

COMPARATIVE ANALYSIS OF BAMBOO-REINFORCED CONCRETE BEAMS WITH CONVENTIONAL CODE REQUIREMENTS FOR SUSTAINABLE CONSTRUCTION

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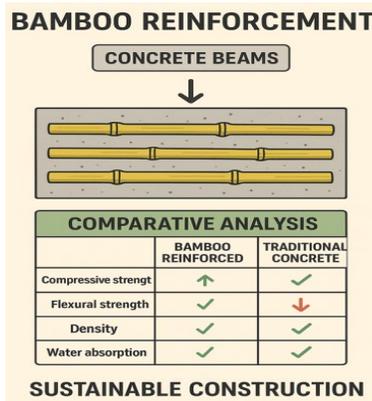
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Graphical abstract



Abstract

By evaluating the structural behaviour of bamboo-reinforced concrete critically in comparison to the demands of significant international design standards, this study explores the potential of bamboo as a sustainable reinforcement material. Although bamboo's regenerative nature and favourable tensile qualities have drawn attention, its suitability as a steel replacement has not received enough attention. To close this gap, the article compares bamboo-reinforced concrete's compressive strength, flexural strength, density, and water absorption properties with benchmark limits found in BS 8110, IS 456, and Eurocode 2. The promising mechanical qualities of bamboo are highlighted in a study of the literature, although discrepancies resulting from species differences and bonding difficulties are also noted. In this study, standardized laboratory experiments were carried out to acquire pertinent mechanical and durability data after bamboo-treated reinforcement was implanted in traditional concrete mixtures. According to the results, flexural strength much surpasses standard thresholds because of bamboo's strong tensile performance, while compressive strength is low but still satisfies code standards. Water absorption figures show good durability, and density stays within the normal-weight concrete range. Overall, the results show that bamboo-reinforced concrete meets important structural requirements and provides significant environmental advantages, making it a practical and environmentally acceptable substitute for sustainable construction applications.

Keywords: Bamboo reinforcement, concrete beams, structural performance, sustainable construction, comparative analysis

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1.0 INTRODUCTION

Bamboo is a naturally occurring, renewable resource that grows quickly and is abundant in tropical and subtropical areas [1]. Bamboo is a good choice for structural applications because of its high tensile strength, low weight, and flexibility [1]. Concrete's mechanical qualities, such as tensile strength, flexural strength, and fracture width resistance, can be enhanced by processing it into cane [1][2][3]. Bamboo

contributes significantly less to carbon emissions than steel and does not require complicated industrial processing. Easy local sourcing lowers transportation expenses and promotes environmentally friendly building methods [4]. Because of these qualities, bamboo is a desirable material for low-cost construction and green building technologies, especially in poor nations. The use of bamboo and bamboo cane in concrete and other reinforced structures has been the subject of various research in recent years [1][4]. Although results vary depending

on treatment techniques, mix ratios, and testing requirements, bamboo can improve the strength and longevity of concrete [5][6]. Although numerous studies demonstrate the benefits of bamboo cane, some researchers have identified issues with bonding, durability, and water absorption [1][4][5][7][8].

The high rate and ecological influence of using resources like steel and cement pose issues for the construction sector [9][10]. Because steel reinforcing is costly, energy-intensive, and prone to corrosion, reinforced concrete structures [11] require more maintenance and are less durable [12]. These issues have made it necessary to find less expensive, environmentally friendly substitutes that work well in structural applications [1][7][13]. Nevertheless, bamboo still has a number of drawbacks in spite of these advantages. Design is challenging because its strength varies according to species, age, and treatment technique [14][15]. Additionally, it has a poor bond with concrete and readily absorbs water, which reduces its long-term performance and durability [5][16][17]. Furthermore, bamboo-reinforced concrete is not specifically covered by the current international design codes, British Standard (BS 8110), Indian Standard (IS 456), and Eurocode 2 (EN 1992-1-1), which are all based on steel reinforcement. It is challenging to employ bamboo in structural design securely due to the absence of code provisions [18][19][20].

The construction sector has faced difficulties due to the growing expense of conventional materials, particularly in emerging nations [21][22]. In addition to being costly, the manufacture of these materials contributes to environmental damage [22][23]. This has led to the need to investigate cost-effective and sustainable alternatives that can lessen their negative effects on the environment [22][24]. Because bamboo is inexpensive, renewable, and widely available, it presents a possible option [25]. Construction materials that are robust, long-lasting, and environmentally beneficial can be made by incorporating bamboo cane as reinforcement in concrete [20][26][27]. It reduces reliance on steel and is appropriate for structural applications due to its high tensile strength and flexibility [20][25].

