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Mechanical Performance of Coconut Fibre Reinforced Bio-Concrete

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Abstract

Fibre reinforced bio-concrete entails cementitious mixes that incorporate discrete reinforcing fibres with a bacteria precursor to trigger microbially induced calcite precipitation (MICP) for autonomous crack repair. This study investigates the influence of coconut fibre reinforcement on the mechanical performance of bio-concrete, with emphasis on flexural strength and split tensile strength, alongside an assessment of aggregate quality to ensure reliable mix performance. Well-graded fine and coarse aggregates satisfying BS EN 12620 requirements were used, with aggregate properties confirming suitability for structural concrete. The coarse aggregate exhibited a low aggregate crushing value of 12.24%, indicating high resistance to crushing and ensuring that aggregate failure did not govern concrete performance. Bio-concrete specimens were produced with varying coconut fibre contents (0%, 0.5%, 1.0%, and 1.5%) and tested for splitting tensile and flexural strength at curing ages of 7, 14, and 28 days. The results revealed that the incorporation of 0.5% coconut fibre yielded the highest flexural and split tensile strengths at all curing ages, achieving maximum values of 5.2 MPa and 2.6 MPa, respectively, at 28 days. These improvements were attributed to effective crack-bridging action and enhanced stress redistribution provided by the fibres, resulting in improved ductility and delayed crack propagation. However, higher fibre contents (≥1.0%) led to a reduction in strength due to fibre agglomeration, increased porosity, and poor matrix continuity. The findings demonstrate that coconut fibre can serve as an effective and sustainable reinforcement in bio-concrete when used at an optimal dosage. A fibre content of 0.5% was identified as the threshold for maximising mechanical performance without compromising matrix integrity. This study highlights the potential of coconut fibre reinforced bio-concrete as a durable and environmentally friendly material for structural applications.

Keywords: Coconut Fibre, Bio-concrete, Crack Healing, Flexural Strength, Tensile Strength**.**

Introduction

Concrete remains the most widely used construction material globally due to its high strength, durability, and cost effectiveness. It remains the foundation of modern infrastructure due to its cost-effectiveness, ease of production, and excellent compressive strength (James et al., 2019; Wei et al., 2024). However, its inherent brittle nature and low tensile capacity make it highly susceptible to microcracking under mechanical loading, shrinkage, thermal variations, and environmental exposure (Ajagbe et al., 2020; Wen et al., 2025). These microcracks, though often invisible at early stages, serve as pathways for aggressive agents such as water, chlorides, and carbon dioxide, which accelerate reinforcement corrosion, reduce structural integrity, and significantly shorten the service life of concrete structures (Makul, 2025; Tenório Filho et al., 2024). Consequently, cracking remains one of the most persistent challenges in concrete engineering, particularly for infrastructure exposed to harsh service conditions (Zhou et a., 2023).

To improve the performance of concrete, reinforcement strategies using fibre have been widely adopted. Synthetic fibres such as steel, polypropylene, and glass can effectively control crack propagation and improve post-cracking behaviour, yet they are associated with high production costs, energy-intensive manufacturing, and environmental concerns (Selvaraj et al., 2025). These drawbacks have stimulated interest in natural fibres as sustainable alternatives. Coconut fibre (coir), a natural lignocellulosic fibre derived from coconut husks, has emerged as a promising reinforcement due to its renewability, biodegradability, low cost, and commendable tensile properties compared to many other natural fibres. Research indicates that the inclusion of coconut fibres in concrete can improve tensile strength, flexural capacity, and toughness by restricting crack growth, enabling stress transfer across cracks, and enhancing ductility under load (Ahmad et al., 2020; Jiang et al., 2021). This behaviour has been linked to better energy absorption and improved mechanical performance relative to plain concrete.

Beyond mechanical enhancement, recent advances in concrete technology have introduced bio-concrete, which incorporates biological agents capable of inducing self-healing through microbially precipitated calcium carbonate (Verma et al., 2025; Wong et al., 2024). Bio-concrete offers a promising solution for mitigating crack propagation by autonomously sealing microcracks, thereby improving durability and reducing maintenance costs. However, despite its crack-healing capability, bio-concrete alone may still exhibit limited mechanical performance under flexural and tensile stresses, particularly when subjected to repeated or dynamic loading (Abdulkareem et al., 2025). This limitation underscores the need for complementary reinforcement strategies.

Despite the mechanical benefits of natural fibre reinforcement, cracks that do form still pose long-term durability risks, particularly in environments susceptible to moisture and chemical attack. To address this, the concept of bio-concrete or self-healing concrete has been developed, where biological agents such as bacteria are introduced into the concrete mix to precipitate calcium carbonate ($CaCO_3$) in the presence of moisture, effectively sealing cracks autonomously (Abdulkareem et al., 2024; Luhar et al., 2022). Studies have demonstrated that microbial self-healing mechanisms can seal cracks and reduce matrix porosity, thereby enhancing compressive and flexural strength while improving durability. This self-healing action is particularly effective for closing microcracks (e.g., within the 0.02–2 mm range) and has the potential to restore mechanical efficiency and prolong service life without manual intervention (Ganiyu et al., 2017; Muhammad et al., 2016).

