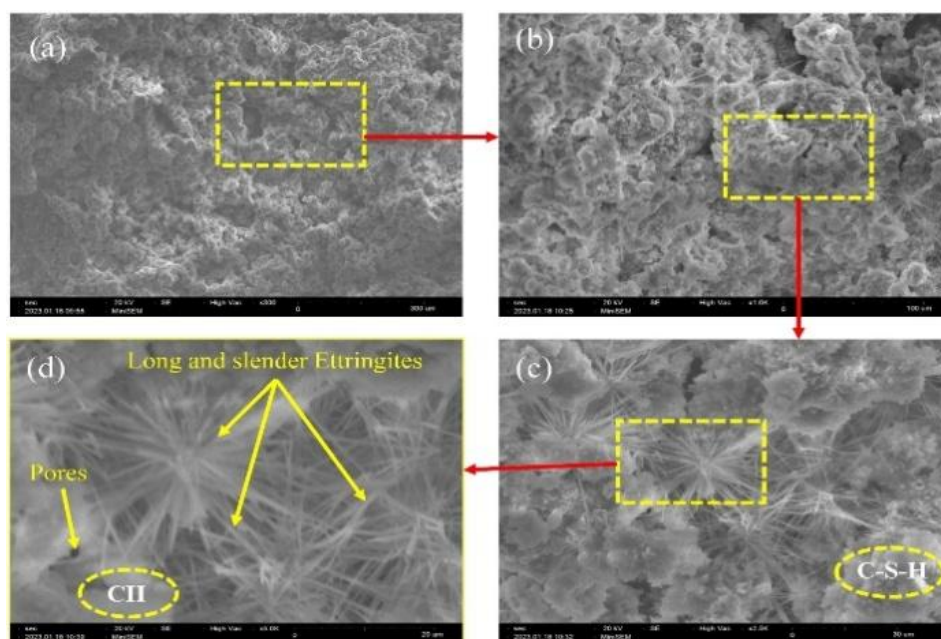


Fig. 7: SEM analysis of CF in bacterial concrete

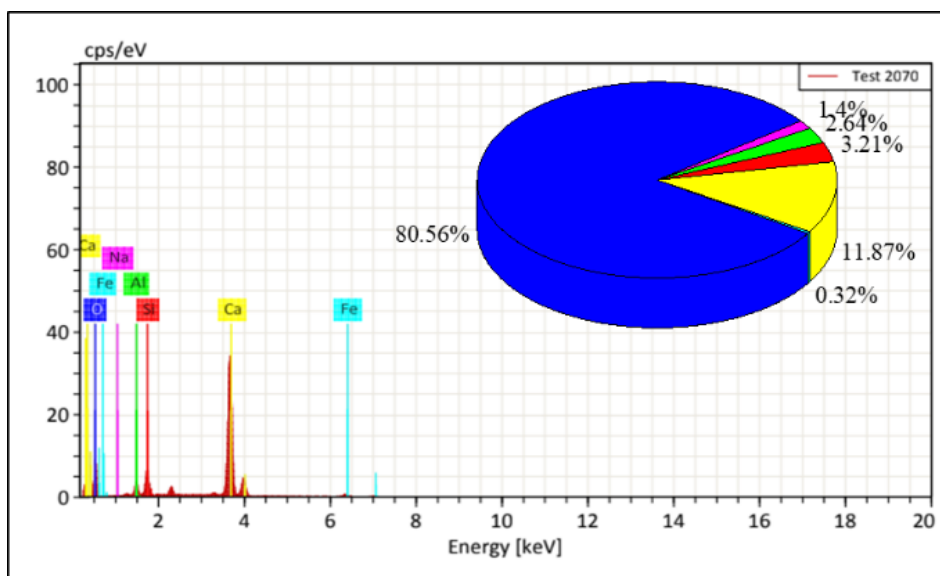


Fig. 8: EDS analysis of CF in bacterial concrete

products, including calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), which facilitate strength enhancement⁵²). The oxygen peak indicates the existence of oxides, whereas aluminum and salt likely originate from extra cementitious materials or mineral additives. The presence of iron may be associated with natural contaminants or microbial activities. Integrating CF in bacterial concrete enhances the mechanical characteristics of the matrix. Natural fibres function as reinforcements, enhancing tensile strength and durability. Bacterial activity promotes calcite precipitation, which occupies voids and decreases porosity, thereby increasing concrete density. The EDS analysis corroborates the SEM results by confirming the chemical composition of the matrix and the interaction between hydration products and microbial activity. The amalgamation of CF and bacteria produces a sustainable, high-performance material with improved self-healing and mechanical attributes.

