Effect of Surface Treatment on Bond Strength and Durability of Bamboo Reinforced Concrete: A Critical Review

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Abstract

Bamboo reinforced concrete (BRC) has gained increasing attention as a sustainable and low-cost alternative to conventional steel-reinforced concrete, particularly in developing regions where material availability and environmental considerations are critical. However, the practical application of bamboo as reinforcement is significantly limited by its poor bond characteristics with concrete and its susceptibility to moisture-induced degradation. This review critically examines the role of surface treatment techniques in enhancing the bond strength and durability performance of bamboo-reinforced concrete systems. Various treatment methods, including bitumen coating, epoxy treatment, chemical modification, and surface roughening, are systematically analyzed with respect to their influence on interfacial bonding, moisture resistance, and long-term structural performance. The review synthesizes findings from experimental studies focusing on pull-out behavior, flexural performance, and durability indicators such as water absorption, biological resistance, and dimensional stability. Key challenges including variability in treatment effectiveness, lack of standardization, and limited long-term performance data are also discussed. The study highlights that appropriate surface modification significantly improves bonding efficiency and durability, thereby expanding the feasibility of bamboo as a reinforcement material. Future research directions emphasizing hybrid treatment techniques, standard design guidelines, and large-scale validation are identified to advance the adoption of bamboo in sustainable construction.

Keywords

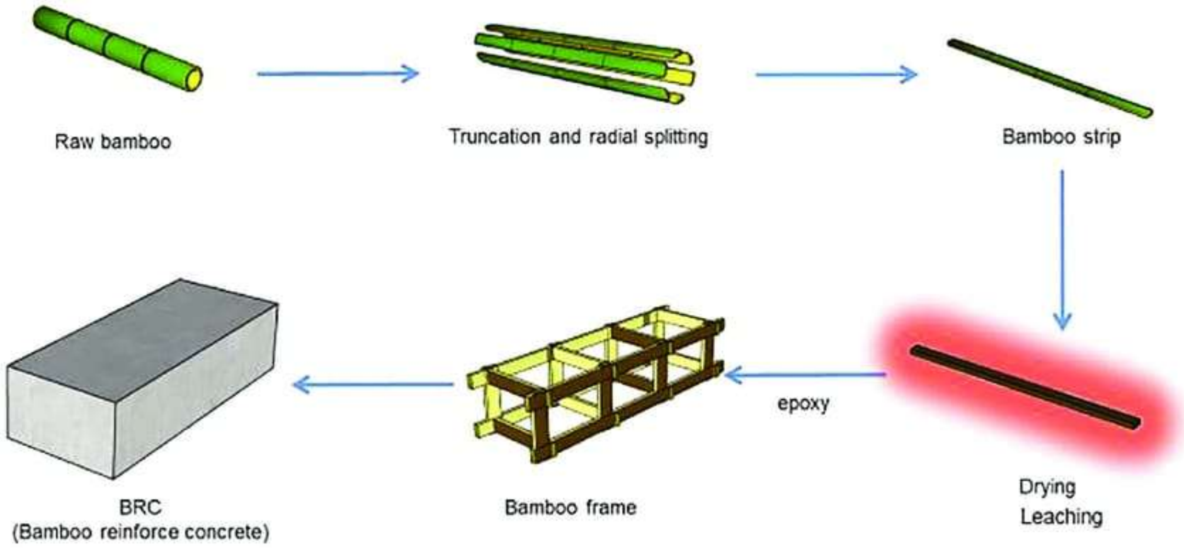
Bamboo reinforced concrete; Surface treatment; Bond strength; Durability; Sustainable construction; Epoxy coating; Bitumen treatment; Natural reinforcement

1. Introduction

The increasing demand for sustainable and environmentally responsible construction materials has driven significant research efforts toward alternative reinforcement systems in structural concrete. Conventional steel reinforcement, while highly effective in enhancing tensile performance, is associated with high energy consumption, carbon emissions, and economic constraints, particularly in resource-limited regions. In this context, bamboo has emerged as a promising natural reinforcement material due to its high tensile strength, rapid renewability, and widespread availability.