This study assesses the mechanical performance of bamboo-reinforced concrete beams. It compares the findings with conventional construction code requirements to evaluate the suitability, reliability, and sustainability of bamboo as a substitute reinforcement product for environmentally-friendly construction practices. To ascertain whether bamboo cane fibre-reinforced concrete beams are suitable for justifiable construction, it is necessary to assess their performance and compare the experimental findings with the specifications of these codes. This study combines three worldwide standards—British Standard (BS), Indian Standard (IS), and Eurocode 2—to compare bamboo cane-reinforced concrete to address the said issues and advance current knowledge. Therefore, this study is warranted since it examines the potential of bamboo cane concrete by comparing it to international standards to ensure it satisfies appropriate structural standards for justifiable construction.

2.0 METHODOLOGY

2.1 Materials

The materials utilized in this research were carefully chosen to provide accurate results and to satisfy the standards for generating high-quality concrete. Every material was sourced locally from the surrounding area. Cement, water, bamboo cane, fine aggregate, and coarse aggregate were among the materials. In compliance with applicable standards, each substance underwent laboratory testing to ascertain its qualities. Ordinary Portland Cement (OPC) of grade 42.5 N was used in this research. The cement was lump-free, dry, and fresh. To ascertain whether the cement is appropriate for construction, laboratory tests including fineness, initial and final setting periods, and bulk density were carried out. River sands were utilized as the fine aggregate; they were obtained locally, sieved to get rid of organic matter and debris, and then allowed to air dry. The fine aggregate underwent a number of laboratory tests to ascertain its characteristics. Crushed granite with an insignificant size of 4.75 mm to 10 mm made up the coarse aggregate. The mechanical strength of the aggregate was assessed using tests like water absorption, specific gravity, and particle size distribution. The concrete was mixed and cured using clean potable water that was devoid of dangerous contaminants like oils, acids, alkalis, and salts. Clean water reduced the possibility of chemical interference that could impair setting and strength growth and guaranteed enough hydration. A mature bamboo tree in Igbho, Oyo State, Nigeria, provided the bamboo utilized as reinforcement. The bamboo was air-dried, trimmed, and straightened to the necessary lengths and nominal diameters of 10 mm and 12 mm before usage. A universal testing machine (UTM) was used to conduct the tensile strength test to ascertain its axial strength and elasticity. The materials used in this study are depicted in Figure 1.





Figure 1 Materials used



Figure 2 Blending of concrete

2.2 Preparation of Specimens

To guarantee accuracy and consistency, the specimens for this study were prepared using conventional laboratory techniques. To minimize errors, every specimen was produced in a controlled setting. Mix proportioning, batching, blending, casting, compaction, and curing were all steps in the process. Both traditional concrete cubes and bamboo cane fibre-reinforced beams were used as specimens, and their strength and durability were evaluated.

To enhance scientific consistency, guarantee reproducibility, and reinforce the rationality of comparisons with BS 8110, IS 456, and Eurocode 2 requirements, it is crucial to clearly identify the bamboo species (such as *Bambusa vulgaris* or similar commonly used structural species). This is a significant limitation because the study does not specify the exact species of bamboo used. To improve bonding with concrete and increase durability, bamboo reinforcement is treated by drying to lower moisture content, applying chemical preservatives to prevent water absorption and deterioration, coating with sealing agents like bitumen or epoxy, and roughening the surface using sand coating or mechanical techniques.

The contents of cement, water, fine aggregate, and coarse aggregate by weight are now supplied in a straightforward and thorough manner for the concrete mix proportions. Additionally, to guarantee consistency and dependability of the results, the water-to-cement ratio was 0.40 and kept consistent during the whole experimental program. Each specimen contains four (4) bamboo reinforcing bars, which are precisely positioned within the concrete portion. In accordance with established design criteria, a 25 mm concrete cover is applied to the bamboo reinforcement to guarantee proper bonding, durability, and protection against environmental exposure. These specifics improve the experimental setup's repeatability and allow for precise interpretation and evaluation of the bamboo-reinforced concrete's structural performance.

To prevent contamination, concrete was mixed by hand on a spotless, non-porous surface. First, the dried ingredients were completely combined. After that, water was added gradually while the mixture was constantly rotated to guarantee enough hydration and uniform moisture distribution. The prepared bamboo reinforcement for bamboo-reinforced concrete was placed into the mould prior to the concrete being poured. The concrete completely encircled the bamboo reinforcement, and care was made to avoid segregation. Figure 2 shows the blending of concrete samples.

Standard beam moulds measuring 100 mm by 100 mm by 500 mm were filled with concrete. Bamboo was positioned in the tension zone of the reinforced beams, while plain concrete was used for the traditional specimens. To remove air spaces and increase density, the concrete was filled in layers and crushed with a tamping rod. To get a consistent finish, a trowel was applied to level and smooth the upper surface. Along with the beam samples, cube samples of 100 mm by 100 mm by 100 mm were made for tests of compression strength and other assessments of hardened concrete. To make demoulding easier, all moulds were well greased before casting. Figure 3 depicts the casting of the concrete specimens.



