Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Experimental investigation of bond behavior between bamboo and concrete: A comparative analysis of bamboo surface treatments

Vivek Pahuja [*,1,a], Pradeep Kumar Ghosh [2,b], Anil Kumar [1,c]

[1]*Department of Civil Engineering, University Teaching Department, Chhattisgarh Swami Vivekanand Technical University, Bhilai, Chhattisgarh, India*
[2]*Department of Civil Engineering, Dr. C.V. Raman University, Bilaspur, Chhattisgarh, India*

Article Info

Article History:

Received 04 Feb 2025

Accepted 23 June 2025

Keywords:
Bamboo;
Bamboo reinforced concrete;
Bond strength;
Pull-out;
Reinforcement

Abstract

With increasing urbanization, there is a growing need to explore sustainable construction materials that can serve as conventional steel reinforcement. Bamboo has emerged as a promising alternative due to its environmental benefits, wide availability, and high strength-to-weight ratio. However, its structural application is limited by challenges such as poor adhesion to concrete and high moisture absorption, which can compromise bond strength and durability. This study investigates the interfacial behavior between bamboo and concrete to improve bamboo's effectiveness as reinforcement. Pull-out tests were performed on specimens treated with various chemical and mechanical surface treatments to evaluate their effects on bond strength. The results indicate that chemical treatments significantly reduced water absorption, while a combination of chemical and mechanical treatments substantially improved bond strength compared to untreated specimens. These findings demonstrate that surface-treated bamboo can serve as a viable reinforcement material in low-cost and sustainable construction, promoting eco-friendly building practices.

1. Introduction

Concrete is globally recognized for its versatility, high compressive strength, and relatively low cost; however, its lack of tensile strength necessitates the use of steel reinforcement. Although steel significantly improves tensile capacity, it has notable drawbacks, including limited availability, high cost, and susceptibility to corrosion (1). Furthermore, steel production is highly energy-intensive, emitting approximately 1.91 tons of CO_2 per ton of steel produced (2), thereby contributing significantly to global greenhouse gas emissions.

In response to these challenges, there has been a growing interest in sustainable alternatives for steel reinforcement. Materials such as natural fibers (e.g., coconut, jute, sugarcane bagasse, sisal), fiber-reinforced polymers (FRPs), bamboo, and precast concrete components have shown promise due to their ecological benefits (3–6). Among these, bamboo stands out as a promising material. Bamboo, a giant woody grass with over 1250 species, with some species growing up to 91 cm per day, as recorded by Guinness World Records. Its rapid growth, high strength-to-weight ratio, low carbon footprint, and widespread availability make bamboo an eco-friendly material (7–10). Each ton of bamboo absorbs an equivalent amount of CO2, making it a carbon-negative material (11). Moreover, bamboo has a strength-to-weight ratio nearly six times higher than that of steel, making it a lightweight material (12,13).

*Corresponding author: vivekpahuja97@gmail.com
[a]orcid.org/0009-0006-1944-1940; [b]orcid.org/0000-0002-8041-7476; [c]orcid.org/0009-0008-5390-7526
DOI: http://dx.doi.org/10.17515/resm2025-658ma0204rs

Despite these ecological and mechanical advantages, bamboo faces certain challenges when used as a reinforcing material in concrete. Bamboo-reinforced concrete (BRC), which has been explored since the mid-19th century, often suffers from high water absorption and poor bond formation due to its smooth surface (14,15). During the casting and curing process of concrete, bamboo absorbs water and expands. Upon drying, it releases the absorbed water and contracts, potentially leading to surface cracks and bond failure between the bamboo and concrete matrix (16,17), as shown in Figure 1. These behaviors limit bamboo's effectiveness and long-term reliability as a reinforcement.

