International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Comparative Analysis of Bamboo and Steel Reinforcement in Concrete for Sustainable Low-Rise Buildings

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Abstract

The rapid growth of the construction industry has driven increased demand for sustainable, affordable, and eco-friendly alternatives to traditional materials like steel. While steel offers excellent strength and ductility, it has notable disadvantages such as high embodied energy, substantial carbon emissions, susceptibility to corrosion, and volatile market prices. These concerns have led researchers to explore renewable and low-carbon options, with bamboo emerging as a promising candidate. This study investigates bamboo's potential as a reinforcement material in concrete, especially for low-rise buildings. Bamboo, a renewable and fast-growing material with high tensile strength and an excellent strength-to-weight ratio, was tested in both untreated and chemically treated forms to evaluate its structural, mechanical, and durability properties in comparison to steel reinforcement. Experiments were conducted on M25 grade concrete using cubes, cylinders, and slabs reinforced with steel rods and bamboo splints. Tests measured tensile strength, bond strength, water absorption, flexural performance, and cyclic load behavior. Results showed that although steel-reinforced slabs had the highest load capacity and energy absorption, bamboo-reinforced slabs performed well, reaching up to 72% of the strength of steel-reinforced concrete and outperforming plain concrete significantly. Coatings like bitumen, epoxy, and boron-based treatments improved the bond between bamboo and concrete and reduced water absorption, thus enhancing durability. Additionally, bamboo's light weight, renewability, low embodied carbon, and cost-effectiveness make it a viable sustainable substitute for low-cost housing, disaster-resistant structures, and rural infrastructure. The research suggests that with appropriate treatment and standardization, bamboo can serve as an eco-friendly reinforcement material in low-rise buildings, helping to address environmental and economic challenges associated with steel while promoting sustainable development.

Keywords: Bamboo reinforcement, sustainable construction, low-rise buildings, steel alternative, bamboo-reinforced concrete (BRC), flexural strength, cyclic loading, bond strength, protective treatments (bitumen, epoxy, boron), eco-friendly materials, strength-to-weight ratio, affordable housing, green building materials, renewable construction material, structural performance.

1. Introduction

Sustainable construction practices have become a vital part of the global effort to minimize the environmental, social, and economic impacts of the built environment. The construction industry is one of the largest consumers of natural resources and energy, significantly contributing to greenhouse gas (GHG) emissions, environmental harm, and the depletion of non-renewable materials. According to the United Nations Environment Program (UNEP), the building and construction sector accounts for nearly 40% of worldwide energy-related carbon emissions, mainly due to energy-intensive processes involved in material production, transportation, and building operations. This urgent issue has driven a worldwide shift toward sustainable construction, aimed primarily at reducing environmental footprints, increasing resource efficiency, and promoting social and economic well-being without compromising the needs of future generations. Sustainable construction involves incorporating environmentally responsible practices throughout a building's entire life cycle, from planning and design to construction, operation, maintenance, and end-of-life management, thereby supporting the principles of the circular economy and sustainable development. [1] Central to sustainable construction is using eco-friendly materials and maximizing resource efficiency. Materials such as recycled aggregates, bamboo, fly ash, geopolymer concrete, reclaimed wood, and other renewable or industrial by-products have gained popularity as alternatives to traditional materials like Portland cement, steel, and natural aggregates, which are energy-intensive to produce. The choice of sustainable materials depends on factors like low embodied energy, reduced carbon footprint, local availability, durability, and potential for reuse or recycling. Life Cycle Assessment (LCA) is often used to evaluate the environmental performance of construction materials and processes, ensuring decisions are made with a complete understanding of their ecological impact. [2] Additionally, sustainable construction promotes energy efficiency through passive and active design strategies, including proper orientation, natural ventilation, high-performance insulation, renewable energy integration, and energy-efficient lighting and HVAC systems. These combined measures reduce operational energy use, which accounts for a significant portion of a building's overall life cycle impact. [3] However, adopting sustainable practices also faces challenges. Barriers such as high initial costs, limited awareness, lack of skilled labor, and weak regulatory enforcement can hinder widespread adoption, especially in developing countries. Overcoming these hurdles requires a collaborative effort from policymakers, engineers, architects, material scientists, and stakeholders across the construction supply chain. Government support through tax incentives, subsidies, and stricter environmental regulations can accelerate the shift to sustainable methods. Equally important are education and professional training to develop the skills necessary for successful green construction projects. [4] In the face of rapid urbanization and increasing climate change impacts, pursuing sustainable construction is not just an environmental obligation but also an economic and social necessity. By reducing resource consumption, lowering emissions, and creating healthier living environments, sustainable construction offers a pathway to a more resilient and equitable built environment that supports the long-term goals of sustainable development. [5] In recent decades, global interest in bamboo as a sustainable and efficient building material has surged. This rising interest is driven by increased awareness of environmental issues, depletion of non-renewable resources, and the urgent need for sustainable construction options. Traditional construction materials like steel, concrete, and timber are widely used but have high environmental impacts due to energy-intensive manufacturing processes, significant greenhouse gas (GHG) emissions, and resource depletion. For example, the production of steel and cement alone accounts for a large share of worldwide carbon dioxide emissions, contributing to climate change and environmental damage. Bamboo, often called the "green steel" of the 21st century, has become a renewable, fast-growing, eco-friendly alternative to traditional materials. It is especially suited for low- and medium-rise buildings, pedestrian bridges, scaffolding, and prefabricated homes. Its biological traits, mechanical strengths, and sustainability qualities make it an attractive choice for structural use, sparking interest among engineers, architects, and material scientists globally. [6] Beyond its environmental advantages, the increased use of bamboo is supported by technological innovations and the formalization of design and construction standards. Historically, bamboo has been widely utilized in traditional architecture across Asia, Africa, and Latin America for scaffolding, roofing, and lightweight structures because of its local availability and ease of handling. However, its use in modern engineering was limited by issues related to durability, vulnerability to biological decay, and a lack of standardized design codes. Recent advances in preservation methods, such as boron salt treatments, water seasoning, and natural or synthetic coatings, have substantially improved bamboo's durability and resistance to fungi, termites, and environmental damage. Additionally, the development of engineered bamboo products, such as laminated bamboo lumber, bamboo scriber, and bamboo fiber composites, has expanded its use to structural beams, columns, and floor panels in modern construction. These innovations provide greater dimensional stability, better mechanical properties, and improved uniformity, enabling bamboo to meet the rigorous standards of contemporary building codes. The recognition of bamboo in official national and international standards, including ISO 22156:2021 for bamboo structural design, has further promoted its integration into mainstream construction projects. [7] [8]