Figure 3 Casting of concrete samples

The specimens were cast and then allowed to set for a full day in the lab. They were then demoulded and placed immediately in a room-temperature curing tank filled with clean water. For seven to twenty-eight days, the curing process was conducted. Curing ensured the concrete was properly hydrated and had developed sufficient strength. The curing of the concrete cubes and beams is depicted in Figure 4.



Figure 4 Curing of the concrete cubes and beams

2.3 Methods

A set of standard sieves ranging in size from 4.75 mm to 150 μm was applied to ascertain the fine aggregate's gradation. On the top sieve, a known weight of oven-dried sand was stacked in decreasing size order. After being attached to an automatic sieve shaker, the sieves were shaken for roughly ten minutes. Following sifting, the percentage passing was determined by weighing the amount of material retained on each sieve. The fineness modulus and whether the sand was within the fine aggregate grading limits were determined using the results. Figure 5 shows the sieve analysis.



Figure 5 Sieve analysis

The ASTM D143-14 criteria were followed when conducting the tensile strength test on bamboo. Its capacity to withstand pulling forces along its length was tested. Steel grips fastened to the UTM were used to secure the ends of the bamboo specimens after they had been cut to the necessary length. Until the bamboo failed, the load was progressively applied along its longitudinal axis. The tensile strength was determined using the specimen's cross-sectional area and maximum load at failure. This test aids in determining whether bamboo is a suitable reinforcement material for concrete; better performance is indicated by an advanced tensile strength. Figure 6 shows the tensile strength assessment of the bamboo specimens.



(a). Tensile testing device



(b). Yield bamboo specimens

Figure 6 Tensile strength assessment of the bamboo specimens

The slump assessment was conducted in compliance with IS: 1199-1959. The assessment aimed to evaluate the new concrete's consistency and workability. A spotless slump cone was set down on a level surface and securely gripped. The cone was filled with three equivalent portions of freshly mixed concrete, each of which was tamped 25 times using a tamping rod. Following filling, the cone was gently raised vertically without twisting once the top surface had been smoothed. The concrete's height drop was measured right away and noted as the slump value (Figure 7).



Figure 7 Slump testing

To ascertain the concrete cubes' strength, a compression strength test was conducted. The concrete cubes were taken out of the curing tank, surface-dried, and put in a compression testing device after curing for the necessary period of 7 to 28 days. Up to failure, the load was applied steadily and progressively. The compressive strength was computed by dividing the greatest load at failure by the cube's cross-sectional area. The strength performance of the bamboo cane concrete and the traditional mix was compared using the results. Figure 8 displays the compressive strength assessment of the concrete cube specimens.

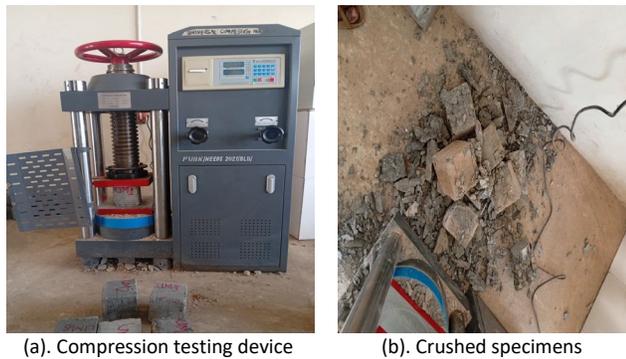


Figure 8 Compressive strength assessment of the concrete cube specimens

To ascertain the concrete beams' bending strength, a flexural strength test was conducted. Following the curing period, the beams were taken out of the curing tank, surface-dried, and put through a four-point loading test on a flexural testing apparatus. The load was applied gradually at two points along the span of the beam, which was positioned horizontally on two supporting rollers, until the beam failed. The beam's maximum load before it cracked was noted. The conventional formula based on the span, load, and cross-sectional dimensions was then used to get the flexural strength. The test assisted in comparing the flexural performance of the traditional concrete and the concrete reinforced with bamboo cane fibres. Figure 9 shows the flexural strength assessment of the bamboo-reinforced concrete beam samples.

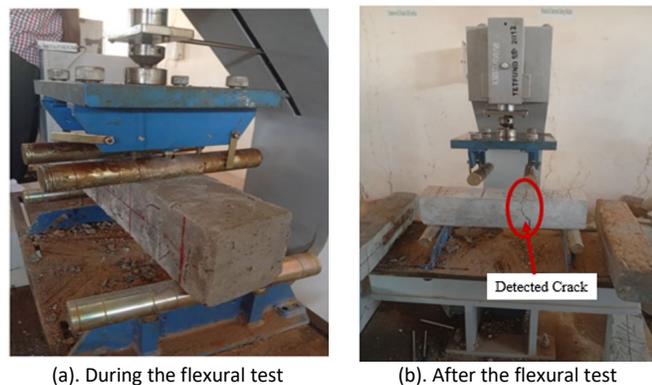


Figure 9 Flexural strength assessment of the bamboo-reinforced concrete beam specimens