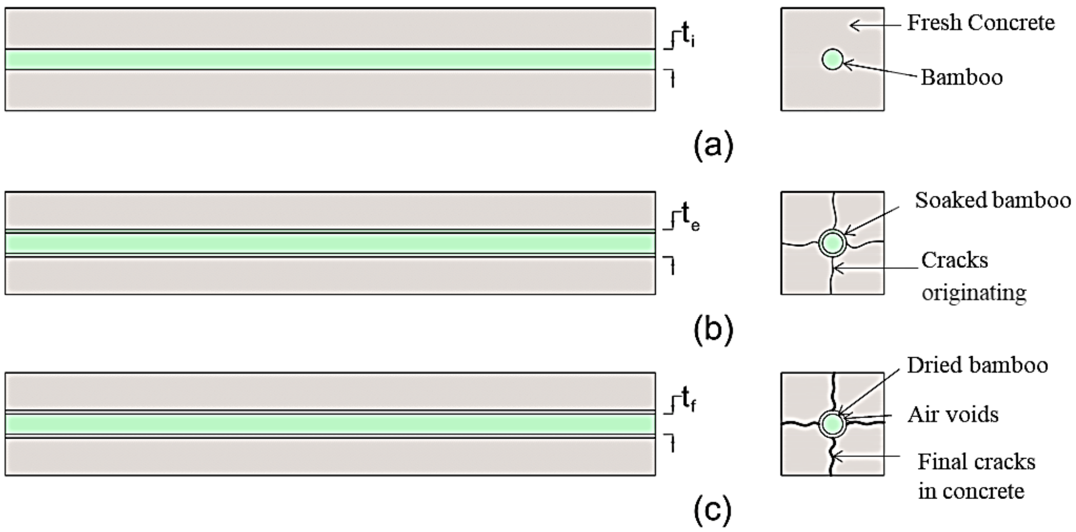

Fig. 1. Illustrates the performance of untreated bamboo when used as reinforcement in concrete: (a) In fresh concrete, (b) during the curing process, and (c) after curing

To mitigate these challenges, various surface treatment techniques, including chemical coatings and mechanical roughening, have been proposed to enhance bamboo's bonding capacity and reduce water absorption. Table 1 provides a summary of such treatments. While most existing studies focus on individual treatment methods, there remains a critical gap in the literature for a comprehensive and comparative analysis of these techniques under controlled testing conditions. This lack of systematic comparison limits the practical implementation of bamboo as a reinforcement material in construction applications.

Table 1. Comparison of bamboo bond strength achieved by several researchers

Treatment	Size of Bamboo [mm]	Embedded length (%)	Size of Specimen	Concrete Strength [MPa]	Bond Strength [MPa]	Increase in Bond	Mode of failure
Untreated [18]					0.73	1	Vertical shearing of the specimen
Untreated with node [18]					0.9	1.23	
Binding wire wound with node [18]					1.25	1.71	
Oil painted, with node & zeolite powder [18]	varying	100	150 mm cube	22.52	0.93	1.27	Slipping at low load
Bituminous paint with node [18]					0.86	1.18	
Bituminous paint, zeolite powder with node [18]					1.19	1.63	
Untreated [19]	26.5-40.72 mm	50		20	0.13	1	Bond Failure