2. Limitations of Steel

Steel is vital in construction due to its strength, durability, ductility, and versatility, used in concrete, frameworks, bridges, and tall buildings. However, its limitations include high costs, embodied carbon, and environmental impact, leading researchers to seek sustainable options. Steel's production is energy-intensive, emitting about 1.85 tons of CO_2 per ton of crude steel, contributing nearly 7–9% of global GHG emissions. Its use of coal-based furnaces and non-renewable resources causes pollution, water contamination, and land degradation. Economically, steel costs fluctuate due to market, energy, and transportation expenses, especially impacting developing countries reliant on imports. Its weight increases transportation costs, and its susceptibility to corrosion raises maintenance costs, particularly in harsh environments. Alternatives like bamboo, timber, or composites often have lower costs and require less maintenance for low- and mid-rise buildings. [9] [10] Steel's environmental impact extends beyond production, including high energy use, emissions, and waste from recycling, demolition, and mining. Its high thermal conductivity worsens urban heat islands and increases cooling costs. These issues hinder sustainable construction goals, such as reducing embodied carbon and improving resource efficiency. As reliance on steel delays progress toward green building standards, alternatives like engineered bamboo and fiber composites gain importance, especially for low-rise and non-structural uses. Encouraging the use of life-cycle assessment and circular economy principles promotes lower-carbon options, with bamboo emerging as a sustainable, affordable, and low-carbon structural material. [11] [12]

3. Comparative Environmental and Economic Benefits of Bamboo Over Steel

The comparison between bamboo and steel in construction shows that bamboo offers significant environmental and economic benefits over traditional steel, especially in low-rise buildings where full steel strength is not always required. Ecologically, bamboo's advantages stem from its renewable nature, fast growth, and minimal processing needs, all of which contribute to a very low embodied carbon footprint. Steel production releases about 1.85 tons of CO_2 per ton of material due to energy-intensive mining, smelting, and manufacturing processes. In contrast, bamboo, a natural grass, absorbs carbon as it grows and requires only low-energy treatments for construction. A mature bamboo plantation can store between 30 and 60 tons of CO_2 per hectare annually, helping to mitigate greenhouse gases and support climate change initiatives. Additionally, bamboo does not necessitate large-scale land disruption for mining or heavy industrial processing, which allows for the preservation of biodiversity, soil health, and water quality, unlike steel production, which has significant environmental impacts from iron ore extraction, coal consumption, and slag disposal. Furthermore, bamboo aligns well with circular economy principles because it is biodegradable, reusable, and recyclable in its natural state. Although steel can be recycled, the process still consumes considerable energy and generates emissions, highlighting bamboo's eco-efficiency. [13] Economically, bamboo can be a cheaper and more attractive alternative to steel for compression parts and other structural components in low-rise buildings. The initial cost of bamboo is much lower than that of steel, especially in regions where bamboo is locally grown, reducing dependence on imported or unstable-priced materials. Its lightweight nature also decreases transportation and handling costs, as bamboo parts can often be moved and assembled manually without heavy equipment or complex logistics. In contrast, steel involves higher transportation and setup expenses due to its weight and the need for cranes, scaffolding, and skilled labor. Maintenance costs for bamboo are also relatively low if it is adequately treated against moisture, fungi, and termites. Unlike steel, which requires regular anti-corrosion treatments or protective coatings in harsh environments, bamboo's durability can be enhanced with affordable, eco-friendly solutions such as boron salts or natural oil finishes. This lowers long-term maintenance expenses for bamboo structures, making them particularly suitable for rural homes, low-rise buildings, and disaster-resistant shelters where budgets are limited. [14]

4. Overview of Low-Rise Buildings

Low-rise buildings, generally one to three stories, are typical in urban outskirts, suburban, and rural areas, characterized by their simplicity, lower costs, and use of traditional or modern materials like brick, timber, reinforced concrete, bamboo, and earth blocks. They experience less lateral wind and seismic load, making them suitable for sustainable and cost-effective construction, especially in developing countries. These structures are easier to maintain, repair, and adapt for passive design strategies, such as natural lighting and ventilation, enhancing energy efficiency. They are resilient in disaster-prone regions and support modular, prefabricated methods, promoting environmentally friendly urban and rural development and reducing environmental impacts through the use of local, low-carbon materials like bamboo and stabilized earth. Overall, low-rise buildings offer flexible designs, lower costs, and sustainable options, playing a vital role in creating affordable, resilient, and eco-friendly housing solutions worldwide. [15] [16] [17]

5. Objectives of Research Work

- To investigate the physical, mechanical, and durability properties of bamboo as a reinforcing material in concrete.
- To evaluate the bond strength, tensile strength, and flexural performance of concrete reinforced with untreated and treated bamboo splints.

- To compare the structural behavior of bamboo-reinforced concrete (BRC) slabs with conventional steel-reinforced concrete (RCC) and plain cement concrete (PCC) slabs under static and cyclic loading.
- To assess the effectiveness of protective treatments (bitumen/epoxy/boron-based) in improving bamboo's durability and bond with concrete.
- To analyze the economic and environmental benefits of bamboo reinforcement over steel, particularly for low-rise buildings in developing regions.
- To propose bamboo as a cost-effective, sustainable alternative to steel reinforcement for affordable housing and disaster-resistant construction.

6. Literature Review:

K.Kantharuban et al. (2022). Construction activities contribute about 40% of all pollution, prompting focus on green materials. This study examines natural bamboo reinforcement and beam-column joints for sustainability. Cementitious materials are crucial for pollution reduction. The relationship between bamboo-reinforced columns and beams was analyzed, focusing on load, earthquake, and other forces. Initial tests utilized various loading systems on a beam-column junction at Bharath Institute's Civil Engineering Lab. Bamboo fasteners, which were unwilling, were used in BC1, BC2, and BC3-sized columns, connected with scaffolding clamps. These samples underwent cyclical loading, with load-deflection data and sphere hysteresis observed. BC1 and BC3 reached a max shear strain of 17.8 kN; BC2 reached 13.76 kN. [30]

Bei-bei Jin et al. (2022). Eight models underwent center compressive testing on ferrocement slab panels reinforced with bamboo strips. The tests measured load-deflection curves and fracture patterns. Fracture loads under theoretical and experimental conditions were nearly identical.

Ikponmwosa et al. (2015). The study examines the structural behavior of foamed concrete slabs reinforced with bamboo. Foamed aerated concrete with bamboo strips shows successful flexural performance, monitored through crack and deflection tests. Bamboo reinforcement at 0.24% area influences the structural behavior, with the FE model indicating how steel chamber dimensions, bamboo thickness, and cross-sectional design impact compression. The study estimates load-bearing ability in traffic areas, noting that the steel chamber enlarges outward and the bamboo sometimes breaks. As the steel chamber's width-to-thickness ratio increases, so does load capacity and flexibility. Optimal bamboo parameters are a thickness of 10 mm and a twisting angle of 75°. Based on capacity and flexibility, circular and square composite segments are suitable, with results aligning well between tests and predictions.