Bamboo possesses a favorable strength-to-weight ratio and has been historically utilized in traditional construction systems. However, despite its mechanical advantages, the application of bamboo in reinforced concrete remains limited due to critical challenges associated with its interaction with cementitious matrices. One of the most significant limitations is the inherently weak bond between bamboo and concrete, primarily resulting from its smooth surface texture and hydrophilic nature. Additionally, bamboo exhibits high moisture absorption capacity, leading to swelling, shrinkage, and subsequent deterioration of the surrounding concrete. To address these limitations, various surface treatment techniques have been proposed to modify the physical and chemical characteristics of bamboo. These treatments aim to improve interfacial bonding, reduce water absorption, and enhance resistance to biological degradation. Despite numerous experimental studies, the effectiveness of different treatment methods remains inconsistent, and a comprehensive synthesis of their impact on both bond strength and durability is lacking.

This review aims to critically evaluate existing research on surface-treated bamboo reinforcement, focusing on its influence on bond behavior and durability performance in concrete systems. By integrating findings from diverse experimental investigations, the study seeks to provide a structured understanding of current advancements, limitations, and future research opportunities in bamboo-reinforced concrete technology.



2. Literature Selection Methodology

A systematic literature review methodology was adopted to ensure comprehensive coverage and critical evaluation of existing research related to bamboo reinforcement and surface treatment techniques. Relevant studies were identified through major academic databases, including Google Scholar, ScienceDirect, and ResearchGate, covering publications from 2000 to 2025.

A keyword-based search strategy was employed using combinations such as “bamboo reinforced concrete,” “surface treatment of bamboo,” “bond strength,” and “durability of bamboo concrete.” The initial search yielded a wide range of studies, which were subsequently screened based on relevance, technical quality, and availability of experimental data.

The selection process followed a structured approach involving identification, screening, eligibility assessment, and final inclusion. Studies focusing specifically on bond behavior, surface treatment methods, and durability aspects were prioritized. Research lacking experimental validation or technical clarity was excluded. The selected studies were then categorized into thematic groups, including treatment techniques, bond strength analysis, and durability performance, to facilitate systematic synthesis and comparison.

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3. Surface Treatment Techniques for Bamboo Reinforcement

Surface treatment plays a critical role in modifying the interaction between bamboo and concrete. Various techniques have been developed to enhance bonding characteristics and durability performance.

Bitumen coating is one of the earliest and most widely used methods, primarily aimed at reducing water absorption. By forming a protective layer around bamboo, bitumen limits moisture ingress and improves resistance to environmental degradation. However, its smooth surface may reduce mechanical interlocking, thereby limiting bond strength.

Epoxy coating has gained prominence due to its superior adhesive properties. Epoxy-treated bamboo exhibits improved interfacial bonding with concrete, resulting in enhanced load transfer efficiency. Additionally, epoxy provides a barrier against moisture penetration, contributing to improved durability.

Chemical treatments, including alkali (NaOH) and borax-boric acid solutions, are employed to modify the internal structure of bamboo. These treatments reduce sugar content, enhance resistance to fungal attack, and improve dimensional stability. However, their effectiveness depends on treatment concentration and duration.

Surface roughening and sand coating techniques are used to improve mechanical interlocking between bamboo and concrete. By increasing surface friction, these methods significantly enhance bond strength and reduce slippage under load.

