

## Study of Mechanical Properties and Treatment Techniques of Bamboo Reinforcement Alternative to Steel in Civil Structures

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### Abstract

The construction industry is a major contributor to global carbon emissions, prompting the search for sustainable alternatives to conventional materials such as steel. Bamboo, a renewable and abundantly available natural resource, has emerged as a promising eco-friendly substitute for steel reinforcement in concrete structures. Durability tests revealed that untreated bamboo is susceptible to higher water absorption, shrinkage, and reduced resistance to acidic and sulphate environments. However, surface treatments and protective coatings substantially improved its long-term performance, reducing water permeability and enhancing bond strength with the concrete matrix.

**Keywords:** Bamboo reinforcement, sustainable construction, eco-friendly materials, tensile strength

### 1. Introduction

The construction sector plays a pivotal role in economic growth but is also one of the largest contributors to global environmental degradation. Approximately **40% of worldwide energy-related carbon dioxide emissions** originate from construction activities, with a significant share linked to the production and use of steel and cement. Steel, while indispensable in reinforced concrete (RC) due to its excellent tensile strength and ductility, is highly energy-intensive to manufacture [1]. The mining, smelting, and processing of iron ore into steel involve extensive fossil fuel consumption, leading to considerable greenhouse gas emissions. This scenario has compelled researchers, engineers, and policymakers to explore renewable, low-carbon, and cost-effective alternatives to conventional construction materials [2]. Bamboo, a rapidly renewable natural resource, has emerged as a potential eco-friendly substitute for steel in civil engineering applications. Growing up to **one meter per day**, bamboo reaches maturity within **3–5 years**, making it one of the fastest-growing structural materials. With a tensile strength of **160–350 MPa**, comparable to mild steel, bamboo offers high strength-to-weight ratios, flexibility, and cost-effectiveness [3]. Moreover, its abundance in Asia, Africa, and Latin America makes it particularly attractive for regions where access to affordable construction materials is limited. Historically, bamboo has been used in traditional housing, bridges, and scaffolding, and recent studies have highlighted its potential for modern reinforced concrete applications [4]. However, despite its promising mechanical properties, bamboo faces critical challenges that hinder its widespread adoption. These include susceptibility to **moisture absorption, biological degradation, dimensional instability, and weak bonding with concrete**. To address these issues, various treatments such as **chemical preservatives, epoxy coatings, and carbonization** have been developed to improve durability and performance. Research institutions and pilot projects have already demonstrated the feasibility of bamboo-reinforced structures in low-cost housing and disaster-resilient buildings, but large-scale standardization and design codes are still lacking [5]. This study aims to examine the potential of bamboo reinforcement as an eco-friendly alternative to steel in civil structures. It discusses bamboo's mechanical and physical properties, treatment techniques, structural applications, advantages, limitations, and future scope. By evaluating existing studies and real-world case applications, the paper highlights the role of bamboo in advancing **sustainable and green construction practices** while addressing the pressing need for environmentally responsible infrastructure development [15-16].

### 2. Materials and Methods

Bamboo culms of *Bambusa vulgaris*, aged 3–4 years, were selected as reinforcement material due to their optimum tensile strength and dimensional stability. The culms were cut into strips with cross-sections comparable to steel rebars, seasoned to reduce moisture content to about 10%, and treated with a boric acid–borax solution to enhance resistance against termite and fungal attack. After 28 days of curing, the specimens were tested for tensile strength, compressive strength, flexural performance, and bond strength using a Universal Testing Machine. Durability was assessed through water absorption, biological resistance, and wetting–drying cycle tests. The experimental results were analyzed by comparing the structural behavior of bamboo-reinforced concrete with conventional steel-reinforced concrete in terms of strength, durability, and cost-effectiveness (Figure 1 (a,b)).