3.6. XRD Analysis

The XRD analysis of CF within bacterial concrete reveals essential insights into its structural characteristics and interaction with the concrete matrix. The observed diffraction peaks confirm the existence of various mineral phases, including calcite (Ca), coesite (C), aluminum oxide (A), iron oxide (I), and titanium oxide (T). The findings, as shown in Figure 9, demonstrate a cooperative effect between natural fibre elements and bacterial-induced mineralization. A significant crystalline peak at a 2θ angle of 22° – 22.7° corresponds to the I002 and I101 cellulosic crystalline planes, indicating the crystalline regions of cellulose. A diminished intensity peak between 15.8° and 16° indicates the amorphous portions of cellulose associated with the irregular, non-crystalline segments of the fibre. The decreased crystallinity of untreated cellulose fibres is ascribed to the crystalline cellulose microfibrils

mostly enveloped by lignin, hemicellulose, and pectin⁵³). Despite 12 weeks of retting in distilled and saline water, these non-crystalline components were not completely eradicated, underscoring the need for extended or enhanced retting methods.

Therefore, fibres treated in saltwater displayed greater diffraction peak intensities than those treated in distilled water, likely due to the elevated salt concentration in seawater, which aided in the retention of specific salts within the fibres. A peak at $2\theta = 31.7^\circ$ indicates the presence of sodium chloride (NaCl), corresponding to its (002) crystalline plane, which remained trapped in the fibres due to insufficient washing post-retting. The XRD results also underscore calcite as a key phase in bacterial concrete, illustrating the influence of microbial activity on calcium carbonate formation. This mineralization, in conjunction with the structural attributes of CF, contributes to the enhanced mechanical performance of bacterial concrete. However, the low crystallinity of untreated fibres

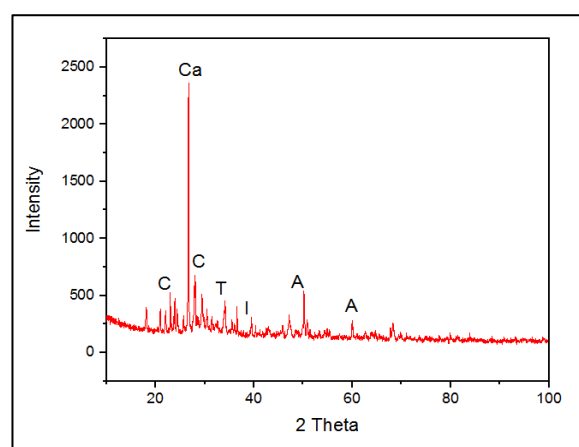


Fig. 9: XRD analysis of CF in bacterial concrete, Ca- Calcite; C- Coesite; A- Aluminum Oxide; I- Iron oxide; T- Titanium Oxide

and the persistence of lignin and hemicellulose may hinder fibre compatibility and durability, indicating a need for further refinement in retting and treatment processes.

3.7. FTIR Analysis

Figure 10 represents the FTIR analysis of CF within the bacterial concrete. The FTIR study of CF provides critical insights into its chemical composition and the effects of biological processes, particularly during oxidation and its use in concrete. The study used the FTIR Nicolet 6700 from Thermo Fisher Scientific, covering a spectrum range of 500 to 4000 cm^{-1} with a resolution of 0.5 cm^{-1} , using the KBr pellet technique to identify functional groups on the fibre's surface⁵⁴. As a natural lignocellulosic material, CF consists of cellulose, hemicellulose, and lignin, vital for their mechanical properties and behavior in composite materials. The spectrum displayed prominent peaks that correspond to the chemical structure of CF. A broad peak at 3393.897 cm^{-1} indicates O-H stretching vibrations, reflecting the presence of hydroxyl groups in cellulose, hemicellulose. Peaks at 1625.458 cm^{-1} correspond to C=O bonds from carboxylate groups in hemicellulose, whereas CH_2 symmetric bending vibrations were observed at 1494.577 cm^{-1} . Furthermore, aromatic C-H bending vibrations were detected in the range of 1097.237 cm^{-1} , characteristic of lignin. Low-frequency peaks between 427.692 cm^{-1} suggest the presence of Si-O-Si bonds, likely due to trace silica in the fibre. Notably, the absence of peaks at 3354 cm^{-1} and 2938 cm^{-1} after removing lignin and hemicellulose underscores these components critical role in the structure of the untreated fibre. The FTIR spectrum of concrete exhibited a peak at 895.357 cm^{-1} , signifying asymmetrical O-C-O stretching and bending