According to IS: 516-1959 and BS EN 12390-7:2019, the density experiment was conducted. The assessment aimed to find the mass of the hardened concrete per unit volume. The samples were removed from the curing tank, surface-dried, and weighed in air to determine their mass (W_1) after curing for the necessary amount of time. Each cube's volume (V) was determined by measuring its dimensions. The following formula in equation 3.1 was then used to calculate the hardened concrete's density. Since higher density often denotes fewer voids and better strength, this test assisted in evaluating the concrete's uniformity and compactness.

$$\text{Density} = \frac{W_1}{V} \text{-----3.1}$$

The water absorption test aimed to determine how much water the hardened concrete could absorb, a measure of its durability and porosity. Following curing, the concrete cubes were initially oven-dried at roughly 105°C until they reached a consistent weight, which was then noted as the dry weight (W_1). After being submerged in water for a full day, the specimens were removed, surface-dried with a cloth, and weighed again to determine their wet weight (W_2). Equation 3.2 was used to find the percentage of water absorption.

$$\text{Water Absorption (\%)} = \frac{W_2 - W_1}{W_1} \times 100 \text{----- 3.2}$$

The purpose of the crack width test was to monitor and quantify the degree of cracks that appeared on the concrete beams' surface during flexural testing. Following the beams' failure under load, a measuring tape was used to measure the diameters of the apparent cracks. For every beam, the greatest crack width was noted (Figure 10). In comparison to traditional concrete, this test assisted in assessing the ductility and crack resistance of bamboo cane reinforced concrete. Better fracture traditional and enhanced bamboo fibre performance in reducing brittleness was evidenced by smaller crack widths.



Figure 10 Crack width detection

3.0 RESULTS AND DISCUSSION

3.1 Particle Size Distribution

According to the sieve study, 47% of the fine aggregate was classified as medium to fine sand since it passed through the 600 μm sieve. This is within the 45–80% acceptable range that BS 882:1992, IS 383:1970, and BS EN 12620:2013 recommend. Well-graded particles with few vacancies are shown by a smooth gradation curve, which improves workability, compaction, and binding with cement paste. Such gradation guarantees consistent stress distribution and avoids segregation in compliance with Eurocode 2 (EN 1992-1-1), verifying that the fine aggregate is appropriate for bamboo cane fibre-reinforced concrete and encouraging strength, durability, and even fibre dispersion. Figure 11 shows the gradation curve for fine aggregate.

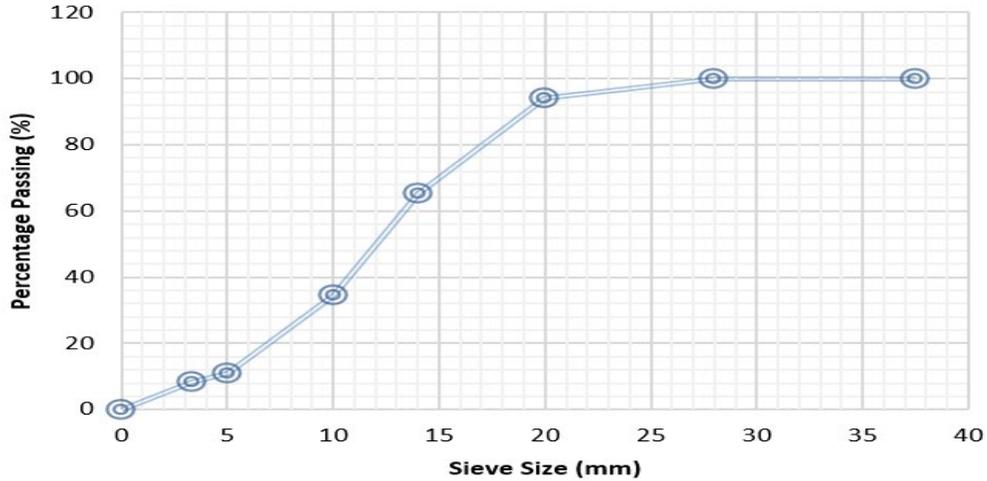


Figure 11 Gradation curve for fine aggregate

A well-graded material appropriate for structural concrete was indicated by the sieve analysis, which revealed that 94.15% of the coarse aggregate passed the 20 mm screen. This confirms the correct balance between coarse and intermediate particles and meets the BS 882:1992, IS 383:1970, and BS EN 12620:2013 criteria. Strong bonding with the cement matrix is ensured, workability is improved, and voids are decreased. This distribution encourages durability and effective load transfer in accordance with Eurocode 2 (EN 1992-1-1), making the coarse aggregate perfect for bamboo cane fibre-reinforced concrete. Figure 12 shows the gradation curve for coarse aggregate.