However, while research on self-healing concrete and natural fibre reinforced concrete exists independently, there is a significant gap at the intersection of these technologies. Few studies have systematically explored how natural fibres like coconut fibre influence not only the mechanical properties (flexural and split tensile strength) of bio-concrete but also its crack-healing efficiency in tandem with biological agents. The integration of coconut fibre in a bio-concrete system alters the internal cracking behaviour, potentially controlling crack widths and creating an environment more conducive for microbial healing agents to be effective (Omoregie et al., 2025). For example, natural fibres can retard crack propagation and provide bridges across crack planes, but they may also increase matrix porosity due to their hygroscopic nature if not properly balanced. The interplay between fibre reinforcement and microbial self-healing mechanisms, including how fibre content, distribution, and interaction with bio-agents affect both mechanical resilience and healing response, remains poorly understood.

Without a clear understanding of how coconut fibre reinforcement influences both strength development and crack-healing behaviour in bio-concrete, its large-scale application in structural and infrastructural systems remains constrained. Therefore, this study addresses the need to evaluate the mechanical performance and crack-healing efficiency of coconut fibre–reinforced bio-concrete, with emphasis on flexural and split tensile behaviour. By establishing the role of coconut fibre in enhancing strength, controlling crack propagation, and supporting healing mechanisms, this research aims to contribute to the development of durable, sustainable, and high-performance bio-based cementitious composites for modern construction. This research is particularly significant in developing nations, where sustainable, low-cost, and locally sourced construction materials are urgently needed to improve infrastructure resilience.

Materials and Methods

The materials employed in this experimental investigation were carefully selected to ensure the production of bio-concrete with consistent quality, reproducibility, and reliable mechanical and crack-healing performance. The constituent materials used in this study included Portland limestone cement, fine aggregate, coarse aggregate, potable water, coconut fibre, bacterial culture (*Alcaligenes faecalis*), distilled water, and sodium hydroxide (NaOH). All materials were sourced locally and prepared in accordance with relevant standards to reflect practical construction conditions.

i. Cement: Portland limestone cement (PLC) was used as the primary binding material in this study. CEM-II, 42.5N cement was supplied by Lafarge Africa Plc, the cement was fresh, free from lumps, and stored in a dry environment prior to use to prevent premature hydration.
ii. Fine Aggregate: The fine aggregate consisted of natural river sand obtained from the Ona River within the premises of University of Ibadan. The sand had a maximum particle size of 4.75 mm and was free from deleterious materials. To maintain a surface-dry condition, the sand was stored in a shaded and rain-protected area.
iii. Coarse Aggregate: Crushed granite was used as the coarse aggregate. The aggregate was sieved to pass through a 20 mm sieve and retained on a 5 mm sieve, resulting in a nominal maximum aggregate size of 20 mm. The particles were irregular in shape and prepared in a saturated surface-dry (SSD) condition prior to mixing.
iv. Mixing and Curing Water: Potable tap water obtained from University of Ibadan was used for concrete mixing and curing. The water was visually clear and confirmed to be free from harmful impurities.
v. Coconut Fibre: Coconut fibre was selected as the natural reinforcement material due to its sustainability, local availability, and favourable mechanical characteristics. The fibres were extracted from mature coconut husks sourced from the Federal College of Agriculture, Ibadan. The fibres were manually cleaned to remove impurities, cut to a uniform length of 50 mm, and air-dried at room temperature. To enhance interfacial bonding with the cement matrix, the fibres were chemically treated using a sodium hydroxide solution prior to incorporation into the concrete mix.
vi. Bacterial Culture (*Alcaligenes faecalis*): The bacterial strain *Alcaligenes faecalis* was employed due to its proven ability to induce calcium carbonate precipitation, thereby facilitating autonomous crack healing in bio-concrete. The bacteria were cultured in a nutrient broth medium and incubated for 48 hours at a temperature of 30°C at Lead City University. After incubation, the bacterial spores were harvested and dried for storage. Prior to use in concrete production, the spores were reactivated by mixing with water and the prepared nutrient solution.
vii. Distilled Water: Distilled water was used in the preparation of the nutrient solution and during fibre treatment to eliminate the influence of dissolved salts or impurities. This ensured controlled biochemical reactions during bacterial activation and prevented any adverse effects on cement hydration and concrete performance.
viii. Chemical Reagent (Sodium Hydroxide – NaOH): Sodium hydroxide (NaOH) was used as a chemical treatment agent for modifying the surface characteristics of the coconut fibres. The fibres were immersed in a prepared NaOH solution for a controlled duration to partially remove surface lignin and hemicellulose, increase surface roughness, and enhance fibre–matrix adhesion. This treatment improves fibre durability and minimizes long-term degradation within the highly alkaline environment of concrete.