vibrations, indicative of calcium carbonate formation as a notable phase. This finding indicates that biochemical processes on the fibre surface, including oxidation, are essential for improving interactions between the fibre and the cement matrix. These results emphasize the importance of FTIR spectroscopy in evaluating the chemical makeup and alterations in CF, primarily when utilized as reinforcements in concrete. An in-depth comprehension of the alterations in functional groups and their interactions with cementitious materials demonstrates the promise of CF as a sustainable and biodegradable resource that improves concrete's mechanical characteristics and durability.

Coconut fibre and bacterial activity impact on the internal structure of concrete is clearly reflected in the density and porosity results. The density and porosity of the control mix were relatively low as they had unfilled voids in the cement matrix. The addition of coconut fibre to the maximum limit of 1% led to the rise of the density and consequent decrease in the porosity which can be explained by the enhanced packing of the particles, good bonding between fibres and matrix as well as calcite precipitation induced by the microorganisms that closed microvoids. The presence of *Bacillus subtilis* catalyzed the production of calcium carbonate which later resulted in the densification of the matrix and refinement of the pore. Nevertheless, a progressive decrease in density and an increase in porosity accompanied by a progressive increase in fibre content above 1% were observed because of poor workability, fibre agglomeration, and entrapped air, which prevented the achievement of a good compaction. At greater levels of added fibres (4-5%), the establishment of interrelated pores was more pronounced to the

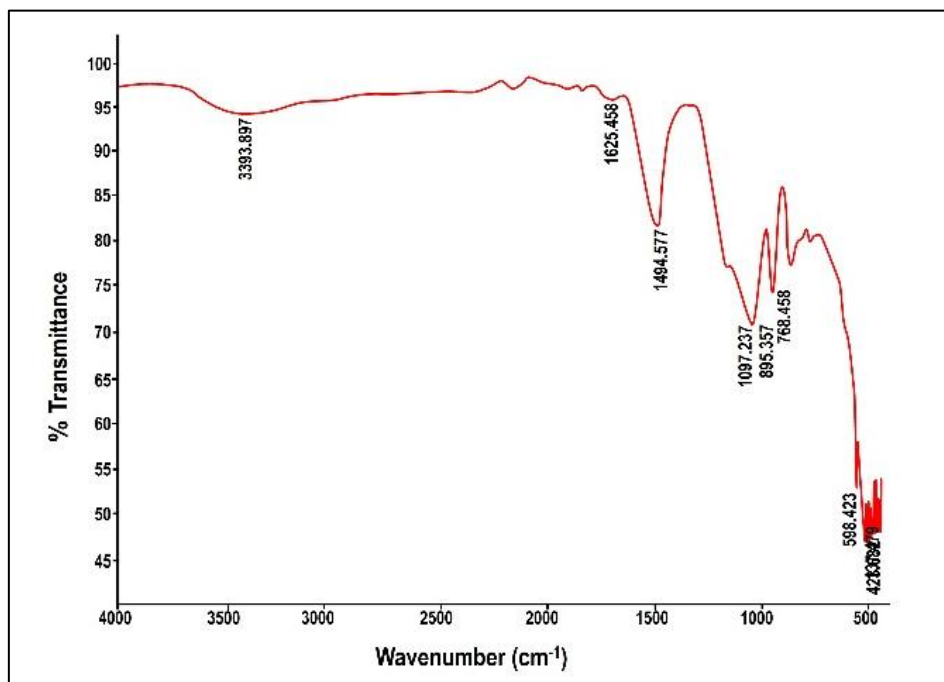


Fig. 10: FTIR analysis of CF in Bacterial concrete

disadvantage of the compactness of the concrete. In general, the addition of bacterial treatment and the controlled amount of fibre led to the significant improvement of the density and the decrease of the porosity, and 1% coconut fibre were found as the most optimal percentage of coconut fibre to be added to the bacterial concrete matrix to obtain a dense and strong material.