Sajjad Qaiser et al. (2020) demonstrated that widespread use is limited due to poor rigidity, with steel being the ideal reinforcement material. Finding affordable, quick solutions for concrete is urgent amid the energy crisis. This study explores bamboo as a potential support in cement footers, since steel rebar manufacturing is energy-intensive. Tests on locally available bamboo examined bond strength, rigidity, and water absorption, leading to the development of bamboo-supported radiators. Cement footers were designed using similar support ratios but with bamboo strips with different surface patterns. Steel rebar served as the primary support in alternative pillar designs under identical load conditions. These were tested to compare yield loads, ultimate loads, failure modes, and protection levels of bamboo versus steel reinforcement. Load diagrams and analysis graphs assessed load failure types, revealing bamboo's impact on strength increase, bond pressure, and its suitability as a rebar alternative. [32]

Li-min Tian et al (2019). Pivotal pressure testing examined the bearing limit and strength of eight bamboo and eight composite segments made of bamboo and composite mortar. Various methods for calculating their strength and reliability limits were recommended. Findings showed clasping caused failure in slim segments, while strength failure at the ends affected short segments. The short composite segment supported by the entire cross-section had an ultimate load and flexibility 1.5 and 2.6 times higher than the short bamboo segment. Results from limited component analysis aligned well with the tests. A method for computing the clasping coefficient based on edge fiber yield was proposed, matching both analysis and experimental results. This approach considered cross-sectional effects and initial deviation on segment integrity. [33]

Pankaj R. Mali et. al. (2019). The report explores the flexural behavior of bamboo-built-up cement footers through a four-point bowing test on 30 shaft tests. Trials included steel-supported cement footers, bamboo-reinforced footers, and plain cement footers. Key measures such as firmness, burden, energy retention, shear, and flexural strength were used to assess performance. Bamboo strips served as longitudinal and shear supports in two BRC types: one with 2.8% bamboo support and another with 3.8%. Results showed BRC outperforms PCC in shear and flexural qualities but is inferior to RCC. A process involves filling steel tube openings with bamboo, adding coagulant, and sealing with plastic. Bamboo bars act as test models for various materials. [34]

P. Rama Mohan Rao et al. (2018). This examination aims to reduce building material costs, especially steel, which is widely used in segments, shafts, and pieces. Steel erodes when exposed to moisture, losing strength and affecting durability. Bamboo rebars were used to increase strength and utilize available resources, with substitution rates of 25%, 50%, 75%, and 100%. Bamboo was installed in high-stress areas of 0.7 m pillars and tested with two-point loads at one-third span. Results show that a pillar with 25% bamboo rebar is stronger than those with higher bamboo content in flexural strength, deflection, and crack resistance compared to conventional steel bars. [35]

Pankaj R. Mali and Datta (2018) finished an examination-based evaluation of bamboo RC chunk boards. Research testing on substantial piece boards showed the practicality and viability of utilizing bamboo profiles as support. There were 15 substantial piece boards made on the whole, as expressed by Eurocode EN-1448-5 (2006). The outcomes showed that, in contrast to PCC and RCC (Supported Concrete Cement) sections, the heap conveying and misshaping limits improved when the previously mentioned bamboo strip was utilized as support in substantial chunk boards. It's essential to see that the recently planned BR has made significant improvements in the flexural execution of the sections. In any case, it was just somewhat better compared to RC sections with M.S. bars as a critical support. [34]

Mali and Datta (2018) found that the bamboo-built-up substantial section boards may be utilized in economic developments, especially as a component of the material in circumstances with zero gravity loads—examination of these BRCs' underlying components. Contrasted with regularly used RC chunks, they are more affordable and ecologically harmless. Ismail et al. concentrated on the behavior of the BRC pieces' solidarity. It was declared that adding more essential support would cause the bowing reaction of the chunk construction to increase. [36]

S. Jeeva Chithambaram et al. (2017). To address affordable housing, use locally available, cost-effective materials like bamboo instead of expensive M.S. or HYSD bars in rural areas. Fly ash from nuclear waste can replace concrete in mortar or cement. A study on bamboo-based ferrocement panels supported by chicken wire found that, after testing 12 panels, the results showed that panels with traditional mortar and those with 15% fly ash had similar initial and failure loads. All panels exhibited significant ductility before failure. [37]

Chithambaram et al. (2016). Flexural tests were conducted on ferro substantial loads measuring 470 mm x 940 mm (40 and 50 mm thick) and hexagonal wire networks in two layers. This included using 15% fly ash to replace 11% of the substantial. Twelve ferrocement chunk boards, each with six sections and thicknesses of 40 and 50 mm, were tested as part of the program. These boards were divided into three sections: standard concrete mortar-shrouded boards and three pieces of 15% concrete-substituted boards. A lattice of bamboo strips (12 mm x 12 mm, spaced 100 mm apart) provided skeletal support. Tests under consistent pressure assessed the heap redirection, bend, and break design. Under experimental conditions, initial break loads for sections were similar, but their end loads were mainly twice as large. [38]

Maruthupandian et al. (2016). Bamboo was utilized as the essential support in section examples, which led analysts to the conclusion that it might replace steel in underlying applications with light loads. Steel-supported concrete (SRC) chunks are possibly better than uncovered concrete (BRC) sections. [39]

According to **Zhu et al. (2015).** A heap of 40 kN, notwithstanding, shows a similar diversion. In this way, in conditions with next to zero stacking, identical to book sections and kitchen chunks, bamboo might be utilized as a primary material. [40]

Ikponmwosa et al. (2015) analyzed bamboo-based blocks that used polyvinyl waste (PW) to replace some fine particles. Frothed air circulated through concrete, which was tested for flexural strength using 1300 mm by 500 mm by 100 mm samples. The 20 mm thick top was covered with bamboo strips 10 mm wide and long. The samples contained at least 0.24% bamboo support (b x h). Treated bamboo strips of 10 mm by 10 mm were used for mixing and distribution. Bamboo scattering was at 250 mm, while on the first bar, it was at 150 mm. Bamboo was wound around a wire-bound lattice, supporting the 1300 mm length. The tests included crack checking and central distribution at 5 kg/cm2 stress testing. [41]

7. Materials

The two main substances used in the experiments are concrete with Bamboo and concrete with steel. The preparation of slab specimens and cylinders was carried out using locally available raw materials that were free from harmful substances. They were visually and physically inspected during material procurement to ensure the required quality of raw materials. Furthermore, the materials were tested for suitability according to Indian Standard Codes before being used in casting the specimens. Additionally, a local type of Bamboo called Bambusa arundinacea was tested.