4. Bond Strength Characteristics

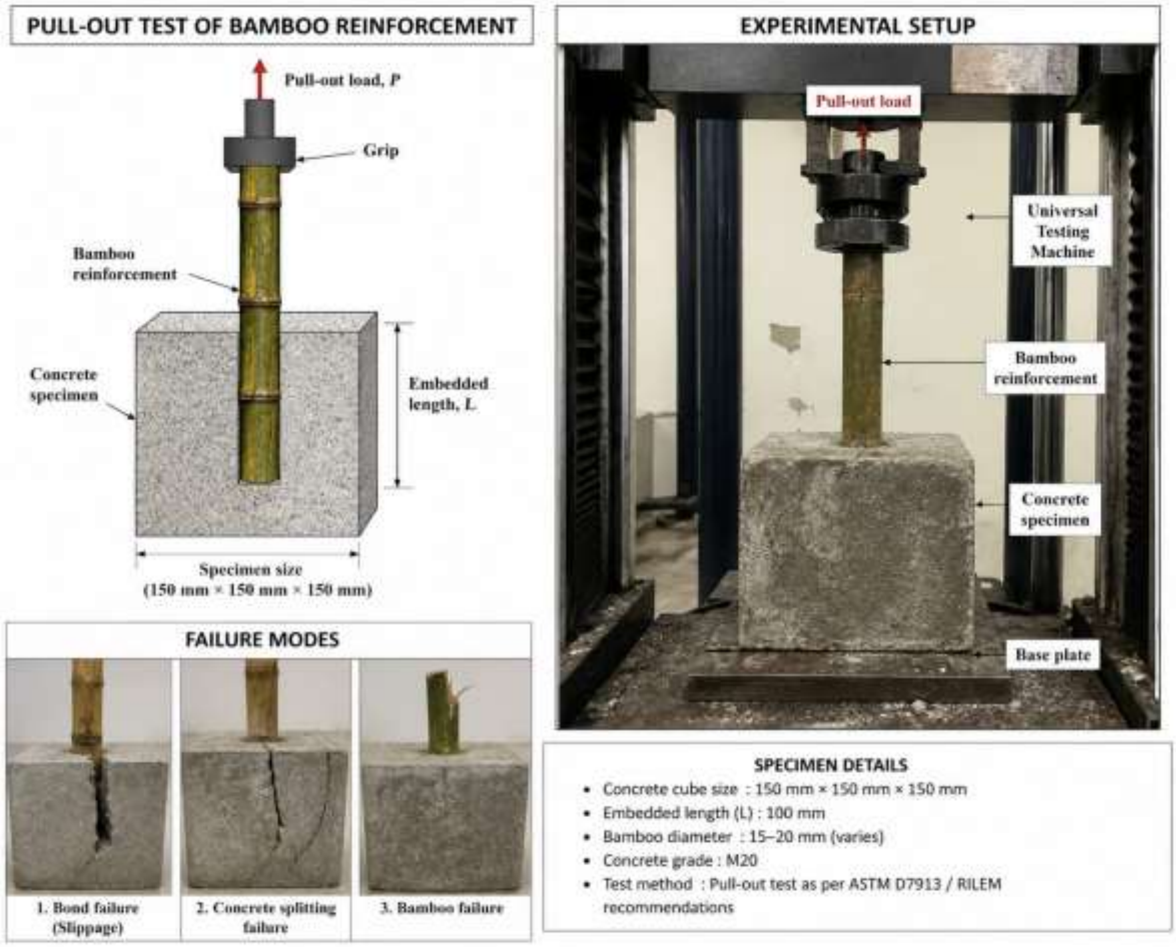

Fig. 6 Pull out testing in UTM

Fig. 7 Pull out testing in UTM

Table 3 Pull out test results of bamboo splints

Sr.No.	Type	Treatment	Specimen	Sample No.	Width (mm)	Thickness (mm)	Contact Perimeter (mm)	Contact Length (mm)	Contact Area (mm^2)	Pull out Load (KN)	Bond stress (Mpa)	Average Bond stress (Mpa)
1	Splint	Plain	Culm 1	P1	19	6	50	260	13000.0	5.9	**0.45**	0.45
2			Culm 2	P2	20	6	52	260	13520.0	5.7	**0.42**	
3			Culm 3	P3	18	7	50	260	13000.0	6.2	**0.48**	
4		Oil paint	Culm 1	P4	18	5	46	260	11960.0	5.6	**0.47**	0.50
5			Culm 2	P5	20	6	52	260	13520.0	6.6	**0.49**	
6			Culm 3	P6	19	6	50	260	13000.0	7.2	**0.55**	
7		Oil paint + sand	Culm 1	P7	16	5	42	260	10920.0	6.4	**0.59**	0.58
8			Culm 2	P8	17	6	46	260	11960.0	7.2	**0.60**	
9			Culm 3	P9	20	8	56	260	14560.0	7.9	**0.54**	
10		Oil paint & wire in one direction	Culm 1	P10	19	6	50	260	13000.0	11.2	**0.86**	0.80
11			Culm 2	P11	20	5	50	260	13000.0	10.8	**0.83**	
12			Culm 3	P12	18	7	50	260	13000.0	9.2	**0.71**	
13		Oil paint & wire in cross	Culm 1	P13	18	5	46	260	11960.0	10.4	**0.87**	0.87
14			Culm 2	P14	17	6	46	260	11960.0	9.4	**0.79**	
15			Culm 3	P15	19	9	56	260	14560.0	13.8	**0.95**	

Table 4 Pull out test results of half bamboo culms

Sr.No.	Type	Treatment	Specimen	Sample No.	Thickness (mm)	Diameter (mm)	Contact Perimeter (mm)	Contact Length (mm)	Contact Area (mm^2)	Pull out Load (KN)	Bond stress (Mpa)	Average Bond stress (Mpa)
16	Half Round	Plain	Culm 1	P16	7	45	133.32	260	34663.2	21.2	**0.61**	0.56
17			Culm 2	P17	7	42.7	126.098	260	32785.5	16.9	**0.52**	
18			Culm 3	P18	8	38.3	111.142	260	28896.9	16	**0.55**	
19		Oil paint	Culm 1	P19	8	44	129.04	260	33550.4	18.1	**0.54**	0.60
20			Culm 2	P20	6	43.7	130.378	260	33898.3	26	**0.77**	
21			Culm 3	P21	7	42	123.9	260	32214.0	16.2	**0.50**	
22		wire in one direction	Culm 1	P22	9	43.3	125.702	260	32682.5	25.2	**0.77**	0.89
