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Mechanical Behaviour of Bamboo as a Natural Composite for Structural Reinforcement and Foundry Sand

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ABSTRACT :

This review paper provides an in-depth analysis of the mechanical behavior, environmental sustainability, and structural feasibility of bamboo as a natural composite material for reinforcing concrete. As the construction industry seeks alternatives to conventional steel reinforcement due to its high cost and significant carbon emissions, bamboo emerges as a promising eco-friendly substitute owing to its high tensile strength-to-weight ratio, renewability, and abundance in tropical regions. The study also investigates the synergistic role of foundry sand, an industrial by-product, as a partial replacement for fine aggregate in concrete mixes, thereby promoting circular economy principles and reducing waste disposal issues.

While bamboo exhibits impressive mechanical characteristics comparable to mild steel in tension, its practical application in concrete is hindered by several limitations, including its poor bonding affinity with the cement matrix, high moisture absorption, dimensional instability, and biological vulnerability to insects and fungi. To overcome these challenges, numerous studies have explored chemical treatments such as borax–boric acid soaking, sodium hydroxide (NaOH) immersion, and surface coatings with natural oils and fibers. These modifications not only enhance bamboo's durability and interfacial bond strength but also improve its performance under thermal and environmental stress conditions.

The review further compiles results from experimental and analytical investigations on M30-grade concrete incorporating 30% foundry sand replacement and chemically treated bamboo reinforcements. The combined use of these sustainable materials has shown remarkable improvements in flexural behavior, crack resistance, and load-bearing capacity, with minimal compromise in compressive strength. Water absorption and durability tests confirm that treated bamboo can sustain structural applications with acceptable moisture retention levels.

Overall, this review emphasizes the potential of bamboo-foundry sand hybrid systems as an eco-efficient alternative to conventional concrete. The integration of bamboo reinforcement and industrial by-products not only addresses mechanical performance and cost reduction but also aligns with the global pursuit of low-carbon, sustainable construction technologies.

Key words:- : Bamboo reinforcement; Foundry sand; Sustainable construction materials; Mechanical properties; Flexural strength; Eco-friendly concrete; Durability; Waste utilization; Low-carbon infrastructure.

Introduction

Background and Motivation

The modern construction industry faces pressing challenges related to environmental sustainability and resource depletion. Steel, one of the most widely used construction materials, contributes significantly to global carbon emissions. Producing one ton of steel emits approximately 1.8 tons of CO_2, while the extraction of iron ore, coal, and limestone further exacerbates ecological degradation. These factors necessitate alternative materials that are both sustainable and structurally reliable.

Bamboo, a fast-growing and abundant natural resource, has emerged as a potential substitute for steel in reinforced concrete. It possesses remarkable tensile strength, low weight, and elasticity, making it suitable for light to moderate structural applications. Moreover, bamboo's renewability and biodegradability align with circular economy principles. Despite these advantages, raw bamboo faces challenges like moisture absorption, dimensional instability, and susceptibility to insect or fungal attacks. Addressing these limitations through appropriate treatment methods can significantly enhance bamboo's performance as a reinforcement material.

Scope and Objectives

The scope of this review focuses on evaluating the mechanical performance, durability, and sustainability potential of bamboo as a natural composite reinforcement in concrete, along with the use of foundry sand as a partial fine aggregate replacement. The study aims to consolidate existing experimental research and identify practical applications where these eco-friendly materials can reduce carbon emissions and resource depletion in the construction industry.

Objectives of the study include:

1. To review the mechanical and durability properties of concrete reinforced with chemically treated bamboo.
2. To investigate the influence of foundry sand as a partial replacement for fine aggregate on workability, strength, and long-term performance.
3. To analyze the combined effect of bamboo reinforcement and foundry sand on the overall sustainability of structural concrete.
4. To identify the limitations, treatment techniques, and potential improvements required for standardizing bamboo as a construction material.
5. To recommend future research directions for optimizing bamboo-based composites in low-carbon and rural infrastructure projects.

Literature Review

Over the past decade, there has been a growing focus on the structural performance and environmental viability of bamboo-reinforced concrete (BRC) systems. Bamboo, being a naturally available, renewable, and high-strength material, has gained attention as a potential substitute for steel in reinforced concrete structures, particularly in developing regions where cost and sustainability are critical factors. Its lightweight nature, high tensile strength, and availability make it a promising alternative; however, its direct use poses challenges such as moisture absorption, poor adhesion with cement paste, and biological degradation. Consequently, researchers worldwide have investigated chemical and physical treatments to overcome these limitations and enhance bamboo's engineering performance.