7.1. Concrete Mix:

Normal-weight concrete of grade M20 or M25 (depending on design requirements) will be used as the matrix material. Cement, fine aggregates, and coarse aggregates will be sourced locally, with a water–cement ratio of 0.45–0.50

7.2. Bamboo:

Locally available bamboo species, such as Bambusa balcooa or Dendrocalamus strictus, are selected because of their high strength-to-weight ratio and widespread availability in tropical and subtropical regions. The culms will be cut into appropriate sizes and chemically treated with boric-borax solution or water seasoning to enhance durability, prevent termite attack, and reduce moisture content. [47]

Bamboo is a naturally occurring, fast-growing, renewable material that has attracted increasing interest as a sustainable substitute for conventional steel reinforcement in low-rise construction. Its unique mechanical, physical, and environmental properties make it a viable structural material when properly treated and used in combination with concrete [48]. Figure 1 represents the diagram of properties of Bamboo.

Figure 1: Chart Diagram of Bamboo Properties

Bamboo possesses excellent tensile and compressive properties, a high strength-to-weight ratio, and environmental benefits such as low embodied carbon and rapid renewability. However, its successful use in reinforced concrete requires proper treatment, surface modification, and standardization to overcome challenges related to durability and variability. The fundamental mechanical and physical properties of bamboo and steel are compared in Table 1 to highlight their potential applicability as reinforcement materials in compression members for low-rise buildings.

Table 1: Properties of Bamboo

Property	Bamboo	Steel	Remarks
Density (kg/m³)	600 – 900	~7850	Bamboo is much lighter, reducing dead load.
Tensile Strength (MPa)	140 – 280 (some species up to 370)	250 – 600 (mild steel ~250)	Comparable in tension, bamboo can rival mild steel.
Compressive Strength (MPa)	40 – 80	250 – 400	Steel is much stronger in compression.
Flexural Strength (MPa)	50 – 150	250 – 600	Adequate for low-rise structures, lower than steel.
Modulus of Elasticity (GPa)	10 – 20	~200	Steel is much stiffer; bamboo is more flexible.

Strength-to-Weight Ratio	High	Moderate	Bamboo provides more strength per unit weight.
Thermal Conductivity (W/mK)	~0.2	~50	Bamboo has excellent insulation; steel conducts heat.
Carbon Footprint (kg CO_2/kg)	~0.02 (absorbs CO_2 during growth)	~1.7 – 3.0	Bamboo is carbon-negative; steel is carbon-intensive.
Renewability	3–5 years to maturity	Non-renewable, mining-based	Bamboo regenerates quickly.
Durability	Needs treatment (susceptible to moisture, termites, fungi)	Highly durable, long service life	Bamboo requires chemical/physical treatment for longevity.
Cost (per kg)	~₹20–40 (varies with treatment & region)	~₹60–80 (depending on grade & market price)	Bamboo is more cost-effective, primarily when locally sourced.

7.3. Protective Coatings (For Bamboo):

Bituminous or epoxy coatings may be applied on bamboo surfaces to enhance bonding with concrete and reduce water absorption.

8. Methodology:

8.1. MIX DESIGEN:

This procedure produces concrete with the appropriate compressive strength for the intended usage, utilizing the most cost-effective and valuable combination of materials. Trial mixes and changes were made as part of the procedure to try to achieve the appropriate balance between workability and strength. It was done under IS 10262:2019.

8.1.1. Mix Design for M25 Grade of Concrete

Concrete mix design for M 25 grade concrete
Type of cement used: OPC 43 grade cement conforming to IS 8112:1989.
Maximum nominal size of aggregate: 12.5 mm.
Exposure condition: Moderate (Table 3 IS 456:2000).
Workability: 75 mm (Slump).
Method of concrete placing: Manual.
Degree of supervision: Good.
Type of aggregate used: Crushed angular aggregate.
Maximum cement content: 450 kg / m^3.

8.1.2. Material Properties

Specific gravity of cement: 3.12
Specific gravity of coarse aggregate: 2.73
Specific gravity of fine aggregate: 2.66
Water absorption of coarse aggregate: 0.40 %
Water absorption of fine aggregate: 1 %
Moisture content of fine and coarse aggregate: Nil

Target Strength

As per IS 10262: 2019 Tables 1 and 2 of page 3

$f'_{ck} = f_{ck}$+1.65 S

or

$f'_{ck} = f_{ck}$ + X

$f'_{ck} = f_{ck}$ +1.65 S

= 25 +1.65 × 4.0

= 31.60 N/mm2

$f'_{ck} = fck$ + 5.5 (The value of X for M 25 grade as per Table 1 is 5.5 N/mm^2) = 25+5.5 = **30.5 N/mm^2**

The higher value is to be adopted. Selection of the water-cement materials ratio

IS 10262: 2019, the water-cement materials ratio required for the target strength of 31.60 N/mm^2 is 0.47 for a maximum size of aggregate of 12.5 mm.

Selection of water content

From IS 10262: 2019, water content for 12.5 mm aggregate = **186 kg/m^3** (for 50 mm slump).

Estimated water content for 75 mm slump = 186 + (3/100) X 186 = **191.58 kg/m^3**

Calculation of cement content

Water–cement ratio = **0.47**

Water content = 171 kg/m^3

Cement content = 171 / 0.47 = **364 kg/m^3**

Check for minimum cementitious materials content,

364 kg/m^3 < 450 kg/m^3. Hence OK

Proportion of volume of coarse aggregate and fine aggregate content

From IS 10262: 2019, the volume of coarse aggregate corresponding to 20 mm size aggregate and fine aggregate grading Zone II = 0.62 per unit volume of total aggregate.

Adjustment in the proportion of volume of coarse aggregate due to w/c ratio = 0.01

Volume of fine aggregate content = 1 – 0.63 = 0.37 per unit volume of total aggregate

Mix calculations

Total volume = 1 m3

Volume of cement = $\frac{\text{Mass of cement / Specific gravity of cement) x 1}}{1000}$

= (364 / 3.12) x 1 / 1000 = **0.117 m^3**

Volume of water = $\frac{\text{Mass of Water / Specific gravity of Water) x 1}}{1000}$

= (164 / 1) x 1 / 1000 = **0.164 m^3**

Volume of all in aggregate = [(1 – (0.117+0.164)] = 0.719 m^3

Mass of coarse aggregate = h × Volume of coarse aggregate × Specific gravity of coarse aggregate × 1000

= 0.719 × 0.63 × 2.73 × 1000 = **1236 kg**

Mass of fine aggregate = h × volume of fine aggregate × Specific gravity of fine aggregate × 1000

= 0.719 × 0.37 × 2.66 × 1000 = **708 kg**

Mix proportion

Cement - 364 kg

M Sand - 708 kg
Coarse aggregate - 1236 kg consists of 742 kg of 12.5 mm and
494 kg of 10 mm coarse aggregates
Water - 171 kg
Table 2 gives the mix proposition of the concrete used in this research.