Mechanical behaviour of bacterial concrete reinforced with coconut fibre shows a synergistic behaviour between the fibre reinforcement and microbial activity. Addition of *Bacillus subtilis* improved the cement matrix by precipitation of calcite microbially, which occupied the microcracks and pores of the cement, resulting in increased transfer of loading and densification of the matrix. Compression, flexural and splitting tensile strengths were greatly enhanced with increasing level of coconut fibre up to maximum percentage of 1 percent as a result of successful crack-bridging, minimizing stresses and enhancing interfacial bonding between coconut fibre and cement matrix. In addition to this optimum content, mechanical performance decreased progressively with larger dosages of fibres leading to reduced workability of fibres, agglomeration of fibres and porosity which negatively impacted compaction and bonding efficiency. The findings show that the tensile and flexural strengths gained more significantly under the influence of fibre compared to compressive strength, which is relevant to the influence of fibres in regulating crack initiation and propagation. In general, an integrated effect of the coconut fibre reinforcement and bacterial mineralization resulted in a stronger, harder and more robust concrete that is characterized by 1% fibre content that is the most balanced in terms of enhancing the strength of a material and ensuring its integrity.

4. Conclusions

This study emphasizes the advantages of incorporating *Bacillus subtilis* bacteria and CF into concrete to enhance its mechanical performance, durability, and sustainability. The primary outcomes are summarized as follows:

- The incorporation of *Bacillus subtilis* bacteria into the concrete mixture results in a significant improvement in overall strength. This improvement is mainly because of the bacteria's capacity to promote the precipitation of calcium carbonate (CaCO_3) via microbial-induced calcite precipitation (MICP), reinforcing the matrix and aiding in fracture repair.
- The research indicates that using 1% CF in bacterial concrete enhances compressive strength by 15.23% relative to the control mix.
- In a comparison of flexural strength, the concrete, including bacteria and CF, surpassed the control

concrete at 28-day curing intervals, exhibiting an enhancement of 13.6%. This indicates that the combined impact of the bacteria and fibres substantially improves the concrete's resilience to bending and cracking.

- The research revealed that the maximum STS of 21.07% was recorded by incorporating 1% CF into the bacterial concrete mixture. This conclusion suggests the ideal fibre content for enhancing tensile strength, while an excessive quantity of fibres may lead to diminished performance owing to insufficient bonding with the matrix.
- X-ray diffraction (XRD) investigation confirmed calcium carbonate phases in the bacterial concrete containing CF. This discovery proves self-healing capabilities, as the precipitated calcium carbonate successfully repairs micro-cracks, restoring the material's structural integrity.
- Furthermore, Scanning Electron Microscopy (SEM) investigation of the bacterial concrete samples revealed the presence of calcite, a form of calcium carbonate. Unlike traditional concrete, bacterial concrete demonstrated distinctive calcite formations that facilitate fracture healing and improve long-term durability.

Addition of *Bacillus subtilis* bacteria with CF results in a sustainable and environmentally friendly concrete material with improved mechanical characteristics and self-healing abilities. This pioneering method tackles structural challenges such as cracking and utilizes agricultural by-products, supporting sustainable construction practices.

Conflicts of interest

The authors declare that there is no conflict of interest.

Authors contributions

M. Yuvaperiyasamy – Methodology, assembly of data.
Pooja Damodaran – Concept, Methodology development.
M. Kalaimani – Writing the article, validation.
K. Sabari – Conducting test.

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References

- 1) M. M. Ali and K. S. Moon, "Advances in Structural Systems for Tall Buildings: Emerging Developments for Contemporary Urban Giants," *Buildings*, vol. 8, no. 8, p. 104, (2018). doi: 10.3390/buildings8080104.
- 2) J. Liu, C. Yu, X. Shu, Q. Ran, and Y. Yang, "Recent