Test Procedures

Physical Properties of the Aggregates: The bulk density test followed BS EN 1097-3:1998. The volume (V) was determined by filling a metal measure with water. Aggregate was added from a height less than 5 cm until overflowing, then levelled with a tamping bar. The weight (W) was recorded in kg. For determining the particle size distribution, 1000 g of the fine aggregate sample was weighed. The sieves used in the analysis included sizes 4.74 mm, 3.71 mm, 2.36 mm, 1.18 mm, 0.6 mm, 0.3 mm, and 0.15 mm. These sieves were arranged in descending order with a fitting lid at the top and a pan at the bottom. The sieve analysis was performed following the guidelines set out in BS EN 933-1: 2012. The specific gravity of soil particles was determined per BS 1377-2:2022. A 400 g sand sample was prepared accordingly. Measurements included: m_1(gas jar and plate), m_2(gas jar, plate, and soil), m_3(gas jar, plate, sand, and water), and m_4(gas jar, plate, and water).

The coarse aggregate sample was air-dried and then sieved to obtain particles passing the 14 mm sieve and retained on the 10 mm sieve for the Aggregate Crushing Value (ACV) test. The test was carried out in accordance with the relevant provisions of BS 812-110: 1990. The ACV was determined as the percentage ratio of the mass of material passing the 2.36 mm sieve to the total mass of the sample. The test was repeated for multiple samples, and the average value was calculated and reported as the ACV. This value was used as an indicator of the aggregate's strength and suitability for use in concrete production.

Mix design: The concrete was designed with the DOE mix design approach to enhance performance, energy efficiency, and sustainability. Engineered for Grade 20, the mix targeted a compressive strength of 26.6 N/mm² at 28 days, with a desired slump of 50–100 mm for optimal workability. The basic concrete constituents including cement, coarse and fine aggregates, and water content, were kept constant. Coconut fibre was mixed at 0%, 0.5%, 1%, and 1.5% of cement weight while Alcagenes faecalis bacteria were uniformly introduced into all mixtures through the mixing water. Table 1 presents the concrete mix design values.

Table 1: Concrete Mix Design

Mix ID	Coconut Fibre (%)	Cement (kg)	Water (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Fibre (kg)	Bacteria (kg)	w/c
M0	0.0	41.01	22.56	93.10	128.70	0.00	0.41	0.55
M1	0.5	41.01	22.56	93.10	128.70	0.21	0.41	0.55
M2	1.0	41.01	22.56	93.10	128.70	0.41	0.41	0.55
M3	1.5	41.01	22.56	93.10	128.70	0.62	0.41	0.55

Batching, Mixing and Curing of Concrete: Concrete specimens were fabricated from 36 distinct batches. Each batch was meticulously blended according to the standardised mix design and utilised to cast the corresponding specimen kinds, ensuring consistency and representativeness among the samples. The specimens were formed in moulds of cylinders and beams that matched their geometric requirements. Cement, fine and coarse aggregates, and water were measured precisely with an electronic scale. The mixing process began with blending fine aggregate and cement for 2–3 minutes, followed by the addition of coarse aggregate and further mixing for 3–4 minutes. Water, measured to maintain the specified water–cement ratio, was gradually added over 5–7 minutes to achieve a consistent and workable mixture. Fibres were distributed evenly in three layers within the specimens to ensure uniform reinforcement. After casting, all specimens were cured in a controlled environment at 20°C and relative humidity above 95% for 28 days in accordance with BS EN 12390-2:2019. The curing procedure was utilised to provide complete hydration of the cementitious components, therefore minimising premature setting and promoting maximal strength development. The specimens were submerged during the curing phase to ensure uniform moisture distribution and optimal strength development until they attained the specified age.

Mechanical Tests

The splitting tensile test was conducted in strict accordance with the provisions of BS EN 12390-6:2009, which specifies standardized procedures for determining the tensile strength of concrete specimens through indirect splitting. The specimen employed for this test comprised a concrete cylinder with a diameter of 100 mm and a length of 200 mm, positioned with its horizontal axis aligned between the platens of the testing apparatus. During testing, the load was applied centrally and increased monotonically at a constant rate until the specimen experienced failure (Figure 1a). This continuous loading approach ensures a uniform distribution of stress along the specimen's length, facilitating an accurate assessment of its tensile capacity. The maximum load sustained by the specimen at failure, denoted as F, was recorded with precision. The horizontal splitting tensile strength (T), expressed in MPa, was calculated using the following formula from BS EN 12390-6:2009.

$$T = \frac{2F}{\pi DL} \quad (1)$$

`where: F = failure load (kN), D = diameter of the specimen (mm), L = length of the specimen (mm).