Araldite coating [19]	wide, 3.67-4.72 mm thick				0.23	1.77	
Araldite coating + thin wire winding [19]			100 x 200 mm cylinder		0.54	4.15	
Tapecrete P 151[19]					0.31	2.38	
Anti Corr RC [19]					0.16	1.23	
Sikadur 32 Gel [19]					0.59	4.54	
Untreated [20]					0.14±0.010	1	Bond Failure
Semi-circular grooved spacing ratios (a: S) 1:1[20]					0.49±0.015	3.5	Bond and Partial Groove Failure
Semi-circular grooved with 1mm steel wire wrapped, sand blasted with [20]							
Triflor PUAL lacquer	20 x 8	50	100 x 200 mm cylinder	28	1.04±0.150	7.43	
Bond tite treatment					2.35±0.083	16.79	
Araldite					1.44±0.021	10.29	Groove Failure
Strepoxy					1.88±0.124	13.43	
Bitumen (VG-30)					0.97±0.086	6.93	
Epibond -21					1.54±0.051	11	
Untreated [17]					0.52	1	
Untreated with node [17]					1.2	2.31	
Negrolin + sand [17]					0.73	1.4	
Negrolin + sand with node [17]	30 mm width	33.33	150 x 300 mm cylinder	19	1.55	2.98	
Negrolin + sand + wire [17]					0.97	1.87	
Negrolin + sand + wire with node [17]					1.8	3.46	
Sikadur 32-Gel [17]					2.75	5.29	
Untreated [21]					1	1	Bond-slip failure
Hose Clamp 10 cm [21]					1.08	1.08	Bond-slip failure
Sikadur 752 + Sand [21]					2.25	2.25	Bond-slip failure
Sikadur 752 + Sand + Hose Clamp 15 cm [21]	15 x 15	66.67	150 x 300 mm cylinder	31.31	3.14	3.14	Bond and concrete cone failure
Sikadur 752+ Sand + Hose Clamp 20 cm [21]					3	3	Bond and concrete cone failure
Untreated with node [22]					0.16	1	Slippage
semi-circular corrugation spacing ratios (a: S) 1:1.5 with node [22]	20 mm width	100	150 x 300 mm cylinder	17.23	0.286	1.79	Breakage of bamboo
2mm diameter wire wrapped with node [22]					0.185	1.16	Slippage
Sikadur 32-LP and medium sand sprayed [23]	20.64 x 10.43	100	150 mm cube	31.65	2.2 + 0.3	1	Bond breakage at the resin–bamboo interface
Sikadur 32-LP and medium sand sprayed with node [23]	20.36 x 11.1				2.7 + 0.33	1.23	

Untreated [24]	20-23 mm wide, 2-4 mm thick	50	100 x 200 mm cylinder	31	0.16	1	Slippage of the bamboo strip
Araldite [24]					0.31	1.94	
Araldite with wire [24]					0.5	3.13	
Untreated [25]	varying	50	150 x 300 mm cylinder	30	1.62	1	Bond failure
Algicoat RC-104 [25]					1.64	1.01	
Untreated [26]	29.5–41 mm width, 4–9 mm thick	50	100 x 200 mm cylinder	22.4	0.93	1	Most samples fail in bond, and a few fails in tensile and splitting failures
Araldite treated [26]					1.24	1.33	
Rectangular corrugated [26]					1.35	1.45	
V-notch corrugated [26]					1.68	1.81	
Trapezoidal corrugated [26]					1.69	1.82	
Untreated [27]	20–30 mm wide	100	cube	40	0.9	1	Bamboo lugs were completely sheared off
Treated with linseed oil [27]					1.11	1.23	
Corrugated 1 mm, spacing ratios (a: S) 1:1[27]					1.46	1.62	
Treated with linseed oil, Corrugated 1 mm, and spacing ratios (a: S) 1:1[27]					1.48	1.64	
Corrugated 2 mm, spacing ratios (a: S) 1:1[27]					1.61	1.79	
Treated with linseed oil, Corrugated 2 mm and spacing ratios (a: S) 1:1.5[27]					2.92	3.24	
Treated with linseed oil, Corrugated 2 mm and spacing ratios (a: S) 1.5:1[27]					2.14	2.38	
surface roughened with node [16]	20 mm wide	50	Concrete cylinder	37	1.93	1	
surface roughened, 1 coat of bitumen + sand with node [16]					2.47	1.28	
surface roughened, 2 coats of bitumen with node [16]				30.4	2.39	1.24	
surface roughened, 2 coats of bitumen + sand with node [16]					2.6	1.35	
Untreated [28]	12.73-15.91 mm diameter	50	100 mm cube	41.1	0.19	1	Bamboo pull-out failure
SJK-61 epoxy mortar (EM) [28]					4.82	25.37	Tensile fracture of bamboo
Polyurethane (PE) [28]					2.35	12.37	Bamboo pull-out failure
Untreated [29]	15-17 mm diameter	100	100 x 100 x 400 mm prism	18.5	0.96±0.13	1	
Rubber coating and sticks inserted inside @ 15 mm pitch [29]					1.22±0.11	1.27	
Rubber coating and sticks inserted inside @ 50 mm pitch [29]					1.08±0.24	1.13	