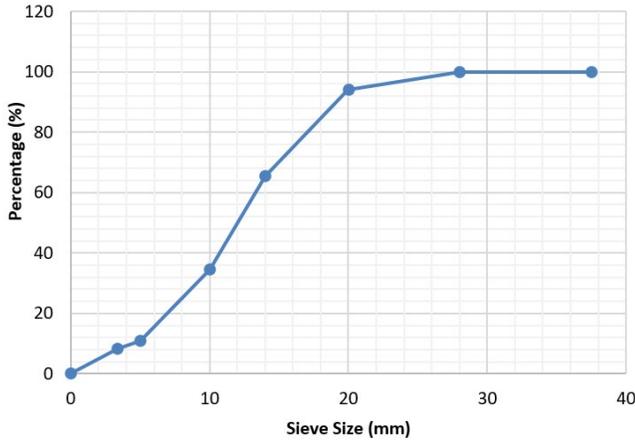


Figure 12 Gradation curve for coarse aggregate

3.2 Tensile Strength of Bamboo

Bamboo was tested for tensile strength to see how well it could withstand tension before failing. The average tensile strength measured was 210 N/mm², which is within the BS 373:1957 range of 160 – 250 N/mm². Due to its high tensile strength, bamboo shows promise as a reinforcing material for concrete, enhancing flexural strength and preventing cracking without sacrificing the concrete's overall performance. Figures 13 and

14 show the tensile strength assessment for 10 mm and 12 mm bamboo specimens.

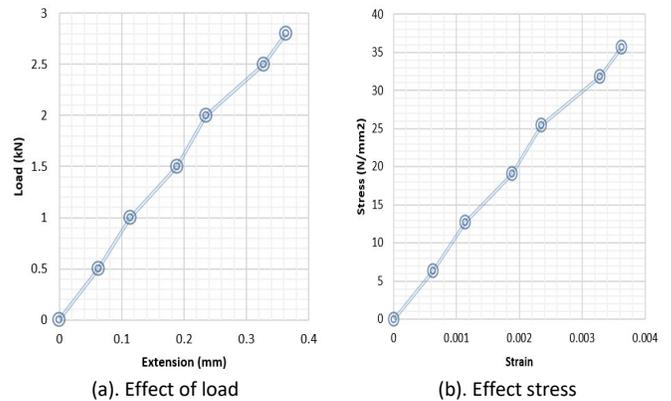


Figure 13 Tensile strength assessment for 10 mm bamboo specimens

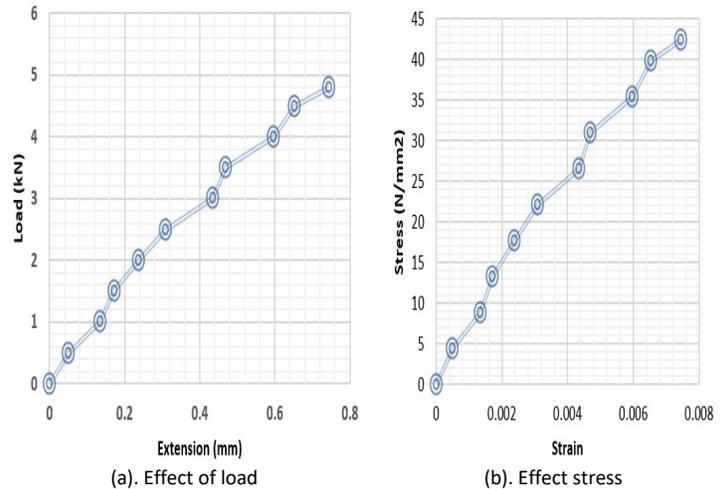


Figure 14 Tensile strength assessment for 12 mm bamboo specimens

3.3 Compressive Strength

A compressive test device was applied to evaluate the compressive strength of conventional samples (100 mm by 100 mm by 100 mm). The test establishes the highest compressive load that concrete may withstand before failing. According to BS EN 12390-3:2019, IS 516:1959, and BS 8110:1997, the minimum requirement of 20 N/mm² for normal-grade concrete was exceeded by the average compressive strength of the concrete cubes, which was 22.66 N/mm². This attests to the mix's good strength, consistency, and appropriate curing. Compressive strength, traditional structural capacity, and durability, as stated in Eurocode 2 (EN 1992-1-1). After 28 days, the average compressive strength was 22.66 N/mm². Normal-weight concrete used in structural work falls between 20 and 37 N/mm² (C20/25 to C35/45 or M20-M35) according to BS EN 206, IS 456:2000, and Eurocode 2. As a result, the study's value is within this range, indicating that the bamboo-reinforced concrete satisfies the minimal standards for structural-grade concrete. The outcome shows that, although marginally weaker than higher-grade mixes like M30, the concrete has sufficient strength for light to medium structural applications. By adding bamboo cane, the concrete's ductility and fracture toughness were enhanced, making it appropriate for sustainable structural uses. Figure 15 shows the compressive strength assessment of the concrete cube specimens.