Table 2 Mix Proposition

Mix	**W/C Ratio**	**Cement**	**Fine Aggregate**	**Coarse Aggregate**	
				12.5 mm	**10 mm**
Ratio	0.47	1	1.95	2.03	1.36

8.2. Test on Cement

Commercially available Ordinary Portland Cement (OPC) of 43 grades, confirming IS 8112-1989 standard specification, was procured from the local market with ISI mark, for this research. The cement samples were subjected to laboratory tests as per IS 4031-1988 (Part 2, 3, 4, 5 & 6) to understand the properties before using them for this study. The significant properties of the cement are provided in the Table. 3

Table 3: Physical Properties of Cement

S. No.	**Types of Test**	**Experimental Values**	**Standards as per IS 8112:1989**
1	Fineness (m^2/kg)	230	Not less than 225
2	Specific Gravity	3.12	-
3	Standard Consistency (%)	31	-
4	Initial Setting Time (Minutes)	53	Not less than 30
5	Final Setting Time (Minutes)	315	Not more than 600
6	Soundness (mm) (by Le Chatelier method)	2	Not more than 10
7	Compressive Strength at 7 days (N/mm^2)	33.45	Not less than 33
8	Compressive Strength at 28 days (N/mm^2)	53.60	Not less than 43

8.3. Tests on Fine Aggregates

Screened sand from locally available dealers was used as fine aggregate. The selected sample of M Sand was tested as per IS 383-2016 and IS 2386-1986 to confirm its suitability as a good concreting material. Deleterious materials, if any, were screened before using it for concreting purposes. The properties of fine aggregate have been given in Table 4.

Table 4: Physical Properties of Fine Aggregate

S. No.	Properties Tested	Experimental Values	IS Code Followed
1	Fineness modulus of Fine Aggregate	2.86	IS: 383-1970
2	Water Absorption	0.8 %	-
3	Bulk Density	1865 kg/m³	IS: 2386 Part 3-1963
4	Specific Gravity	2.66	IS: 2386 Part 3-1963
5	Bulking of Sand	2 %	-
6	Grading Zone	Zone II	-

8.4. Tests on Coarse Aggregates

Coarse aggregates of basaltic origin have been selected with a maximum size of 12.5 mm and a minimum size of 10 mm from a nearby stone crusher. The aggregates were used under Saturated Surface Dry conditions to avoid the effect of moisture content on the quality of concrete. This study was done to determine the basic properties of aggregates to be used in concrete. Table 5 enlists the characteristics of the coarse aggregate.

Table 5: Physical Properties of Coarse Aggregate

Properties	12.5 mm Aggregate	10 mm Aggregate	IS Code Followed
Shape	Angular	Angular	IS: 2386 Part 1-1963
Water Absorption (%)	0.40	0.50	-
Fineness Modulus by Dry Sieving	6.654	6.320	IS: 2386 Part 3-1963
Bulk Density (kg/m³)	1630	1710	IS: 2386 Part 3-1963
Specific Gravity	2.73	2.82	IS: 2386 Part 3-1963

8.5. Mass density of bamboo:

This test was conducted following IS 6874:2008 to determine the unit weight of bamboo, both treated and untreated. The weight of the test specimen was measured using a Shimadzu AUX 220 weighing machine with an accuracy of 0.1 mg. The green volume of the bamboo was calculated according to the procedure outlined in IS 6874:2008, using the same Shimadzu AUX 220 balance. The bamboo sample was then oven-dried, and its unit weight was calculated. The unit weight of mild steel is 7850 kg/m³, while the density of raw untreated bamboo was approximately 862 kg/m³.

Table 6: Mass density

S. No.	Reinforcing Materials Used	Density, ρ (kg/m³)
1	Steel rod of 8 mm diameter	7850
2	Natural Bamboo	862

8.6. Details of Concrete Specimen

For the compression test on a concrete cube, the size of the cube is 150 mm x 150 mm x 150 mm. For the flexure test, slabs measuring 600 mm x 450 mm x 50 mm were used, and for the bond strength test, concrete cylinders with a diameter of 150 mm and a height of 300 mm embedded with bamboo (both treated and untreated) were cast. This research proposes M25 grade concrete and designs the material proportions needed to achieve its characteristic strength. Based on the mix proportions listed in the table, various mixtures were prepared and tested on both fresh and hardened concrete at different curing ages. Concrete cubes measuring 150 mm x 150 mm x 150 mm were cast to determine compressive strength per IS 516-1959. Cylinder specimens with embedded reinforcement, such as steel, untreated bamboo splints, and treated bamboo splints, were cast to assess the bond strength between the reinforcement and the concrete interface. Slabs measuring 600 mm x 450 mm x 50 mm were cast with steel and bamboo (both untreated and treated) reinforcements to compare their behavior through flexure tests under static and cyclic loading conditions.

9. Result

9.1. Tension test on steel rod

This test was aimed at determining the tensile strength of 8 mm diameter steel bars of grade Fe415 by using a Universal Testing Machine of capacity 10 Tons. The IS 1608:2005 codal recommendations for the conduct of tension test on steel rod were followed. The results of the tension test on steel bars are given in Table 6.

Table 7: Tension Test on steel rod

Sl. No.	Mechanical Properties	Results
1	Unit Weight	0.632 kg/m
2	Young's Modulus, E_{steel}	2.3×10^5 N/mm²
3	Yield Strength, σ_γ	415 N/mm²
4	Ultimate Tensile Strength	479 N/mm²
5	Percentage of Elongation	22 %

9.2. Tension test on natural bamboo without a node

The selected bamboo was cut into splints for tension tests. The inner and outer curves were not altered because the splints were made to maintain a consistent width throughout. To prevent slipping at the tabs at the ends or grips of the tension testing machine, the cross-sectional area of the sample was kept small. Bamboo culms were used to create the test specimens. Bamboo splints were sliced from the whole bamboo lengthwise, with each splint measuring 450 mm in length. Tensile strength tests were conducted on these splints according to IS 6874:2008. When chiseling a rectangular specimen from split bamboo, it is necessary to remove the dense fiber region, which results in significantly lower tensile strength values. The elongation of the bamboo rod was measured over a gauge length of 60 mm.