- advance of chemical admixtures in concrete,” *Cement and Concrete Research*, vol. 124, p. 105834, (2019). doi: 10.1016/j.cemconres.2019.105834.
- 3) S. B. Daneti, C. T. Tam, T. Tamilselvan, V. Kannan, K. H. Kong, and M. R. Islam, “Shrinkage Cracking Potential of Lightweight Aggregate Concrete,” *J. of Phys.: Conference Series*, vol. 2779, no. 1, p. 012067, (2024). doi: 10.1088/1742-6596/2779/1/012067.
 - 4) R. Wang, Z. Hu, Y. Li, K. Wang, and H. Zhang, “Review on the deterioration and approaches to enhance the durability of concrete in the freeze–thaw environment,” *Constr. Build. Mater.*, vol. 321, p. 126371, (2022). doi: 10.1016/j.conbuildmat.2022.126371.
 - 5) W. L. Baloch, H. Siad, M. Lachemi, and M. Sahmaran, “A review on the durability of concrete-to-concrete bond in recent rehabilitated structures,” *J. Build. Eng.*, vol. 44, p. 103315, (2021). doi: 10.1016/j.jobe.2021.103315.
 - 6) C. Zhang, J. Li, M. Yu, Y. Lu, and S. Liu, “Mechanism and Performance Control Methods of Sulfate Attack on Concrete: A Review,” *Materials*, vol. 17, no. 19, p. 4836, (2024). doi: 10.3390/ma17194836.
 - 7) D. Ma, M. Zhang, and J. Cui, “A review on the deterioration of mechanical and durability performance of marine-concrete under the scouring action,” *J. Build. Eng.*, vol. 66, p. 105924, (2023). doi: 10.1016/j.jobe.2023.105924.
 - 8) S. Rajadesingu, K. C. Mendonce, N. Palani, P. Monisha, P. Vijayakumar, and S. Ayyadurai, “Exploring the potential of bacterial concrete: A sustainable solution for remediation of crack and durability enhancement – A critical review,” *Constr. Build. Mater.*, vol. 439, p. 137238, (2024). doi: 10.1016/j.conbuildmat.2024.137238.
 - 9) J. T. Kolawole, A. J. Babafemi, E. Fanijo, S. Chandra Paul, and R. Combrinck, “State-of-the-art review on the use of sugarcane bagasse ash in cementitious materials,” *Cem. Concr. Compos.*, vol. 118, p. 103975, (2021). doi: 10.1016/j.cemconcomp.2021.103975.
 - 10) S. A. Memon, U. Javed, M. I. Shah, and A. Hanif, “Use of Processed Sugarcane Bagasse Ash in Concrete as Partial Replacement of Cement: Mechanical and Durability Properties,” *Buildings*, vol. 12, no. 10, p. 1769, (2022). doi: 10.3390/buildings12101769.
 - 11) L. Zhang, M. Zheng, D. Zhao, and Y. Feng, “A review of novel self-healing concrete technologies,” *J. Build. Eng.*, vol. 89, p. 109331, (2024). doi: 10.1016/j.jobe.2024.109331.
 - 12) P. Damodaran, M. Nagarajan, and L. Thangasamy, “Assessing the Durability, Mechanical, and Microstructural Properties of Nanosilica-enhanced Coconut Shell Concrete: A Sustainable Approach,” *J. Environ. Nanotechnol.*, vol. 13, no. 3, pp. 237–245, (2024). doi: 10.13074/jent.2024.09.243845.
 - 13) R. Garg, R. Garg, and N. O. Eddy, “Microbial induced calcite precipitation for self-healing of concrete: a review,” *J. Sustain. Cem.-Based Mater.*, vol. 12, no. 3, pp. 317–330, (2022). doi: 10.1080/21650373.2022.2054477.
 - 14) N. Senthilkumar, M. Yuvaperiyasamy, B. Deepanraj, and K. Sabari, “Fuzzy logic-based prediction and parametric optimizing using particle swarm optimization for performance improvement in pyramid solar still,” *Water Sci. Technol.*, vol. 90, no. 4, pp. 1321–1337, (2024). doi: 10.2166/wst.2024.277.
 - 15) L. Jiang, H. Xia, W. Wang, Y. Zhang, and Z. Li, “Applications of microbially induced calcium carbonate precipitation in civil engineering practice: A state-of-the-art review,” *Constr. Build. Mater.*, vol. 404, p. 133227, (2023). doi: 10.1016/j.conbuildmat.2023.133227.
 - 16) M. Nanthini, R. Ganesan, and J. R. Xavier, “Experimental and theoretical investigation of the influence of graphene oxide/nanozirconia on the mechanical and durability properties of geopolymer concrete,” *Polymer Bulletin*, vol. 82, no. 6, pp. 2025–2057, (2024). doi: 10.1007/s00289-024-05607-0.
 - 17) P. Damodaran and L. Thangasamy, “Novel Methods of Analysing Environmental and Biological Benefits of *Bacillus* Species for Sustainable Green Building: Enhancing the Mechanical Properties and Longevity of M20 Grade Concrete,” *In. Res. J. Multidiscip. Scope*, vol. 06, no. 02, pp. 805–815, (2025). doi: 10.47857/irjms.2025.v06i02.03458.
 - 18) P. Damodaran, L. Thangasamy, and M. Nagarajan, “Bio-enriched light weight concrete using *Bacillus subtilis* in coconut shell aggregate system - a complete dissertation,” *J. Mater. Cycles Waste Manag.*, vol. 27, no. 5, pp. 3650–3664, (2025). doi: 10.1007/s10163-025-02324-2.
 - 19) T. Zhu and M. Dittrich, “Carbonate Precipitation through Microbial Activities in Natural Environment, and Their Potential in Biotechnology: A Review,” *Front. Bioeng. Biotechnol.*, vol. 4, (2016). doi: 10.3389/fbioe.2016.00004.
 - 20) M. Yuvaperiyasamy, N. Senthilkumar, and B. Deepanraj, “Enhancing Pyramid Solar Still Performance through Varied Heat Storage Materials and Water Depths: A Comprehensive Experimental Study,” *Recent Pat. Mech. Eng.*, vol. 18, no. 2, pp. 148–157, (2025). doi: 10.2174/0122127976288061240228045000.
 - 21) M. Kanwal, R. A. Khushnood, M. Shahid, and A. G. Wattoo, “An integrated and eco-friendly approach for corrosion inhibition and microstructural densification of reinforced concrete by immobilizing