23			Culm 2	P23	8	41.7	121.818	260	31672.7	28.7	**0.91**	
24			Culm 3	P24	9	39.7	114.398	260	29743.5	29.9	**1.01**	
25		wire in cross	Culm 1	P25	7	38.3	112.282	260	29193.3	32.4	**1.11**	1.12
26			Culm 2	P26	7	36.3	106.002	260	27560.5	30.1	**1.09**	
27			Culm 3	P27	9	34	96.5	260	25090.0	28.7	**1.14**	

The results described in the above two tables shows that the average bond strength between the bamboo splints and concrete is highest i.e. 0.87 MPa for oil paint sprinkled with sand and wrapped with wire in both direction (cross). The enhancement in strength is almost 193%. Similarly the average bond strength between the half bamboo culms and concrete is again maximum i.e. 1.12 MPa for oil paint sprinkled with sand and wrapped with wire in both direction (cross). The enhancement in strength is almost 200%. Hence, the bamboo coated with oil paint is selected for all further studies. It is found from the series of experiments that, many of the samples underperformed due to slippage of bamboo splints from the concrete cubes as shown in Fig.8. However, in some cases, during the slippage, it is observed that bamboo samples are broken in spite of having much more tensile strength compared to its bonding strength between bamboo splints and the concrete. The reason may be the non-alignment of the bamboo splints which further leads to strength of treated and improved samples are found to be more comparable with design bond strength values .This study also explores the potential of new type of economical and easy to apply treatment (oil paint). To further improve the effectiveness of the surface treatment for the better bonding between bamboo and concrete, needs further investigations and experimentation to assess its structural performance and durability aspect. However this research shows the significant improvement in the bond strength between bamboo and concrete.