Solahuddin Bin Azuwa (2024) conducted a comprehensive review of more than 30 experimental studies focusing on the structural behavior of bamboo-reinforced concrete elements. The study revealed that treated bamboo reinforcement significantly improved the ductility, crack resistance, and load-bearing capacity of beams and slabs. This improvement was primarily attributed to enhanced bonding between bamboo and concrete after chemical treatments such as sodium hydroxide (NaOH) and boric acid immersion, which effectively removed the outer waxy layer and surface starch. The roughened surface texture obtained from these treatments increased the interfacial friction and mechanical anchorage between bamboo and the cement matrix, resulting in improved tensile load transfer and reduced slippage.

Similarly, Muthukumar and Senthil Kumar (2022) investigated the incorporation of bamboo fibers as a partial replacement for cement in M30-grade concrete. Their research identified an optimal replacement level of 5%, which yielded a 12% increase in compressive strength and a 9% improvement in flexural strength compared to conventional concrete. This enhancement was attributed to the fiber's ability to bridge microcracks, delay crack propagation, and improve post-cracking behavior. Their findings support the notion that bamboo fibers, even in small proportions, can effectively enhance the toughness and energy absorption capacity of concrete mixtures.

Further studies have explored hybrid reinforcement systems and advanced treatment techniques to expand bamboo's applicability in modern construction. Widayanto et al. (2025) investigated the influence of soaking bamboo in salt and molasses solutions followed by fiberglass wrapping, aiming to enhance both strength and durability. The treated bamboo beams achieved load capacities between 12–14.5 tons, which is nearly equivalent to those of mild steel-reinforced beams. The combination of organic treatment and external wrapping improved surface bonding, reduced water permeability, and protected the bamboo from microbial decay—critical factors for maintaining long-term stability in humid environments.

In parallel, researchers have also explored surface modification and heat resistance enhancements for bamboo to improve its performance under extreme environmental conditions. Moy and Wang (2025) examined the use of tung oil combined with zirconia powder to enhance bamboo's thermal resistance and dimensional stability. Their results demonstrated a marked improvement in the material's ability to withstand elevated temperatures without significant deformation or loss of strength. These findings are particularly relevant for applications in tropical climates, where high humidity and temperature fluctuations can adversely affect natural materials.

Long-term durability remains a key consideration in the structural application of bamboo. Khatun et al. (2025) studied the preservative treatment of Dendrocalamus giganteus and Bambusa vulgaris using chromated copper arsenate (CCA). The treated specimens exhibited extended lifespans and higher resistance to fungal and termite attack compared to untreated samples. The study concluded that chemical preservatives and heat treatment together can substantially increase bamboo's service life, making it more suitable for structural reinforcement purposes.

Collectively, these studies underscore the crucial role of treatment techniques, surface modification, and material hybridization in optimizing the structural efficiency of bamboo. Treated bamboo has proven capable of providing sufficient tensile reinforcement, improved crack control, and enhanced durability when used in concrete. Moreover, the integration of bamboo with industrial by-products like foundry sand presents an innovative approach to sustainable construction, reducing both environmental impact and material costs.

Materials and Methods Overview

The experimental investigation was carried out to evaluate the mechanical behavior, durability characteristics, and sustainability performance of bamboo-reinforced concrete (BRC) incorporating foundry sand as a partial replacement for fine aggregate. The primary objective was to assess how the integration of treated bamboo reinforcement and industrial by-products could enhance the strength, workability, and eco-efficiency of conventional concrete.

The concrete used in this study was designed for M30-grade strength following the guidelines of IS 10262:2019 and IS 456:2000. The mix proportion adopted was 1:0.75:1.5 (cement: fine aggregate: coarse aggregate) with a water–cement ratio of 0.40. Ordinary Portland Cement (OPC 53 Grade) conforming to IS 12269:2013 was employed as the binding material, providing the necessary strength and consistency. The fine aggregate used was manufactured sand (M-sand) with a maximum particle size of 4.75 mm, and coarse aggregates of 20 mm nominal size were chosen in compliance with IS 383:1970. These aggregates were clean, well-graded, and angular in shape to ensure dense packing and good interlocking within the concrete matrix.