- Bacillus subtilis in pyrolytic sugarcane-bagasse,” *J. Clean. Prod.*, vol. 355, p. 131785, (2022). doi: 10.1016/j.jclepro.2022.131785.
- 22) J. Feng, B. Chen, W. Sun, and Y. Wang, “Microbial induced calcium carbonate precipitation study using Bacillus subtilis with application to self-healing concrete preparation and characterization,” *Constr. Build. Mater.*, vol. 280, p. 122460, (2021). doi: 10.1016/j.conbuildmat.2021.122460.
 - 23) W. Zhang, Q. Zheng, A. Ashour, and B. Han, “Self-healing cement concrete composites for resilient infrastructures: A review,” *Compos. Part B: Eng.*, vol. 189, p. 107892, (2020). doi: 10.1016/j.compositesb.2020.107892.
 - 24) K. Van Tittelboom, E. Gruyaert, H. Rahier, and N. De Belie, “Influence of mix composition on the extent of autogenous crack healing by continued hydration or calcium carbonate formation,” *Constr. Build. Mater.*, vol. 37, pp. 349–359, (2012). doi: 10.1016/j.conbuildmat.2012.07.026.
 - 25) C. Stuckrath, R. Serpell, L. M. Valenzuela, and M. Lopez, “Quantification of chemical and biological calcium carbonate precipitation: Performance of self-healing in reinforced mortar containing chemical admixtures,” *Cem. Concr. Compos.*, vol. 50, pp. 10–15, (2014). doi: 10.1016/j.cemconcomp.2014.02.005.
 - 26) Y. S. Zhang et al., “Application of microbially induced calcium carbonate precipitation (MICP) technique in concrete crack repair: A review,” *Constr. Build. Mater.*, vol. 411, p. 134313, (2024). doi: 10.1016/j.conbuildmat.2023.134313.
 - 27) W. Khaliq and M. B. Ehsan, “Crack healing in concrete using various bio influenced self-healing techniques,” *Constr. Build. Mater.*, vol. 102, pp. 349–357, (2016). doi: 10.1016/j.conbuildmat.2015.11.006.
 - 28) M. Anas, M. Khan, H. Bilal, S. Jadoon, and M. N. Khan, “Fiber Reinforced Concrete: A Review,” *The 12th Int. Civil Eng. Conf.*, p. 3, (2022), doi: 10.3390/engproc2022022003.
 - 29) G. Ramakrishna and T. Sundararajan, “Impact strength of a few natural fibre reinforced cement mortar slabs: a comparative study,” *Cem. Concr. Compos.*, vol. 27, no. 5, pp. 547–553, (2005). doi: 10.1016/j.cemconcomp.2004.09.006.
 - 30) C. Hettiarachchi and G. Thamarajah, “Effect of Surface Modification and Fibre Content on the Mechanical Properties of Coconut Fibre Reinforced Concrete,” *Adv. Mater. Res.*, vol. 1159, pp. 78–99, (2020). doi: 10.4028/www.scientific.net/amr.1159.78.
 - 31) V. Devi, P. Saraswat, S. Kumar, S. K. Sharma, S. Suman, and S. Gupta, “Effect of M Sand and Demolished Concrete Aggregates as a Replacement of Natural Fine Aggregates in Mix Design,” *Int. J. Civ. Eng.*, vol. 9, no. 4, pp. 15–19, (2022). doi: 10.14445/23488352/ijce-v9i4p103.