The flexural strength was determined per BS EN 12390-5:2019 using 100 mm × 100 mm × 400 mm concrete beams (Figure 2). Load was applied symmetrically at third points until failure, with the maximum load (F) recorded. The modulus of rupture, MOR was calculated by using the following formular from BS EN 12390-5:2019.

$$f_r = \frac{FL}{bd^2} \quad (2)$$

where F is the maximum load (kN), L is the span length (mm), b is the specimen width (mm), and d is the height (mm). (Figure 1b)

(a)

(b)

Figure 1 (a & b): Split tensile strength and flexural strength tests

Result and Discussion

Sieve Analysis

Figure 2 shows the result for the sieves analysis of fine aggregates. It is well-graded fine aggregate (smooth S-shape, no gaps), with 100% passing 4.75 mm, ~50% at 0.6 mm (D50), and ~0.4% fines (<0.075 mm), classifying as Zone II sand and fell within the limits specified by BS EN 12620: 2013. The fineness modulus calculated is 2.94 mm, confirming medium sand suitable for concrete workability.

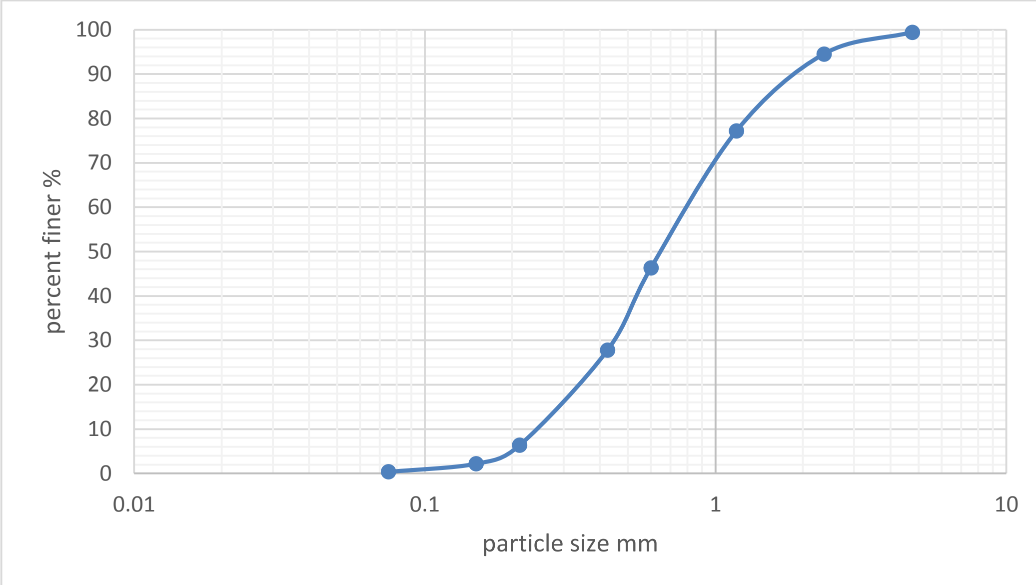

Figure 2: Particle size distribution of fine aggregates

Specific Gravity, Bulk density and Aggregate Crushing Value of Aggregates

The specific gravity of the fine aggregate was found to be 2.62, based on the average of two trials. This value sits within the expected range of 2.60 to 2.80 for natural sand. Since the specific gravity is above 2.60, the aggregate is sufficiently dense and lacks the high porosity that often weakens construction materials. The packing characteristics and volumetric weight of the fine aggregate were evaluated through bulk density measurements. The results from two independent trials yielded an average bulk density of 1632.6 kg/m³. The bulk density of 1632.6 kg/m³ is characteristic of well-graded, normal-weight silica sand. This parameter is a critical indicator of the void ratio within the aggregate skeleton; a higher bulk density suggests a more efficient particle packing arrangement, which reduces the volume of cement paste required to fill inter-granular voids.

For the development of bacteria-incorporated concrete, this dense packing is advantageous as it optimizes the matrix for microbially induced calcium carbonate precipitation (MICP). By minimizing the void spaces that require filling by the cementitious binder, the bacterial precipitates can more effectively target the remaining micro-pores, thereby enhancing the overall density and potential durability of the hardened composite. These results, alongside the specific gravity data, confirm that the physical properties of the fine aggregate are within the standard specifications for high-performance structural concrete.