Foundry sand, a silica-rich by-product obtained from the metal casting industry, was utilized as a 30% partial replacement for fine aggregate by weight. The reuse of foundry sand aimed to promote waste minimization and reduce the extraction of natural river sand. Its high silica content (SiO_2 85–95%), uniform grain structure, and fine particle size contributed to better packing density and a reduced void ratio within the concrete mix. These characteristics improved compressive and flexural strength while enhancing long-term durability. The use of foundry sand also aligns with the circular economy approach, transforming industrial waste into a valuable construction material.

The bamboo reinforcements used in the study were sourced from the species Bambusa vulgaris, selected for its high tensile strength and availability. To

overcome its natural drawbacks—such as high water absorption, biological decay, and dimensional instability—the bamboo strips were chemically treated using a borax–boric acid solution. This treatment was performed by soaking the bamboo in the solution for 24 hours, following which the specimens were air-dried for 48 hours and kiln-dried at temperatures between 60°C and 80°C. The treatment process effectively enhanced bamboo's resistance to insects, fungi, and moisture. After drying, the outer smooth surface of the bamboo was lightly sanded to improve adhesion with the cement matrix, while some specimens received a thin epoxy coating to further reduce water permeability and swelling.

Concrete mixing was performed using a mechanical mixer to ensure uniform distribution of materials and consistency of the mix. The fresh concrete properties were evaluated using the slump cone test, which measured the workability and flow characteristics of the mix. Slump values ranging between 75 mm and 92 mm indicated medium workability, which is suitable for reinforced concrete applications. The concrete was then poured into steel moulds containing pre-treated bamboo reinforcements and compacted in layers to eliminate air voids.

After 24 hours of casting, the specimens were demoulded and water-cured for 7, 14, and 28 days under controlled laboratory conditions as per IS 516:1959. Various mechanical and durability tests were then performed on the cured specimens. The compressive strength test evaluated the load-bearing capacity of cube samples, while the flexural strength test measured the bending performance of beam specimens under two-point loading. The water absorption test determined the moisture uptake capacity of treated bamboo and concrete composites, yielding a value of 17.86%, which falls under the "Good" classification according to IS 287:1987. Additionally, the rapid chloride permeability test (RCPT) assessed the resistance of the composite concrete to chloride ion penetration, which is a critical parameter in evaluating long-term durability and corrosion resistance.

To examine the behavior of treated bamboo under thermal exposure, heat resistance tests were conducted using the kiln-drying method (38°C–80°C) and hot-plate method (100°C–110°C). These tests simulated real-world temperature variations and assessed the dimensional stability and structural integrity of the treated bamboo within the concrete.

Discussion and Key Findings

The experimental results demonstrated that the integration of chemically treated bamboo reinforcement and foundry sand as a fine aggregate replacement significantly improved both the mechanical and durability performance of concrete. The findings highlight that when bamboo is properly treated and foundry sand is optimally incorporated, the resulting composite exhibits favorable strength characteristics, enhanced workability, and notable environmental benefits compared to conventional concrete systems.

The average flexural strength obtained for the bamboo-reinforced concrete was 16.25 N/mm² after seven days of curing, indicating a substantial ability to withstand tensile stresses. This performance reflects the improved bonding efficiency between the bamboo reinforcement and the concrete matrix, primarily due to the chemical modification of bamboo using borax–boric acid treatment. The removal of surface starch and the smoothing of the outer layer during treatment enhanced interfacial adhesion, ensuring more uniform stress transfer under load. The natural elasticity of bamboo also contributed to improved crack control and post-cracking ductility, making it particularly beneficial for flexural members such as beams and slabs.

The water absorption test revealed a value of 17.86%, categorizing bamboo as "Good" in accordance with IS 287:1987. This result signifies that chemical treatment effectively minimized bamboo's inherent moisture sensitivity, which otherwise could lead to swelling, shrinkage, and bonding failure. The reduction in water absorption not only improved the dimensional stability of bamboo within the concrete but also enhanced its long-term durability by mitigating biological degradation such as fungal and termite attacks.

The use of foundry sand as a 30% fine aggregate replacement proved advantageous in terms of both performance and sustainability. The fine particle size and high silica content of foundry sand improved the packing density of the mix, resulting in a denser matrix with fewer voids. This microstructural refinement enhanced the compressive and flexural strength while maintaining the workability of the concrete mixture. Slump values between 75 mm and 92 mm indicated medium workability, suitable for reinforced applications. The enhanced matrix compaction also improved resistance to chloride penetration and reduced permeability, which are critical factors in preventing corrosion and degradation over time.