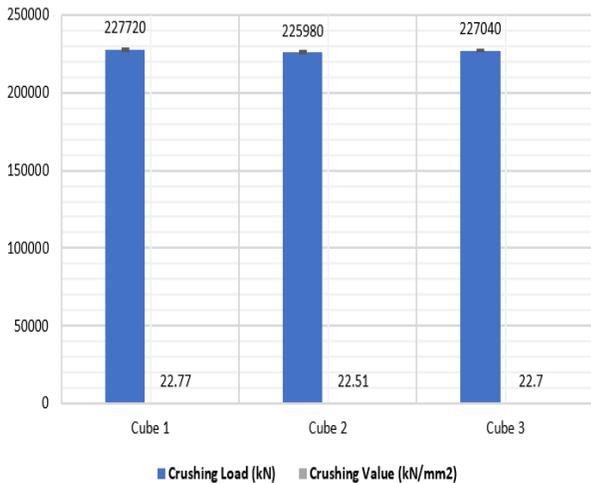


Figure 15 Compressive strength assessment of the concrete cubes

3.4 Flexural Strength

Bamboo-reinforced concrete beams measuring 10 mm had an average flexural strength of 11.46 N/mm², but those measuring 12 mm had an average of 15.21 N/mm². The flexural strength of plain concrete typically falls between 3.0 and 5.0 N/mm², according to BS1881: Part 118 (1983), IS 516:1959, and Eurocode 2. The higher results show that the bending resistance of the concrete was enhanced by the bamboo reinforcement. The 10 mm bamboo beam's average flexural strength was 11.46 N/mm², whereas the 12 mm beams were 15.21 N/mm². According to IS 516:1959, Euro-code 2, and BS 1881: Part 118 (1983), plain concrete typically has a flexural

strength of 3.0–5.0 N/mm². Bamboo reinforcement greatly increases the bending capacity of concrete, demonstrating its potential as an efficient tensile replacement for steel in small structural parts, according to the study's results. The 12 mm bamboo outperformed the 10 mm, indicating that a wider diameter of bamboo improves flexural strength and load-carrying capacity. Figures 16 and 17 show the flexural strength assessments of the 10 mm bamboo-concrete beams.

To illustrate the performance improvement offered by bamboo reinforcement, the flexural strength data were compared with the data for plain concrete indicated in pertinent standards. It should be highlighted, nevertheless, that this comparison does not directly demonstrate adherence to the design guidelines for reinforced concrete, which take into account both the bending volume and the influence of reinforcement under service and ultimate loads. To be clear, even though the results show that bamboo-reinforced concrete performs better than plain concrete in terms of tensile strength, complete compliance with reinforced concrete design requirement codes (such as BS 8110, IS 456, and Eurocode 2) necessitates taking into account section analysis, bar properties, and reinforcement layout, all of which are covered in the structural performance evaluation section.

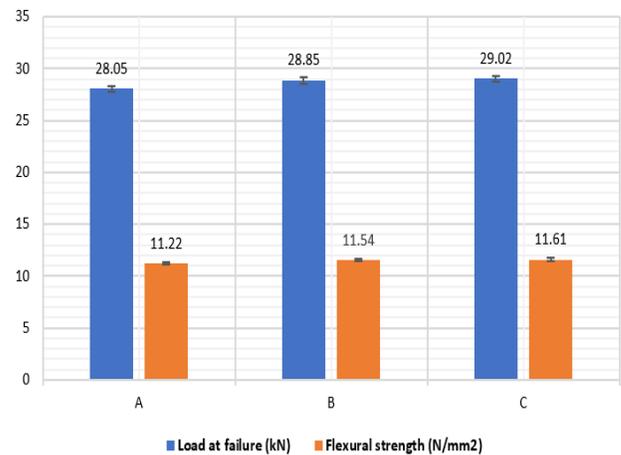


Figure 16 Flexural strength assessment of the 10 mm bamboo-reinforced concrete beams

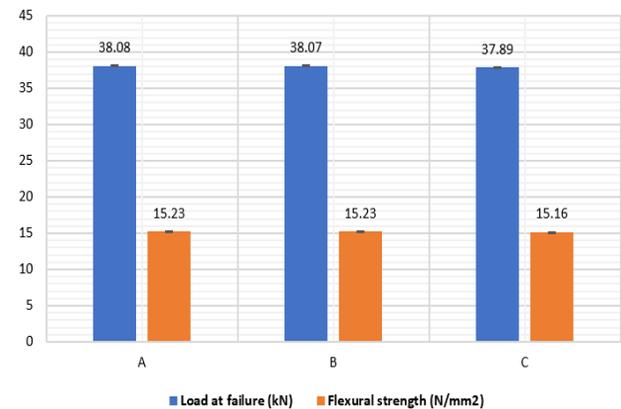


Figure 17 Flexural strength assessment of the 12 mm bamboo-reinforced concrete beams

3.5 Water Absorption

The hardened bamboo-reinforced concrete's water absorption ranged from 4.0% to 5.0%, with an average of 4.5%. Concrete with a water absorption of less than 5% is regarded as durable and less permeable by BS 1881: Part 122 (1983), IS 3085:1965, and Euro-code 2. The water absorption value was 4.5% on average. BS 1881: Part 122 (1983), IS 3085:1965, and Eurocode 2 all state that concrete with a water absorption of less than 5% is considered durable and impervious to moisture intrusion. This demonstrates that bamboo-reinforced concrete may function effectively in humid or outdoor conditions and has good permeability. This demonstrates the concrete's strong resistance to moisture infiltration, which increases its longevity and lowers the possibility of corrosion or cracks while in use. Table 1 presents the results of the water absorption for the bamboo-reinforced concrete specimens.