The recorded average ACV of 12.24% signifies that the aggregates are strong and suitable for high-strength concrete and heavy-duty wearing surfaces. This confirms that the coarse aggregate provides a robust structural skeleton. Since the aggregate itself is highly resistant to crushing, any observed changes in the compressive strength of the final bacteria-incorporated concrete can be more accurately attributed to the interfacial transition zone (ITZ) and the microbially induced calcium carbonate precipitation (MICP) within the cement paste, rather than the mechanical failure of the mineral phase. This high resistance to fragmentation ensures that the aggregate will not be the weak link in the concrete composite, allowing for a clear assessment of the bio-calcification effects on the material's overall performance.

Flexural Strength Test Result

The relationship between coconut fibre content and the flexural performance of bio-concrete follows a consistent trend at 7, 14, and 28 days of curing. From Figure 3, the control sample (0% fibre) demonstrated a standard strength progression, increasing from 3.8 MPa to 4.8 MPa. However, the incorporation of 0.5% coconut fibre consistently yielded superior results, peaking at a maximum of 5.1 MPa by the 28th day. This enhancement represents a 6.25% growth over the control sample, and it is primarily attributed to the high tensile capacity of the coir fibres. At this optimal dosage, the fibres act as internal bridges that arrest micro-crack propagation and enhance the modulus of rupture (Kumar et al., 2025).

In contrast, increasing the fibre volume to 1.0% and 1.5% triggered a significant decline in flexural capacity. Notably, the 1.5% mix registered a 28-day strength of only 3.5 MPa, which is lower than even the 28-day strength of the control mixture, about 27% strength loss. This performance degradation at higher concentrations is technically associated with fibre agglomeration and increased porosity. Excessive fibres create structural discontinuities and "balling" effects that hinder proper compaction and prevent the cement paste from fully encapsulating the reinforcement (Farooqi & Ali, 2022). Collectively, these findings establish that while coconut fibre is a potent, sustainable reinforcement, its efficacy is highly sensitive to dosage (Agrawal & Malviya, 2025; Alenezi et al., 2025). The 0.5% inclusion of Coconut fiber is identified as the optimal threshold for maximizing the flexural integrity of bio-concrete, beyond which the mechanical benefits are eclipsed by the loss of matrix homogeneity. The result is comparable to the outcome of similar research by Abdulkareem et al. (2024) which utilised a different natural material, kenaf fibre, a bacillus subtilis bacteria, and recycled aggregate. Agboola et al. (2024) which utilised Sisal fibre also obtained the optimal percentage for flexural strength test at 5% fibre content.

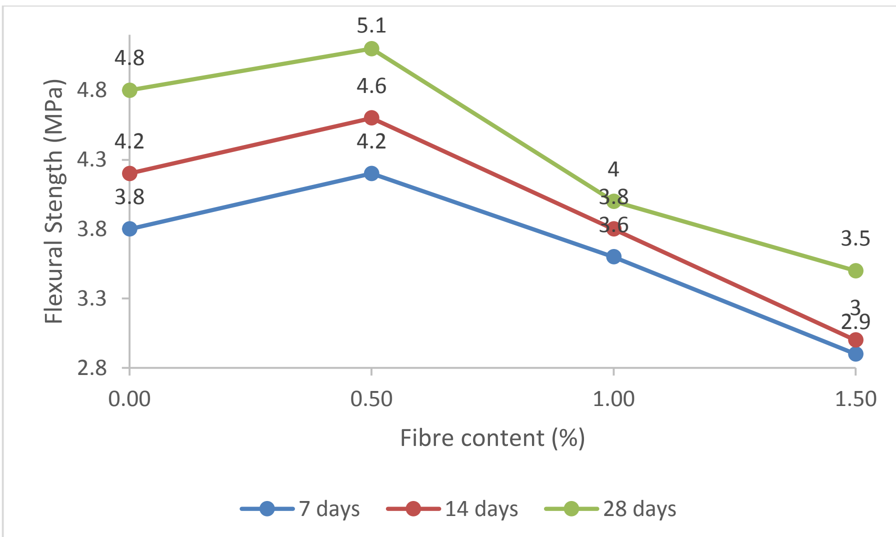

Figure 3: Flexural strength of concrete

Split Tensile Test Result

Figure 4 presents the split tensile test results across all curing ages at 7, 14 and 28 days. It exhibits a consistent parabolic relationship relative to the coconut fibre volume fraction. The split tensile strength increases proportionally with curing duration, reflecting the progressive hydration of the cementitious matrix. The control specimens (0% fibre) demonstrated a linear growth from 1.6 MPa at 7 days to 2.5 MPa at 28 days. However, the incorporation of 0.5% coconut fibre consistently yielded superior performance, achieving a peak tensile strength of 2.6 MPa by the 28th day. This enhancement is attributed to the bridging effect of the high-tensile coir fibres, which intercept transverse splitting stresses and transform the failure mode from a sudden, brittle fracture to a more ductile, energy-dissipating process (Madueke et al., 2024; Wang et al., 2023). Conversely, the performance curves reveal a sharp decline when fibre content exceeds the 0.5% threshold. At dosages of 1.0% and 1.5%, the tensile strength falls significantly below the baseline control values. Notably, the 1.5% mix at 28 days (1.4 MPa) failed to even reach the 7-day strength of the control mixture (1.6 MPa). This drastic reduction is technically associated with fibre agglomeration and the introduction of excessive macro-voids within the internal structure of the concrete. These clusters act as stress concentrators and planes of weakness, facilitating premature debonding rather than reinforcing the matrix (Li et al., 2024). The optimal percentage of 0.5% agrees with previous research by Islam et al. (2011) which utilised coir for regular fibre reinforced concrete.