 - 32) S. Sonule, Y. S. Chauhan, K. C. Tayade, and S. Naik, “New generation fine aggregate for using in high performance concrete,” *Int. J. Civ. Eng. Technol.*, vol. 16, no. 4, pp. 86-97, (2025). doi: 10.21203/rs.3.rs-7157718/v1.
 - 33) P. Damodaran and L. Thangasamy, “Experimental investigation on mechanical properties and characterization of steel fibre concrete with Bacillus subtilis,” *E3S Web of Conferences*, vol. 387, p. 03002, (2023). doi: 10.1051/e3sconf/202338703002.
 - 34) M. Nanthini, R. Ganesan, and V. Jaganathan, “Experimental Investigation of the Durability of Ambient-Cured Metakaolin-Based Geopolymer Concrete in Different Sustainable Environmental Conditions,” *J. Environ. Nanotechnol.*, vol. 13, no. 3, pp. 73–81, (2024). doi: 10.13074/jent.2024.09.242754.
 - 35) M. Nanthini, R. Ganesan, and V. Jaganathan, “Incorporation of Nanoalumina in Potassium Feldspar-based Phosphoric Acid Activated Geopolymer Composites: A Sustainable Approach,” *J. Environ. Nanotechnol.*, vol. 13, no. 3, pp. 89–98, (2024). doi: 10.13074/jent.2024.09.243840.
 - 36) H. Othman, H. Marzouk, and M. Sherif, “Effects of variations in compressive strength and fibre content on dynamic properties of ultra-high performance fibre-reinforced concrete,” *Constr. Build. Mater.*, vol. 195, pp. 547–556, (2019). doi: 10.1016/j.conbuildmat.2018.11.093.
 - 37) M. Khan and M. Ali, “Improvement in concrete behavior with fly ash, silica-fume and coconut fibres,” *Constr. Build. Mater.*, vol. 203, pp. 174–187, (2019). doi: 10.1016/j.conbuildmat.2019.01.103.
 - 38) L. A. Sanchez-Echeverri, E. Ganjian, J. A. Medina-Perilla, G. C. Quintana, J. H. Sanchez-Toro, and M. Tyrer, “Mechanical refining combined with chemical treatment for the processing of Bamboo fibres to produce efficient cement composites,” *Constr. Build. Mater.*, vol. 269, p. 121232, (2021). doi: 10.1016/j.conbuildmat.2020.121232.
 - 39) S. H. A. Shah, M. T. Amir, B. Ali, and M. H. El Ouni, “Mechanical performance and environmental impact of normal strength concrete incorporating various levels of coconut fiber and recycled aggregates,” *Environ. Sci. Pollut. Res.*, vol. 29, no. 55, pp. 83636–83651, (2022). doi: 10.1007/s11356-022-21608-w.
 - 40) D. Falliano, D. De Domenico, G. Ricciardi, and E. Gugliandolo, “Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density,” *Constr. Build. Mater.*, vol. 198, pp. 479–493, (2019). doi: 10.1016/j.conbuildmat.2018.11.197.
 - 41) P. Yan, B. Chen, S. Afgan, M. Aminul Haque, M. Wu, and J. Han, “Experimental research on ductility