This study aims to address the identified gap by investigating the interfacial behavior of bamboo and concrete through a comparative evaluation of various chemical and mechanical surface treatments. Using bamboo species Bambusa pallida, a series of pull-out tests were conducted on treated and untreated specimens to evaluate improvements in bond strength and reductions in water absorption. The objective is to identify the most effective surface treatment method to enhance the structural performance of bamboo-reinforced concrete, thus contributing to the development of sustainable alternatives to steel reinforcement in construction.

2. Materials and Methodology

2.1. Selection and Preparation of Bamboo

With the increasing use of bamboo as a construction material, a new Indian Standard (IS) code 15912:2018 has been developed to specify various guidelines and testing procedures for bamboo. The code, titled "Structural Design Using Bamboo — Code of Practice IS 15912:2018," recommends only sixteen species of bamboo for structural applications in their round form. Furthermore, the code classifies these bamboo species into three groups (A, B, C) based on their strength characteristics (30). For the present study, Bambusa Pallida, classified in group B, was selected due to its straight culms, high strength, and availability (31). The bamboo culms of Bambusa Pallida, approximately 4 years old, were sourced from the forests of Assam, India. The diameter of the culm ranged between 20 to 25 mm, with a wall thickness of 10 to 12 mm, and having average node spacing of 240 mm.

Fig. 2. Bamboo samples with holes at internodal sections

Fig. 3. Pressure treatment chamber for Bamboo

Raw bamboo culms were manually cleaned and air-dried for approximately 6 weeks. A pressure treatment method was subsequently employed to enhance the bamboo's longevity and resistance to pests. To facilitate this treatment, two 3 mm holes were drilled at each internodal section, positioned opposite each other (see Figure 2). These holes allowed the preservative to penetrate from both sides, thereby increasing the effectiveness of the treatment. The bamboo culms were then placed inside a pressure vessel (see Figure 3), where a vacuum was applied to extract air and moisture from the bamboo. The bamboo remained under pressure for approximately 4 hours to ensure the preservative fully impregnated the material. Creosote was used as the preservative, following the guidelines specified in IS 9096: 2006, "Preservation of Bamboo for Structural Purposes" (32). A pressure of 4 kg/cm^2 was maintained within the vessel, enabling the preservative to penetrate deeply into the bamboo.

2.2 Treatment of Bamboo

The bamboo bars were treated with two epoxy-based bonding agents: Sikadur-32 LP (SD), manufactured by Sika India Private Ltd., and 211 Dr. Fixit Epoxy (DF), manufactured by Pidilite Industries Ltd. SD was prepared by mixing components A (resin) and B (hardener) in a 2:1 weight ratio, while DF was prepared by mixing components A and B in a 1:0.87 weight ratio. Both bonding agents were thoroughly mixed to achieve a smooth consistency and uniform color. A thin layer was then uniformly applied to the portion of each bamboo bar intended for embedding in concrete using a brush. After 24 hours, a second layer was applied to ensure consistent coverage and improve adhesion. The characteristics of each bonding agent, as detailed in their respective technical data sheets, are presented in Table 2.