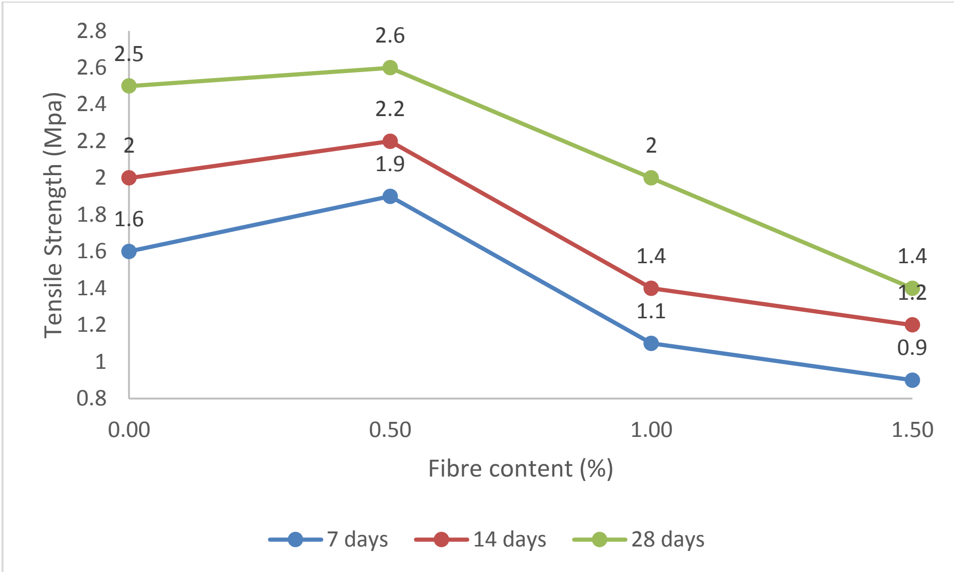

Figure 4: Split tensile strength of concrete

Conclusion

Fibre bio-concrete consists of discrete fibres to control crack widths together with bacteria that precipitate calcium carbonate to improve crack control and enable self- healing by microbially induced calcite precipitation (MICP) for autonomous crack repair. This study investigated the mechanical performance of coconut fibre–reinforced bio-concrete with emphasis flexural strength, and split tensile strength. Physical properties of constituent materials were determined and optimal fibre content for the mechanical properties were investigated.

The flexural strength results revealed that coconut fibre incorporation significantly influenced the bending performance of the Bio-Concrete. An optimum fibre content of 0.5% consistently produced the highest flexural strength across all curing ages, with a maximum value of 5.2 MPa at 28 days. This improvement was attributed to effective crack-bridging and stress redistribution by the fibres, which enhanced the modulus of rupture and delayed crack propagation. Similarly, the addition of 0.5% coconut fibre led to the highest tensile performance, achieving 2.6 MPa at 28 days and outperforming the control mix. This enhancement was associated with improved tensile stress transfer and a transition from brittle to more ductile failure behaviour. Conversely, excessive fibre contents caused a significant decline in both the flexural and tensile strength.

Likewise, the incorporation of 0.5% coconut fibre consistently yielded superior performance for the split tensile strength, achieving a peak tensile strength of 2.6 MPa at the 28th day. This enhancement is attributed to the bridging effect of the high-tensile coir fibres, which intercept transverse splitting stresses and transform the failure mode to more ductile, energy-dissipating process. When the fibre content exceeds the 0.5% threshold, the tensile strength falls below the baseline control values because of fibre agglomeration and the subsequent introduction of excessive macro-voids within the internal structure of the concrete.

Overall, the study concludes that coconut fibre is an effective and sustainable reinforcement for bio-concrete when used at an optimal dosage. Beyond this threshold, the adverse effects of poor dispersion and increased porosity outweigh the reinforcing benefits. The findings demonstrate that properly proportioned coconut fibre–reinforced bio-concrete, combined with high-quality aggregates, has strong potential for use in durable and sustainable construction applications.