Bond strength is a critical parameter governing the performance of reinforced concrete systems, as it ensures effective stress transfer between reinforcement and surrounding concrete. In bamboo-reinforced concrete, bond behavior is influenced by surface texture, moisture interaction, and treatment methods.
Experimental studies consistently indicate that untreated bamboo exhibits poor bond performance, primarily due to its smooth surface and high water absorption. Pull-out tests reveal significant slippage and premature failure in such cases.

Surface-treated bamboo demonstrates improved bonding characteristics. Epoxy-coated bamboo generally exhibits the highest bond strength due to enhanced adhesion and reduced moisture interaction. Sand-coated bamboo also shows significant improvement due to increased surface roughness and mechanical interlocking. Despite these improvements, variability in bond performance remains a challenge due to differences in bamboo species, treatment processes, and testing conditions. Standardization of testing methodologies is therefore essential for reliable comparison and practical implementation.

5. Durability Performance

Durability is a major concern in bamboo-reinforced concrete due to the organic nature of bamboo. Exposure to moisture, biological agents, and environmental conditions significantly affects its long-term performance.

Water absorption is one of the primary factors influencing durability. Untreated bamboo absorbs significant moisture, leading to swelling and cracking of surrounding concrete. Surface treatments such as bitumen and epoxy effectively reduce water absorption and improve dimensional stability.

Biological degradation, including fungal and termite attack, poses another major challenge. Chemical treatments enhance resistance to such degradation by altering the chemical composition of bamboo.

Shrinkage and expansion behavior due to moisture variation can induce internal stresses within concrete, leading to cracking and reduced structural integrity. Proper treatment and sealing techniques are essential to mitigate these effects.

Overall, treated bamboo demonstrates significantly improved durability compared to untreated bamboo, although it still does not match the long-term performance of steel reinforcement.

6. Comparative Analysis

A comparative evaluation of different surface treatment techniques indicates that no single method provides optimal performance in all aspects. Epoxy coating offers superior bond strength, while chemical treatments enhance durability. Bitumen coating is effective in moisture protection but may compromise bonding efficiency.

Hybrid treatment approaches combining multiple techniques have shown promising results, suggesting potential for improved overall performance. However, further experimental validation is required to establish their effectiveness under real-world conditions.

7. Challenges and Research Gaps

Despite significant progress, several challenges remain in the application of bamboo reinforcement. The lack of standardized treatment procedures and design guidelines limits practical implementation. Variability in bamboo properties due to species and environmental conditions further complicates performance prediction.

Long-term durability studies are limited, particularly under varying climatic conditions. Additionally, large-scale structural applications of bamboo-reinforced concrete remain insufficiently explored.

Future research should focus on developing standardized testing protocols, exploring hybrid treatment methods, and conducting field-scale validation studies to enhance reliability and acceptance.

8. Future Prospects

The future of bamboo-reinforced concrete lies in the development of advanced treatment techniques and integration with modern construction practices. Hybrid surface treatments combining chemical and mechanical modifications offer potential for enhanced performance.

Incorporation of sustainability assessment and life-cycle analysis can further strengthen the case for bamboo as an eco-friendly reinforcement material. Additionally, the development of design codes and guidelines will be essential for widespread adoption.

9. Conclusion

This review highlights the critical role of surface treatment in improving the bond strength and durability of bamboo-reinforced concrete. While untreated bamboo exhibits significant limitations, appropriate treatment techniques can substantially enhance its performance.

Among the various methods, epoxy coating and surface roughening provide significant improvements in bond strength, while chemical treatments enhance durability. Despite these advancements, challenges related to standardization, variability, and long-term performance remain.

Bamboo reinforcement presents a viable alternative for sustainable construction, particularly in low-cost and rural applications. Continued research and development are essential to unlock its full potential and ensure reliable structural performance.

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