Table 8: Tension Test on natural bamboo without a node

Axial Load, P (kN)	Elongation, δl (mm)	Stress, σ (N/mm²)	Strain, $\varepsilon \times 10^{-2}$
0	0.000	0	0.00
0.5	0.023	6	0.04
1.0	0.033	12	0.07
1.5	0.053	16	0.09
2.0	0.067	22	0.13
4.0	0.083	42	0.16
6.0	0.125	63	0.26

8.0	0.184	82	0.37
10.0	0.240	101	0.45
12.0	0.290	124	0.58
14.0	0.342	144	0.67
16.0	0.390	163	0.75
18.0	0.450	185	0.85
18.75	0.540	189.5	0.94

9.3. Water absorption test on bamboo

Bamboo is currently being studied for its potential use in the construction industry as a replacement for steel reinforcements. As a naturally available fibrous material, it tends to absorb water when exposed to moisture. Therefore, a detailed study on bamboo's water absorption properties was conducted on both untreated and treated surfaces. The effectiveness of the proposed treatment in reducing water absorption was also evaluated. When used as reinforcement, bamboo, which is a woody material, absorbs water from the surrounding concrete and swells, causing cracks in the concrete before gaining strength during the curing period. The interaction between bamboo and concrete is negatively affected when bamboo is treated to prevent water absorption. The study focused more on inexpensive treatments since it aims at low-cost housing; more costly treatments discourage the use of bamboo as reinforcement. Hourly observations were recorded on the first day, followed by readings every 24 hours for the next seven days. Changes in the dimensions of bamboo specimens were observed and compared as a result of water absorption. Results of the dimensional changes in natural bamboo splints are displayed in Table 9.

Table 9: Water absorption test on bamboo.

Duration in days	Length (mm)	Breadth (mm)	Thickness (mm)	% Change in Length	% Change in Breadth	% Change in Thickness	% Change in Volume
1	600.0	10.00	10.00	0.00	0.00	0.00	0.00
2	601.2	10.04	10.04	0.20	0.40	0.40	0.03
3	601.4	10.05	10.05	0.23	0.50	0.50	0.06
4	601.6	10.05	10.05	0.27	0.50	0.50	0.07
5	601.8	10.06	10.06	0.30	0.60	0.60	0.11
6	601.8	10.06	10.06	0.30	0.60	0.60	0.11
7	602.0	10.07	10.07	0.33	0.70	0.70	0.16

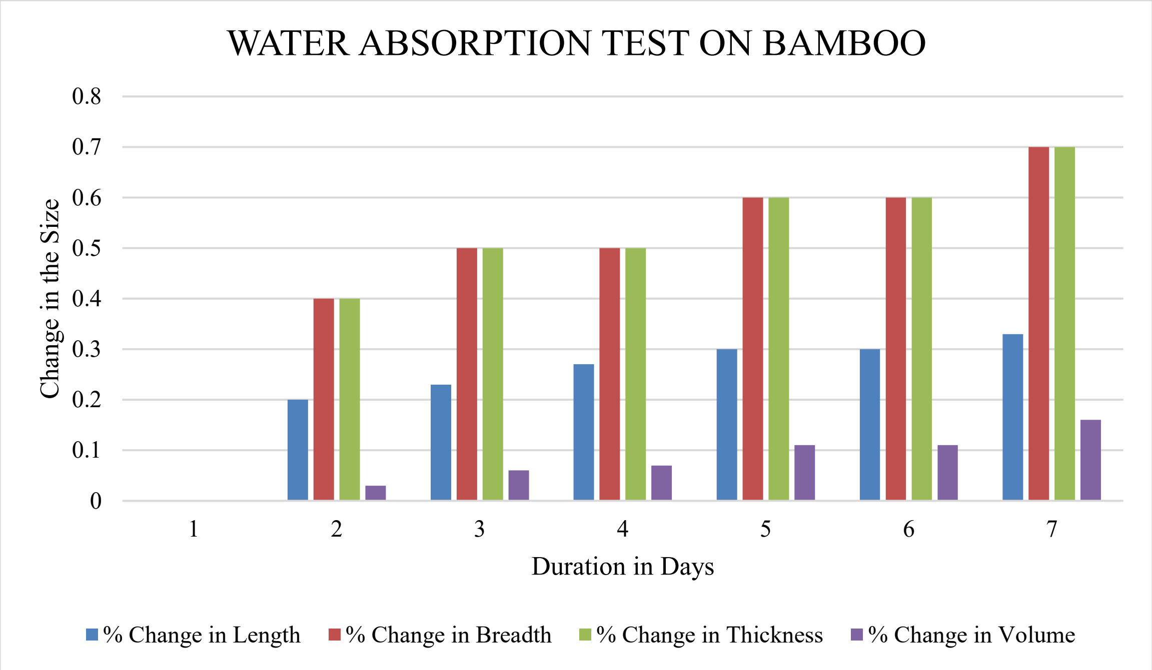

Figure 2: Water absorption test on bamboo

9.4. Pull Out Test

The behavior of reinforced concrete composite depends mainly on the bonding force established between the surface of Bamboo and the interface of concrete with Bamboo. Hence, a pull-out test was conducted on the cylindrical specimen cast using M25 grade concrete, implanted with a steel rod, untreated and treated Bamboo.

For casting 300 mm high and 150 mm diameter cylinders, the concrete used had a mix ratio of 1 (cement): 1.95 (fine aggregate): 2.03 (12.5 mm CA): 1.36 (10 mm CA), combined to produce a uniform mixture at a 0.47 w/c ratio. Specimens from the inter-nodal zone, including the node, were selected for this test. Bamboo splints, 10 mm square cross-section and 750 mm long as required by UTM, were coated with the proposed types of coatings and left to dry in air at room temperature. Water absorption test results served as a reference for specimen preparation and handling. The bamboo was carefully inserted into well-greased cylinder molds, and the concrete mixture was poured, ensuring the bamboo splints were positioned concentrically. The bamboo was embedded 200 mm into the concrete from the free surface. After 24 hours, the cast cylindrical specimens for the bond strength test were demolded and cured in a water bath for 28 days. The designation of each variety of Bamboo splints used in this bond strength test and flexure test is shown in Table 10.

Table 10: Pull Out Test

Specimen	Embedment length (mm)	Pull-out load at failure (kN)	Bond strength (MPa)
RCS	200	58.3	7.29
BRS	200	34.1	4.26

Any reinforcement in a concrete composite must have adequate bonding with the surface of the reinforcement. In this research, the bond strength of treated bamboo splints was compared with that of untreated bamboo and conventional steel reinforcement. It illustrates the bond failure and tensile failure experienced by the reinforcements used in this study. The load-deflection curve shows an elastic and linear increase before failing in tension. Linear behavior persisted until slippage occurred, after which a plateau-like region appeared on the load-displacement plot. The reinforcing bar separated from the concrete due to bond failure, resulting in a decrease in the load-deflection pattern. The bamboo-reinforced specimens in this study failed because of bond failure. However, splitting failure was not considered. Higher bond strength was observed in the RCS with steel reinforcement, which also showed no slippage or bond failure. The failure was purely tensile and closely related to the tensile-bond failure curve.