References

Abdulkareem, M., Ayeronfe, F., Jassam, T. M., AlAteah, A. H., Al-Sodani, K. A. A., Al-Tholaia, M. M. H., Yam, H., Ganiyu, A., & Alih, S. C. (2024) Compressive and Flexural Strengths of Bio-Recycled Concrete Incorporated with Kenaf Fibre. Journal of Natural Fibers, 21(1). https://doi.org/10.1080/15440478.2023.2296913

Abdulkareem, M., Ganiyu, A., AlAteah, A. H., Al-Sodani, K. A. A., Al-Tholaia, M. M., & Ayeronfe, F. (2025) Static and Dynamic Resistance of Bio-concrete Incorporated with Kenaf Fiber. *Journal of Natural Fibers*, *22*(1), 2462976.

Agboola, B. D., Onabote, E. J., Nwauju, C. D., Braimoh, S. O., Ejigboye, P. O., Ajamu, S. O., & Gana, A. J. (2024) *Investigation of the Mechanical Properties of Sisal Fiber Reinforced Pervious Concrete* 2024 International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG),

Agrawal, A., & Malviya, N. (2025) Advanced geopolymer concrete with coconut fiber reinforcement: optimizing strength, durability, and predictive modelling for sustainable construction. *Architecture, Structures and Construction*, *5*(1). https://doi.org/10.1007/s44150-025-00152-4

Ahmad, W., Farooq, S. H., Usman, M., Khan, M., Ahmad, A., Aslam, F., Yousef, R. A., Abduljabbar, H. A., & Sufian, M. (2020) Effect of Coconut Fiber Length and Content on Properties of High Strength Concrete. *Materials (Basel)*, *13*(5). https://doi.org/10.3390/ma13051075

Ajagbe, W. O., Ganiyu, A. A., Okoloekwe, C., & Al-Alawi, H. S. (2020) Impact of Corroded Bars and Spalling on the Bond Strength of Reinforced Concrete Structures.

Alenezi, D., Mohammad, D., Alfoudari, F., Saeedi, M., Alajmi, R., & Mustafaraj, E. (2025) Strength and Water Absorption Behavior of Untreated Coconut Fiber-Reinforced Mortars: Experimental Evaluation and Mix Optimization. *Construction Materials*, *5*(3). https://doi.org/10.3390/constrmater5030069

British Standards Institution. (2012) *BS EN 933-1:2012: Tests for geometrical properties of aggregates—Part 1: Determination of particle size distribution—Sieving method*. London: BSI.

British Standards Institution. (1998) *BS EN 1097-3:1998: Tests for mechanical and physical properties of aggregates—Determination of loose bulk density and voids*. London: BSI.

British Standards Institution. (2022) *BS 1377-2:2022: Methods of test for soils for civil engineering purposes—Part 2: Classification tests*. London: BSI.

British Standards Institution. (1990) *BS 812-110:1990: Testing aggregates—Part 110: Methods for determination of aggregate crushing value (ACV)*. London: BSI.

British Standards Institution. (2019) *BS EN 12390-2:2019: Testing hardened concrete—Part 2: Making and curing specimens for strength tests*. London: BSI.

British Standards Institution. (2019) *BS EN 12390-5:2019: Testing hardened concrete—Part 5: Flexural strength of test specimens*. London: BSI.

British Standards Institution. (2009) *BS EN 12390-6:2009: Testing hardened concrete—Part 6: Tensile splitting strength of test specimens*. London: BSI.

British Standards Institution. (2013) *BS EN 12620:2013: Aggregates for concrete*. London: BSI.

Farooqi, M. U., & Ali, M. (2022) A study on Natural Fibre Reinforced Concrete from Materials to Structural Applications. *Arabian Journal for Science and Engineering*, *48*(4), 4471-4491. https://doi.org/10.1007/s13369-022-06977-1

Ganiyu, A. A., Badr, A., Ajagbe, W. O., Muhammad, N. Z., Keyvanfar, A., & Majid, M. Z. A. (2017) *Properties of Biological Self-Healing Concretes; A Short Review* 1st International Conference on Cement & Concrete Technology, Military Technological College - Sultanate of Oman.

Islam, S. M., Hussain, R. R., & Morshed, M. A. Z. (2011) Fiber-reinforced concrete incorporating locally available natural fibers in normal- and high-strength concrete and a performance analysis with steel fiber-reinforced composite concrete. *Journal of Composite Materials, 46*(1), 111-122. https://doi.org/10.1177/0021998311410492

James, A., Bazarchi, E., Chiniforush, A. A., Panjebashi Aghdam, P., Hosseini, M. R., Akbarnezhad, A., Martek, I., & Ghodoosi, F. (2019) Rebar corrosion detection, protection, and rehabilitation of reinforced concrete structures in coastal environments: A review. *Construction and Building Materials, 224*, 1026-1039. https://doi.org/10.1016/j.conbuildmat.2019.07.250