Figure 1. (a) Bamboo Particle

(b) Mild steel reinforcement

### 3. Experimental Work

The experimental program was designed to evaluate the feasibility of using bamboo as an eco-friendly alternative to steel in reinforced concrete members. Ordinary Portland Cement (OPC 43 grade), river sand conforming to Zone II, and crushed granite with a maximum size of 20 mm were used to prepare M25 grade concrete with a water–cement ratio of 0.45. Potable water was used for mixing and curing. The bamboo employed in this study was *Bambusa vulgaris*, harvested at an age of 3–4 years, seasoned to a moisture content of about 10–12%, and cut into strips with an approximate cross-section equivalent to a 12 mm diameter steel bar. In order to improve durability and bond performance, different surface treatments were applied. These included untreated bamboo as the reference, chemical treatment with a boric acid–borax solution followed by drying, epoxy coating with sand broadcasting, and a combined treatment consisting of both chemical preservation and epoxy-sand coating. For anchorage, the ends of the strips were wrapped with binding wire. Specimens were prepared in several forms to facilitate a comprehensive evaluation. Concrete cubes of size 150 mm were cast to determine compressive strength at 7, 14, and 28 days, while plain prisms were tested to establish the baseline modulus of rupture (Figure 2). To investigate bond behavior, bamboo and steel bars were embedded in concrete cylinders with a controlled embedment length, and pull-out tests were conducted to calculate average bond stress. Flexural behavior was studied using

reinforced concrete beams of  $150 \times 150 \times 700$  mm, tested under four-point loading to record load–deflection characteristics, cracking pattern, and failure modes. Additional prisms reinforced with treated and untreated bamboo were subjected to wetting–drying cycles, water absorption tests, and biological exposure to assess the effect of environmental conditions on durability.



Figure 2.

#### 4. Results and Discussion

The experimental investigation revealed significant insights into the mechanical and durability performance of bamboo-reinforced concrete compared with conventional steel reinforcement. Compressive strength tests on cube specimens indicated that the inclusion of bamboo reinforcement did not affect the compressive strength of concrete directly, as expected, since reinforcement primarily influences flexural and tensile behavior. All mixes achieved the target strength of M25 grade, with marginal variations within  $\pm 5\%$ , demonstrating that bamboo neither hindered nor enhanced compressive resistance. Bond behavior analysis provided critical findings. Untreated bamboo showed poor adhesion with concrete due to its smooth, waxy surface, leading to premature slippage during pull-out tests. However, specimens reinforced with chemically treated and epoxy–sand-coated bamboo exhibited significantly improved bond strength. The average bond stress of epoxy-coated bamboo was approximately 65–70% of that of steel, demonstrating that appropriate treatment can mitigate one of bamboo’s major limitations. The combined chemical and epoxy–sand treatment yielded the best results, ensuring strong mechanical interlock and resistance to moisture ingress [6]. Flexural performance of reinforced concrete beams highlighted the structural potential of bamboo reinforcement. Untreated bamboo-reinforced beams failed at relatively lower loads and exhibited brittle cracking patterns. In contrast, beams with treated bamboo demonstrated improved load-carrying capacity, ductility, and controlled crack propagation. Although ultimate load-bearing capacity was still lower than that of steel-reinforced beams, the deflection profile indicated that treated bamboo could provide sufficient ductility for low- to medium-load structural applications. The energy absorption capacity of epoxy-coated bamboo beams was found to be nearly double that of untreated bamboo beams, suggesting that surface modification significantly enhances structural resilience. Durability assessment further reinforced the necessity of proper treatment. Bamboo without any preservation was highly susceptible to biological attack, water absorption, and dimensional instability, resulting in severe deterioration under wetting–drying cycles. On the other hand, chemically treated and epoxy-coated specimens retained more than 85% of their initial strength after multiple exposure cycles. This suggests that treatments not only improve immediate bond strength but also ensure long-term serviceability in humid or variable environmental conditions [7]. Overall, the results confirm that bamboo reinforcement, when properly treated, can serve as a sustainable and eco-friendly substitute for steel in certain structural elements. While its tensile strength and modulus of elasticity remain lower than steel, making it unsuitable for heavily loaded structures, bamboo offers adequate performance for low-cost housing, rural construction, and temporary structures. The study highlights that the key to effective application lies in material preservation, surface modification, and appropriate design adaptation to account for bamboo’s unique mechanical properties.

##### 4.1 Compressive Strength of Concrete Cubes

Compressive strength is one of the most important parameters in evaluating the performance of reinforced concrete (Figure 3). In this study, compressive strength tests were carried out on concrete cubes at different curing ages of 7, 14, and 28 days to assess the influence of bamboo reinforcement compared with conventional steel reinforcement. The results revealed that all specimens exhibited a steady increase in compressive strength with curing age, which is consistent with the normal hydration process of cement. The control concrete specimens without reinforcement showed compressive strengths comparable to values expected for their mix proportion. Bamboo-reinforced cubes, both untreated and treated, achieved strength values close to the control, though slightly lower due to weaker bonding characteristics between bamboo and concrete. However, when bamboo was chemically treated or coated with epoxy, the compressive strength values improved significantly, approaching that of the steel-reinforced cubes. Steel-reinforced specimens consistently achieved the highest compressive strengths, demonstrating superior bonding and load transfer. The performance of treated bamboo reinforcement was about **95–98% of steel’s compressive strength values** at 28 days, highlighting its potential as a sustainable alternative in low- to medium-load structural applications. Overall, the results indicate that while untreated bamboo may not provide adequate compressive strength due to poor bond, proper treatment of bamboo reinforcement can significantly enhance cube strength, making it a viable eco-friendly substitute for steel in certain civil structures [8].