Comparatively, bamboo-reinforced concrete displayed slightly lower overall strength than steel-reinforced concrete. However, this marginal reduction in strength was offset by significant environmental and economic advantages. Bamboo is renewable, locally available, and far less carbon-intensive than steel, while foundry sand reuses industrial waste that would otherwise contribute to land pollution. Together, these materials substantially reduce the embodied carbon of reinforced concrete, aligning the system with sustainable construction and circular economy principles.
Microstructural analyses from related research provide insight into the improved bond behavior of treated bamboo. NaOH treatment, for instance, enhances the surface roughness of bamboo and exposes cellulose fibers, thereby increasing the mechanical interlock between bamboo and hydrated cement phases such as calcium silicate hydrate (C–S–H). Similarly, borax–boric acid treatment reduces lignin and hemicellulose content, improving moisture resistance and dimensional stability. These treatments collectively lead to enhanced interface adhesion, reduced slippage, and improved load transfer efficiency within the composite.

Furthermore, the ductile nature of bamboo allowed for gradual failure modes under flexural loading, as opposed to the brittle behavior typically observed in unreinforced or steel-reinforced concrete when cracking occurs. This property enhances the overall toughness of the composite and provides a safer mode of failure in structural applications.

From a sustainability perspective, the combined use of treated bamboo and foundry sand has demonstrated measurable environmental benefits. The substitution of 30% foundry sand for natural sand reduces the dependency on river sand mining, thereby conserving natural resources and reducing ecological disturbance. Additionally, bamboo's carbon sequestration capacity offsets a portion of the emissions associated with cement production, further improving the material's sustainability profile.

Conclusion and Future Scope

The investigation reaffirms that bamboo, when properly treated and integrated into concrete systems, holds significant potential as a sustainable, cost-effective, and eco-friendly alternative to conventional steel reinforcement. Its high tensile strength, low density, and renewability make it particularly suitable for low-rise and rural construction, where affordability and accessibility are crucial. The study further demonstrates that the combination of treated bamboo reinforcement with foundry sand-modified concrete offers a promising pathway toward achieving mechanical reliability and environmental responsibility in modern construction practices.

The experimental observations confirmed that chemically treated bamboo reinforcement, when combined with M30-grade concrete incorporating 30% foundry sand, provides satisfactory flexural strength, durability, and resistance to moisture-related degradation. The borax–boric acid treatment was found to improve bamboo's dimensional stability, bonding strength, and biological resistance, while foundry sand enhanced matrix compaction, surface finish, and microstructural integrity. Together, these materials contribute to reducing the carbon footprint of concrete production, promoting waste valorization through the reuse of industrial by-products, and aligning with green building and sustainable development goals.

Moreover, the study highlights that although bamboo-reinforced concrete exhibits slightly lower compressive strength than steel-reinforced concrete, the trade-off is justified by its environmental benefits, low cost, and renewability. The incorporation of foundry sand not only replaces non- renewable river sand but also improves mechanical performance, demonstrating the feasibility of using such eco-friendly composites for sustainable infrastructure.

Future Scope

While the results are encouraging, further research is essential to fully establish the use of bamboo and foundry sand in mainstream structural engineering. Future work should focus on the following key areas:

- Standardization of bamboo species and treatment methods: Developing unified guidelines for selecting bamboo species, treatment concentrations, and curing conditions to ensure consistent performance across regions.
- Long-term durability assessment: Evaluating treated bamboo's behavior under cyclic loading, humidity variations, and chemical
- exposures to ensure long service life in diverse climatic conditions.
- Development of hybrid composites: Exploring the potential of bamboo–polymer composites, bamboo–geopolymer binders, and fiber-reinforced hybrid materials to enhance bonding and moisture resistance.
- Analytical and numerical modeling: Utilizing Finite Element Modeling (FEM) and simulation tools to predict the mechanical behavior of bamboo–concrete interfaces and optimize reinforcement configurations.
- Field applications and performance monitoring: Implementing pilot projects using bamboo-reinforced and foundry sand-based concretes to validate laboratory findings under real-world conditions.

In conclusion, the findings affirm that integrating bamboo reinforcement and industrial by-products like foundry sand into concrete mixtures can pave the way toward a low-carbon, circular, and sustainable construction industry. With continued research, standardized practices, and technological innovation, these natural and waste-derived materials can significantly transform the future of green civil engineering.

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