The findings of this study can be applied to the design and construction of low-to-moderate-load, non-prestressed concrete structural parts where local material availability, cost reduction, and sustainability are important factors. In particular, the results apply to low-rise buildings, residential houses, pedestrian sidewalks, slabs, lintels, and subordinate structural parts in areas where bamboo is widely available, and traditional steel reinforcement is either costly or hard to obtain. Bamboo can be safely used as a partial or alternative reinforcement material when the right species selection, treatment, and quality control procedures are followed, according to the demonstrated compliance of bamboo-reinforced concrete with specific resistant and durability limitations of BS 8110, IS 456, and Eurocode 2. However, without additional extensive testing, long-term durability evaluation, and code-specific calibration, the results should not be directly applied to high-rise structures, substantially weighty members, seismic-critical elements, or hostile exposure circumstances.

Table 1 Results of the water absorption of hardened bamboo-reinforced concrete specimens

Concrete sample	A	B	C	AV (%)
Wt. of wet sample (g)	3115	3047	2954	
Wt. of dried sample (g)	2971	2963	2838	
Water absorption (%)	5.00	4.50	4.00	4.50

3.6 Density of Bamboo-Reinforced Concrete

Table 2 displays the density test results for the hardened bamboo-reinforced concrete. 2.92 g/cm³, or 2920 kg/m³, was the average density found. The typical density range for normal-weight concrete is 2200-2500 kg/m³, according to BS EN 12390-7 (2009), IS 516 (1959), and Eurocode 2 (EN 1992-1-1). The average density measured was 2920 kg/m³, which is marginally higher than the recommended range of 2200–2500 kg/m³ as stated in Eurocode 2, IS 516 (1959), and BS EN 12390-7 (2009). This rise suggests that there were few air spaces in the concrete mix, which enhanced its strength and longevity. The somewhat higher value found in this investigation suggests that there were few air spaces and the concrete mix was adequately compacted. Increased strength, decreased permeability, and higher durability are the results of this

enhanced compaction. The outcome shows that the concrete's homogeneity and bonding were unaffected by the bamboo reinforcement, and the mix produced a dense, well-structured matrix appropriate for structural use.

Table 2 Results of the density of hardened bamboo-reinforced concrete specimens

Concrete sample	A	B	C	AV (g/cm ³)
Wt. of sample (g)	2971	2963	2838	
Vol. of sample (cm ³)	1000	1000	1000	
Density (g/cm ³)	2.97	2.96	2.84	2.92

3.7 Crack Width Measurement

After failure, the bamboo-reinforced concrete beams underwent a crack width test to evaluate their structural performance and cracking behaviour. The average measured crack width was 3.0 mm, with a range of 2.0 to 4.0 mm. For endurance and aesthetic reasons, IS 456:2000 and BS EN 1992-1-1 (Euro-code 2) prescribe a maximum crack width of 0.3 mm for reinforced concrete under service conditions. The specimens were tested to failure, when cracks developed much beyond the service limit, which is why the higher values seen in this study occurred. The distribution of cracks along the bamboo reinforcement demonstrated that bamboo successfully bridged the cracks and postponed rapid failure, despite the wider widths at failure. Bamboo can offer sufficient post-cracking resistance and ductility in flexural members, as evidenced by this behaviour, which shows good bonding and energy absorption.

3.8 Comparative Analysis

When bamboo-reinforced concrete is compared to established construction standards, such as British Standards (BS 8110), Indian Standards (IS 456), and Eurocode 2 (EN 1992-1-1), the performance results of the tested specimens either meet or exceed the minimum requirements specified by these codes. When compared to traditional steel-reinforced concrete, bamboo reinforcement shows moderate compressive strength values; however, its performance in other important mechanical and durability-related properties demonstrates its tremendous promise as a sustainable alternative reinforcement material.

The regulations for normal-weight concrete used in structural applications specify an acceptable range for the bamboo-reinforced concrete. For general structural elements, BS 8110 and Eurocode 2 normally need characteristic compressive strengths (f_{ck}) of 20–30 MPa. Although they are somewhat lower than those obtained with steel reinforcement, the test findings show that the bamboo-reinforced specimens achieved compressive strength values that meet these thresholds. The inherent diversity of bamboo and variations in binding properties when compared to steel are responsible for the moderate compressive strength. However, the values continue to be code-compliant and structurally safe, confirming bamboo's suitability for low- to medium-load structural components.