Jiang, Z., Zhang, L., Zhang, J., Sun, Z., & Li, J. (2021) Effect of Coconut Fiber Dosage on Flexural Performances of Magnesium Phosphate Cement. *Frontiers in Materials*, *8*. https://doi.org/10.3389/fmats.2021.557355

Kumar, A., Ghosh, P. K., Sharma, R., & Pahuja, V. (2025) Optimization of Hybrid Glass Fibre-Reinforced Geopolymer Concrete: A Multi-criteria Evaluation of Fibre Lengths. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. https://doi.org/10.1007/s40996-025-02067-y

Li, M., Wu, J., Liu, X.-C., & Qi, M.-l. (2024) Advancements in Characterizing Fiber Distribution in Fiber-Reinforced Concrete Using X-ray Computed Tomography. *Journal of Physics*: Conference Series,

Luhar, S., Luhar, I., & Shaikh, F. U. A. (2022) A review on the performance evaluation of autonomous self-healing bacterial concrete: mechanisms, strength, durability, and microstructural properties. *Journal of Composites Science*, *6*(1), 23.

Madueke, C. I., Ekechukwu, O. M., & Kolawole, F. O. (2024) A Review on Coir Fibre, Coir Fibre Reinforced Polymer Composites and Their Current Applications. *Journal of Renewable Materials*, *0*(0), 1-10. https://doi.org/10.32604/jrm.2024.055207

Makul, N. (2025). *Dictionary of Concrete Technology*. Springer.

Muhammad, N. Z., Shafaghat, A., Keyvanfar, A., Abd. Majid, M. Z., Ghoshal, S. K., Mohammadyan Yasouj, S. E., Ganiyu, A. A., Samadi Kouchaksaraei, M., Kamyab, H., Taheri, M. M., Rezazadeh Shirdar, M., & McCaffer, R. (2016) Tests and methods of evaluating the self-healing efficiency of concrete: A review. *Construction and Building Materials*, *112*, 1123-1132. https://doi.org/10.1016/j.conbuildmat.2016.03.017

Omoregie, A. I., Wong, C. S., Rajasekar, A., Ling, J. H., Laiche, A. B., Basri, H. F., Sivakumar, G., & Ouahbi, T. (2025) Bio-based solutions for concrete infrastructure: *a review of microbial-induced carbonate precipitation in crack healing*. *Buildings*, *15*(7), 1052.

Selvaraj, S., Sasi Kumar, M., Makeshkumar, M., Sivanantham, G., Loganathan, P., Gopinathan, M., & Nirmalsagayaraja, R. (2025) Recent developments in natural and synthetic fibers, polymers, and their composites. In *Surface Modification and Coating of Fibers, Polymers, and Composites* (pp. 19-41). https://doi.org/10.1016/b978-0-443-22029-6.00002-2

Tenório Filho, J. R., De Belie, N., & Snoeck, D. (2024) The Effects of Internal Curing and Shrinkage Cracking Avoidance on the Corrosion of Reinforced Concrete Walls with Superabsorbent Polymers. *Applied Sciences*, *14*(16). https://doi.org/10.3390/app14166901

Verma, N., Satya Eswari, J., & Mahapatra, C. (2025) Revolutionizing concrete: Unveiling bio-concrete's advantages and challenges in self-healing through microbial-induced calcium carbonate precipitation. *Sustainable Materials and Technologies*, *45*. https://doi.org/10.1016/j.susmat.2025.e01465

Wang, B., Yan, L., & Kasal, B. (2023) Long-term Pull-out behaviour of coir fiber from cementitious material with statistical and microstructural analysis. *Construction and Building Materials*, *385*. https://doi.org/10.1016/j.conbuildmat.2023.131533

Wei, X.-X., Jia, Q., Zheng, C., Zhu, J.-H., & Pei, C. (2024) Enhancement in durability and performance for cement-based materials through tailored water-based graphene nanofluid additives. *Construction and Building Materials*, *457*. https://doi.org/10.1016/j.conbuildmat.2024.139455

Wen, X., Pagcaliwagan, A. M., Hou, H., & Yin, X. (2025) Advancements in self-healing concrete: Material mechanisms, durability assessment, and implications for infrastructure lifecycle management. *Alexandria Engineering Journal*, *131*, 104-124. https://doi.org/10.1016/j.aej.2025.10.011

Wong, P. Y., Mal, J., Sandak, A., Luo, L., Jian, J., & Pradhan, N. (2024) Advances in microbial self-healing concrete: A critical review of mechanisms, developments, and future directions. *Sci Total Environ*, *947*, 174553. https://doi.org/10.1016/j.scitotenv.2024.174553

Zhou, X., Mao, Z., Luo, P., & Deng, M. (2023). Effect of mineral admixtures on the mechanical and shrinkage performance of MgO concrete. *Materials*, *16*(9), 3448.