9.5. Flexural Strength:

Using reinforcements in concrete structural elements helps absorb the tensile or flexural loads they experience. This research also studies the flexural behavior of concrete slab panels reinforced with untreated and treated bamboo, comparing them with RCS and PCS. The step-by-step procedure for conducting the flexural strength test is explained, and the results are discussed.

A conventional steel-reinforced slab was constructed using 8mm diameter Fe415 rods, while a Bamboo-reinforced slab was cast with 10mm square cross-section Bamboo splints with nodes. For steel-reinforced slabs, eight 8mm diameter rods were placed in the shorter direction, and six in the longer direction. In contrast, for Bamboo-reinforced slabs, 10mm square cross-section splints were provided, with six in each direction. According to IS 456:2000 recommendations, the minimum steel reinforcement for slabs should be no less than 0.12% of the gross area of the slab. The steel area used was 402mm², meeting the minimum requirement specified by IS 456:2000, and the Bamboo area was 49% greater than the steel amount. Given Bamboo's very low weight-to-density ratio, using 49% of its excess area over the steel bars was considered acceptable.

Table 11: Results of Static load test on slabs and corresponding deflections

Mix	First Crack		Ultimate Crack		Ultimate to first crack load ratio	Ultimate to first crack deflection ratio	Energy absorption (J)
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)			
PCS	37.4	2.24	39.84	2.52	1.07	1.13	58.81
RCS	50.61	1.98	71.95	9.21	1.42	4.65	381.03
BCS	37.35	2.99	52.19	5.13	1.40	1.40	153.95

The materials used in treating bamboo and their combinations showed better performance than raw bamboo reinforcement. Under vertical static load, the first crack appeared at 37.40 kN for plain cement concrete, with a deflection of 2.24 mm. Since it lacked reinforcement to provide flexibility, the PCS failed quickly at 39.84 kN with a deflection of 2.52 mm. The initial and ultimate load-carrying capacities of PCS were very low. The first crack occurred at 37.40 kN with a deflection of 2.24 mm measured behind the loading point at mid-span. The slab failed at 39.84 kN, but the deflection did not increase further. It failed in a brittle manner with a deflection of 2.52 mm, as it was made solely of aggregates and binder. Due to the absence of reinforcement to enable flexural behavior, the deflection remained very low. When steel reinforcement was used, the RCS slab demonstrated excellent load-carrying capacity at both the first crack and ultimate crack points. The deflection at the ultimate load was 9.21 mm, with a load of 71.95 kN causing this deflection. RCS showed approximately an 80.60% increase in load capacity compared to PCS. The energy absorbed by the steel-reinforced concrete slab was 381.03 J. An alternative reinforcement material, bamboo, was studied for concrete structural elements. The selected bamboo was surface-treated to enhance its mechanical properties and behavior under static and cyclic loads. The untreated bamboo-reinforced slab, BRS, was subjected to static load testing. The load and corresponding deflection at both the first and ultimate cracks were measured at mid-span. The ultimate load reached 52.19 kN, with a central deflection of 5.13 mm. The load-carrying capacity increased by 31% over PCS and was 72.54% of RCS's capacity. The total energy absorbed by BRS was 153.95 J.

9.6. Comparison of cost: steel vs. Bamboo reinforcement:

Reinforced concrete is a widely used material in construction, offering strength, durability, and versatility. Traditionally reinforced with steel bars for tensile resistance, steel has drawbacks like high costs, energy use, corrosion, and a large carbon footprint, conflicting with sustainable goals. Bamboo has emerged as a promising alternative due to its comparable tensile strength, high flexural capacity, and excellent strength-to-weight ratio—ideal for lightweight, disaster-resistant housing. Its rapid growth, renewability, and carbon sequestration add environmental benefits. Properly treated bamboo improves durability and bonds with concrete, overcoming natural limitations. Studies show bamboo-reinforced concrete (BRC) can achieve adequate load capacity and ductility, suitable for affordable housing, rural projects, and disaster shelters. It also reduces costs due to local availability and easier handling than steel. This combination of sustainability and affordability makes bamboo a viable alternative, supporting low-carbon, resource-efficient, and resilient construction.

Table 12: Comparison of cost: steel vs. Bamboo reinforcement

Parameter	Steel Reinforcement (Fe-415, 8–10 mm rods)	Bamboo Reinforcement (Treated Splints)	Remarks
Material Cost (₹/kg)	60 – 80	20 – 40	Bamboo is 50–70% cheaper
Density (kg/m³)	~7850	600 – 900	Bamboo is much lighter → reduces transport & dead load
Cost per Running Meter (₹)	50 – 70	15 – 25	Bamboo splints cut & treated locally
Processing/Treatment Cost (₹/kg)	Negligible (factory processed)	5 – 10 (boron/bitumen/epoxy treatment)	Still far below steel

Transportation & Handling	High (requires cranes/trucks, heavy load)	Low (manual handling possible)	Cost-saving in rural projects
Maintenance Cost	High (regular anti-corrosion coating, rust protection)	Low (only periodic surface protection)	Bamboo is durable if treated
Service Life	50+ years (with protection)	25–40 years (with treatment)	Suitable for low-rise & semi-permanent structures
Overall Cost Advantage	Baseline (100%)	40–60% cheaper	Depends on treatment & project scale

9.7. PRACTICAL IMPLICATIONS FOR LOW-RISE CONSTRUCTION

This research shows bamboo-reinforced slabs and beams are suitable for low-rise construction, with ~72.5% the load capacity of steel. Bamboo's lower bond strength isn't a limiting factor when properly treated, and its lighter weight reduces foundation load, especially on weak soils. Bamboo reinforcement cuts costs by 55–65%, making it ideal for low-income housing, particularly in developing countries, as it can be processed with low-cost techniques and easily handled manually. Its strength-to-weight ratio benefits disaster-resistant and temporary housing, like cyclone shelters, flood-resistant homes, and modular structures, enabling quick, cost-effective, resilient construction. Overall, bamboo offers a practical, eco-friendly alternative to steel, promoting sustainable, affordable, and resilient low-rise buildings in rural and disaster-prone areas. Incorporating bamboo into design standards and building codes could encourage widespread adoption, enhancing social welfare and environmental sustainability.

10. Discussion:

The experimental investigation demonstrates the potential of bamboo as an alternative reinforcement material in concrete, particularly for low-rise and cost-sensitive construction. The results of the mechanical, bond, and flexural strength tests provide valuable insights into the comparative performance of bamboo- and steel-reinforced concrete slabs.