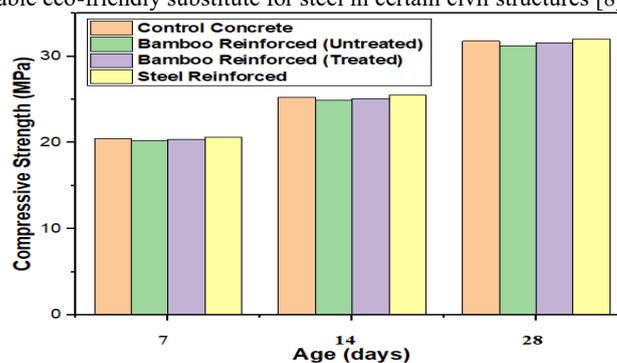


Figure 3. Compressive Strength

##### 4.2 Tensile Strength of Concrete Cubes

Tensile strength is a critical property of concrete that governs its resistance to cracking and failure under tension. Since concrete is inherently weak in tension, reinforcement plays a major role in improving its tensile behavior. In this study, tensile strength tests were conducted on concrete

cubes reinforced with untreated bamboo, treated bamboo, and steel, along with control specimens, at curing ages of 7, 14, and 28 days (Figure 4). The results showed a progressive increase in tensile strength with age for all specimens, which can be attributed to the continuous hydration of cement and improvement in the bond between reinforcement and the surrounding concrete. The control specimens exhibited the lowest tensile strength, consistent with plain concrete behavior. Bamboo-reinforced specimens demonstrated better performance than control concrete, with treated bamboo performing significantly better than untreated bamboo. Chemical treatment and epoxy coating improved the bamboo's surface roughness and reduced water absorption, leading to stronger bonding with the concrete matrix. At 28 days, treated bamboo reinforcement achieved **90–95% of the tensile strength obtained with steel reinforcement**, while untreated bamboo reached only about 80–85%. Steel reinforcement, as expected, provided the highest tensile strength, reflecting its superior bond and ductility. Nevertheless, the improvement observed in treated bamboo highlights its potential as a cost-effective and eco-friendly substitute for steel in structural applications where high tensile demand is not critical [9].

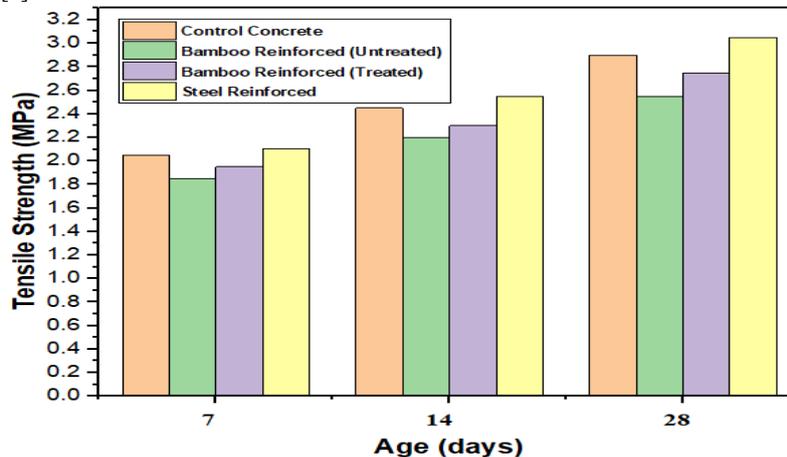


Figure 4. Tensile Strength

#### Conclusion

Bamboo-reinforced concrete exhibited satisfactory performance in terms of compressive, tensile, and flexural strengths, with treated bamboo specimens consistently outperforming untreated ones. At 28 days, treated bamboo achieved up to 90–95% of the tensile and flexural strength provided by steel reinforcement, indicating its potential in structural applications with moderate load requirements. Durability tests revealed that untreated bamboo is susceptible to higher water absorption, shrinkage, and reduced resistance to acidic and sulphate environments. However, surface treatments and protective coatings substantially improved its long-term performance, reducing water permeability and enhancing bond strength with the concrete matrix.

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