- enhancement of ultra-high performance concrete incorporation with basalt fibre, polypropylene fibre and glass fibre,” *Constr. Build. Mater.*, vol. 279, p. 122489, (2021). doi: 10.1016/j.conbuildmat.2021.122489.
- 42) M. A. Al-Osta, M. N. Isa, M. H. Baluch, and M. K. Rahman, “Flexural behavior of reinforced concrete beams strengthened with ultra-high performance fiber reinforced concrete,” *Constr. Build. Mater.*, vol. 134, pp. 279–296, (2017). doi: 10.1016/j.conbuildmat.2016.12.094.
- 43) K. T. Chaka, F. E. Ahmed, L. H. Zegeye, and B. G. Worku, “Compressive Strength of Floor Tile Composites from Recycled PET Reinforced with Natural Fibers,” *J. Nat. Fibers.*, vol. 20, no. 1, (2022). doi: 10.1080/15440478.2022.2146249.
- 44) M. Z. Khan, S. K. Srivastava, and M. Gupta, “Tensile and flexural properties of natural fiber reinforced polymer composites: A review,” *J. Reinf. Plast. Compos.*, vol. 37, no. 24, pp. 1435–1455, (2018). doi: 10.1177/0731684418799528.
- 45) M. Rauf, W. Khaliq, R. A. Khushnood, and I. Ahmed, “Comparative performance of different bacteria immobilized in natural fibers for self-healing in concrete,” *Constr. Build. Mater.*, vol. 258, p. 119578, (2020). doi: 10.1016/j.conbuildmat.2020.119578.
- 46) F. M. D. S. More and S. S. Subramanian, “Impact of Fibres on the Mechanical and Durable Behaviour of Fibre-Reinforced Concrete,” *Buildings*, vol. 12, no. 9, p. 1436, (2022). doi: 10.3390/buildings12091436.
- 47) F. R. B. Martinelli, F. R. C. Ribeiro, M. T. Marvila, S. N. Monteiro, F. da C. G. Filho, and A. R. G. de Azevedo, “A Review of the Use of Coconut Fiber in Cement Composites,” *Polymers*, vol. 15, no. 5, p. 1309, (2023). doi: 10.3390/polym15051309.
- 48) K. Elakkiya, S. K. Jayaharishini, R. P. Nithya Sri, A. Rajesh, and A. Sumathi, “Study on properties of bacteria concrete with two different fibres and carbon-negative supplementary cementitious materials,” *BioConvers. Biorefin.*, vol. 15, no. 23, pp. 30615–30638, (2025). doi: 10.1007/s13399-025-06510-y.
- 49) J. Ahmad et al., “Mechanical and Durability Performance of Coconut Fiber Reinforced Concrete: A State-of-the-Art Review,” *Materials*, vol. 15, no. 10, p. 3601, (2022). doi: 10.3390/ma15103601.
- 50) A. Rajesh and A. Sumathi, “Strength and self-healing behavior of bacteria biocomposite concrete in soil exposure condition,” *Structures*, vol. 59, p. 105673, (2024). doi: 10.1016/j.istruc.2023.105673.
- 51) W. Elkhateeb, M. O. Elnahas, and G. Daba, “Review: Microbial induced mineralization of calcium carbonate for self-healing concrete,” *Asian J. Nat. Prod. Biochem.*, vol. 19, no. 1, Mar. (2021). doi: 10.13057/biofar/f190101.
- 52) S. Barbhuiya, B. B. Das, and D. Adak, “Insights into cementitious materials: exploring atomic structures and interactions,” *Discover Concrete and Cement*, vol. 1, no. 1, (2025). doi: 10.1007/s44416-025-00006-8.
- 53) R. S. Abolore, S. Jaiswal, and A. K. Jaiswal, “Green and sustainable pretreatment methods for cellulose extraction from lignocellulosic biomass and its applications: A review,” *Carbohydr. Polym. Technol. Appl.*, vol. 7, p. 100396, (2024). doi: 10.1016/j.carpta.2023.100396.
- 54) S. Pasieczna-Patkowska, M. Cichy, and J. Flieger, “Application of Fourier Transform Infrared (FTIR) Spectroscopy in Characterization of Green Synthesized Nanoparticles,” *Molecules*, vol. 30, no. 3, p. 684, (2025). doi: 10.3390/molecules30030684.