TENSILE PROPERTIES

- The tensile strength of **mild steel bars** (Fe-415, 8 mm diameter) was measured at **479 N/mm²**, with a yield strength of **415 N/mm²**.
- In comparison, **bamboo splints** recorded tensile strengths in the range of **140–280 MPa**, with some species (e.g., *Dendrocalamus asper*) reaching up to **370 MPa**.
- Although bamboo's tensile strength is lower than steel, its **strength-to-weight ratio is significantly higher** because bamboo's density (~862 kg/m³) is about **1/9th of steel (~7850 kg/m³)**.

BOND STRENGTH WITH CONCRETE

- In pull-out tests, the **bond strength of steel** reinforcement was **7.29 MPa** at a failure load of **58.3 kN**.
- For **treated bamboo splints**, bond strength reached **4.26 MPa** at a failure load of **34.1 kN**, which is about **58% of steel's value**.
- Surface treatments such as **bitumen or epoxy coating** improved bamboo–concrete adhesion, minimizing slippage and dimensional instability due to moisture.

FLEXURAL STRENGTH OF SLABS

- **Steel-reinforced concrete slabs (RCS)** achieved an ultimate load of **71.95 kN**, with a maximum deflection of **9.21 mm**.
- **Bamboo-reinforced concrete slabs (BRS)** recorded an ultimate load of **52.19 kN** with a deflection of **5.13 mm**, corresponding to **~72.5% of the load-carrying capacity of RCS**.
- Energy absorption capacity for RCS was **381.03 J**, while BRS reached **153.95 J**, which is **40% of steel-reinforced slabs** but much higher than plain concrete slabs (58.81 J).

WATER ABSORPTION & DURABILITY

- Untreated bamboo showed water absorption exceeding **50% of its dry weight** in 7 days, leading to swelling and cracking in the concrete interface.
- Treated bamboo (boron + bitumen coating) reduced water absorption by **70–80%**, significantly improving dimensional stability and long-term bond with concrete.

ECONOMIC COMPARISON

- The cost of steel reinforcement was calculated at **₹60–80/kg**, while bamboo reinforcement costs **₹20–40/kg**, plus **₹5–10/kg for treatment**.
- For a typical low-rise slab requiring ~100 kg of reinforcement, the cost of steel would be **₹7,000–8,000**, compared to **₹2,500–3,500 for bamboo**, a **~55–65% reduction**.
- Considering transport and handling, bamboo further reduces costs since it can be manually cut, carried, and assembled without heavy machinery.

ENVIRONMENTAL IMPACT

- Steel production emits approximately **1.85 tons of CO_2 per ton**, contributing nearly **7–9% of global GHG emissions**.
- In contrast, bamboo sequesters up to **50–60 tons of CO_2 per hectare per year**, making it a **carbon-negative material** during growth.
- Life-cycle assessment suggests that substituting steel with bamboo in low-rise housing could cut embodied carbon in reinforcement by **70–80%**.

PRACTICAL RELEVANCE FOR LOW-RISE BUILDINGS

- Bamboo-reinforced slabs reached 72.5% of steel's capacity, which is structurally sufficient for 1–3 story structures.
- Bamboo's lower dead load helps in weak soil regions.
- Cost savings (55–65%) make it ideal for affordable housing and rural projects.

The study shows bamboo reinforcement offers 60–75% of steel's performance at less than half the cost, making it a cost-effective alternative. Proper treatments like boron salt, bitumen, or epoxy enhance its bond and durability, suitable for low-rise concrete slabs, beams, and housing. Besides mechanical benefits, bamboo's rapid renewability and carbon sequestration add environmental advantages, positioning it as a sustainable, low-carbon material. These benefits support affordable housing, rural infrastructure, and disaster-resistant structures, especially where cost, resource efficiency, and resilience are vital.

11. Conclusion

This study concludes that bamboo reinforcement can achieve 60–75% of the structural performance of steel while reducing costs by 55–65%. Treated bamboo demonstrated adequate bond strength (4.26 MPa), flexural capacity (52.19 kN), and tensile resistance (up to 370 MPa), making it suitable for low-rise structures. Its lightweight nature (862 kg/m³ vs. 7850 kg/m³ for steel) further reduces handling and construction costs. Environmentally, bamboo is carbon-negative, sequestering 50–60 tons of CO_2 per hectare annually, compared to steel production's 1.85 tons of CO_2 per ton emission. These combined benefits establish bamboo as a sustainable, economical, and resilient alternative for affordable housing, rural infrastructure, and disaster-resistant construction.

- The present study establishes bamboo as a viable, cost-effective, and eco-friendly alternative to conventional steel reinforcement in low-rise concrete structures. Experimental results revealed that steel-reinforced slabs (RCS) achieved an ultimate load of 71.95 kN with a maximum deflection of 9.21 mm. In contrast, bamboo-reinforced slabs (BRS) with treated splints sustained an ultimate load of 52.19 kN and a deflection of 5.13 mm, corresponding to about 72.5% of the load-carrying capacity of steel-reinforced slabs.
- Bond strength tests further highlighted that steel achieved 7.29 MPa at a failure load of 58.3 kN, while treated bamboo recorded 4.26 MPa at 34.1 kN, equal to 58% of the bond strength of steel. Tensile strength measurements showed mild steel reaching 479 N/mm², compared to bamboo's range of 140–280 MPa, with particular species achieving up to 370 MPa, demonstrating that although bamboo's absolute tensile strength is lower, its strength-to-weight ratio is nearly six times higher due to its density of only 862 kg/m³ compared to steel's 7850 kg/m³.
- From an economic perspective, steel reinforcement costs ₹60–80/kg, leading to a total reinforcement expense of around ₹7,000–8,000 for a typical slab, while bamboo reinforcement, including treatment costs, is ₹25–50/kg, reducing the total cost to ₹2,500–3,500, representing a 55–65% saving. Environmentally, steel production emits approximately 1.85 tons of CO_2 per ton, contributing nearly 7–9% of global greenhouse gas emissions, whereas bamboo plantations sequester 50–60 tons of CO_2 per hectare annually, making bamboo a carbon-negative material.
- These results collectively prove that bamboo can deliver 60–75% of the structural performance of steel at less than half the cost, while simultaneously offering unmatched sustainability benefits, making it particularly suitable for affordable housing, rural infrastructure, and disaster-resistant construction in developing regions

Given that low-rise buildings generally experience lower structural demands than high-rise structures, the findings of this study are particularly applicable to the design of affordable housing, rural infrastructure, and disaster-resistant shelters. This positions bamboo as a practical reinforcement solution for sustainable low-rise construction

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