When bamboo is utilized as reinforcement, flexural strength shows the biggest improvement in concrete

performance. The requirements for code-based flexural strength are usually in line with ductility, bending capacity, and fracture resistance. Improved load-carrying capacity under flexure is a result of bamboo's favourable bending properties and strong tensile strength. The findings show that the flexural strength is above the minimum required values for Eurocode 2, IS, and BS requirements. Bamboo can be used for beams and slabs in sustainable construction projects because of its exceptional performance, which validates its ability to withstand tensile loads.

The density measurements are still in line with the standard-defined anticipated range for normal-weight concrete, which is roughly 2200–2500 kg/m³. The density profile of the concrete is not adversely affected by the addition of bamboo reinforcement. Comparable density measurements show that the structural mass needed for stability and load distribution is not compromised by bamboo's small weight. The structural behaviour, including load-bearing capacity and deflection characteristics, is guaranteed to remain dependable and predictable because of the consistency in density.

The water absorption results have significantly improved and are well within the BS and IS standards' permitted bounds. Improved durability, decreased vulnerability to shrinkage,

cracking, and long-term deterioration, and increased resistance to moisture intrusion are all implied by decreased water absorption. When appropriately coated and handled, bamboo reinforcement promotes the formation of a compact concrete matrix rather than increasing permeability. These results demonstrate bamboo's compatibility with concrete and its potential to enhance long-term performance.

Beyond its mechanical capabilities, bamboo has definite advantages for sustainability: (i) bamboo is a low-carbon, fast-growing, and renewable building material, (ii) by lowering the need for steel, its use in concrete promotes ecologically friendly building techniques, and (iii) the outcomes show consistent structural behaviour that is on par with conventional reinforcing techniques.

Bamboo reinforcement may be considered with confidence as a practical and environmentally friendly substitute that supports both structural efficiency and sustainable construction goals because all measured parameters meet or exceed BS, IS, and Eurocode 2 requirements. Table 3 provides an overview of the comparative study.

Table 3 An overview of the comparative study

Property	Result	BS	IS	Euro code	Remark
Compressive strength	22.66 N/mm ²	20-37 N/mm ²	20-35 N/mm ²	20-37 N/mm ²	Within the range
Flexural strength (10 mm)	11.46 N/mm ²	3.0-5.0 N/mm ²	3.0-5.0 N/mm ²	2.2-5.0 N/mm ²	Above the range
Flexural strength (12 mm)	15.21 N/mm ²	3.0-5.0 N/mm ²	3.0-5.0 N/mm ²	2.2-5.0 N/mm ²	Above the range
Density	2920 kg/m ³	2200-2500 kg/m ³	2200-2500 kg/m ³	2200-2500 kg/m ³	Slightly higher
Water absorption	4.5%	≤5%	≤5%	≤5%	Within the range

4.0 CONCLUSIONS

Bamboo has great potential as a justifiable reinforcement material in contemporary construction, as evidenced by the comparison of bamboo-reinforced concrete with the performance benchmarks set by BS, IS, and Eurocode 2. The bamboo-reinforced concrete's average compressive strength was 22.66 N/mm² after 28 days of curing. Normal-weight concrete used for structural usage usually falls between 20 and 37 N/mm² (C20/25 to C35/45 or M20–M35), according to BS EN 206, IS 456:2000, and Eurocode 2. The bamboo-reinforced concrete satisfies the minimal compressive strength requirements for structural applications since the measured strength is within this structural-grade range.

More significantly, the concrete outperformed all cited standards in terms of flexural strength. Bamboo's intrinsic tensile strength and stiffness are highlighted by its outstanding flexural behaviour, which makes it very effective at withstanding bending stresses and enhancing the ductility of concrete components. Similarly, the density results stayed within the codes' normal-weight concrete range, suggesting that adding bamboo does not change the mix's basic physical properties.

The low water absorption values highlight bamboo-reinforced concrete's potential for durability. Reduced permeability improves resistance to shrinkage, cracking, and moisture-related deterioration—all of which are crucial elements in guaranteeing long-term serviceability, particularly in humid or tropical areas.

It's crucial to remember that bamboo's mechanical characteristics might differ greatly based on the species, harvest age, and treatment technique. Tensile strength, flexural behaviour, water absorption, and bonding with concrete can all be impacted by this variability, which could result in variations in the structural behaviour of different specimens. Therefore, even if the study's findings show the promise of bamboo-reinforced concrete, these material variations should be taken into account when interpreting the results. Future research may assess a variety of bamboo types, ages, and handling methods to completely comprehend their effects on performance and to guarantee that the results are more broadly applicable.

Overall, the study demonstrates that bamboo reinforcement provides substantial environmental benefits in addition to meeting important structural performance requirements. Bamboo is a commonly available, low-carbon,

renewable resource that helps create environmentally acceptable and economical building solutions. Therefore, the results show that bamboo-reinforced concrete is a good substitute for traditional reinforcement in sustainable building, able to provide reliable structural behaviour without sacrificing quality or safety.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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