Table 2. Characteristics of Bonding agents

Bonding agent	Mix Density [kg/m^3]	Compressive strength [MPa]	Tensile strength [MPa]	Shear bond strength [MPa]
SD	1700	>55	18-20	>10
DF	1120	60	10.4	Concrete failure

Additionally, to enhance friction, five different mechanical treatments were applied after the first layer of the bonding agent, followed by the application of a second layer. These treatments included steel wire, a PVC clamp, sand particles, a hose clamp, and a steel wire mesh. A 1 mm diameter steel wire is wrapped around the coated surface in a spiral pattern, with both ends of the wire tightened together to ensure a secure connection between the bamboo and the wire. A polyvinyl chloride (PVC) clamp is positioned 75 mm from the end of the bamboo bar and secured around it using the bonding agent. A steel wire mesh with a 10 mm grid size is securely fastened around the bamboo bar by tightening the ends of the wire mesh together. A hose clamp with a diameter ranging from 20 to 32 mm is securely tightened using the screw provided and is positioned 75 mm from the end of the bamboo. The sand particles, ranging from 1.18 to 2.36 mm in size, are sprinkled onto the first layer of the bonding agent, followed by the application of a second layer of the bonding agent. Each sample set consisted of three specimens, with a few of them depicted in Figure 4.

Fig. 4. Bamboo samples after treatment

2.3 Mix Proportions

The concrete mix used was M20, with proportions of 1:1.69:2.87:0.5 (cement: fine aggregate: coarse aggregate: water-cement ratio). The mix design followed the guidelines of IS 10262:2019 (33). The concrete mix was prepared using Portland pozzolana cement (PPC), crushed stone with nominal sizes of 20 mm and 10 mm, with a specific gravity of 2.78, and local river sand meeting Zone III specifications with a specific gravity of 2.7. To ensure adequate workability and interlocking, the volume of coarse aggregate was divided into two different nominal sizes: 20 mm and 10 mm, in a ratio of 60:40.

Table 3. Properties of the concrete

Mix Proportion	Slump [mm]	Compressive strength [MPa]	Tensile Strength [MPa]	Flexural Strength [MPa]
1:1.69:2.87 w/c 0.5	85	26.8	2.95	3.92

The slump value achieved for the design mix ranges from 85 mm to 100mm. After 28 days of curing, the specimens were tested for the strength properties of the designed concrete mix, determined according to the test procedures specified in IS 516:2021(34). The measured average compressive strength of the cubes was 17 MPa at 7 days and 26.8 MPa at 28 days. The test results are presented in Table 3.

2.4 Test Method for Water Absorption of Bamboo

This research investigates the water absorption characteristics of three types of bamboo samples: untreated bamboo, bamboo treated with SD, and bamboo treated with DF. These treatments were applied to create a protective layer on the bamboo surface, aiming to reduce its natural tendency to absorb water. The water absorption test was conducted as per the IS 1124 guidelines, ensuring standardized and reliable measurements. To understand how water absorption progresses over time, observations were systematically recorded at specific intervals: 1, 2, 3, 5, 10, 15, and 30 days. This approach allowed for a comprehensive assessment of both initial and long-term water absorption trends for each treatment type.

2.5 Test Method for Pull-Out Test

This test was conducted to evaluate the bond performance between bamboo and concrete. Currently, there is no standardized code specifically for assessing the bond strength of bamboo. Therefore, the procedure outlined in IS:2770-1 (Methods of Testing Bond in Reinforced Concrete for Pull-out Test of Steel Rebars) is utilized. A series of pull-out tests was conducted on thirty-nine samples using a computerized Universal Testing Machine (UTM). Pull-out test samples were prepared using bamboo specimens embedded into 150 mm concrete cubes, with the node positioned at the center. Each bamboo specimen was cut to a total length of 600 mm to fit the requirements of the UTM.

Fig. 5. Pull-out samples after casting

Each treated category was further subdivided into six distinct treatment types: bamboo with an epoxy coating, bamboo wrapped with steel wire, bamboo with a PVC clamp, bamboo coated with sand particles, bamboo with a hose clamp, and bamboo encased in a steel wire mesh, as detailed in Table 4. The casted pull-out samples are shown in Figure 5. After the 28-day curing period, these samples were subjected to testing. Additionally, a schematic representation of the pull-out sample and the forces related to the bond is provided in Figure 6, while Figure 7 illustrates the loading apparatus. An equilibrium of resistive forces (R) and applied force (P) in the axial direction is expressed in Equation (1).

$$P = \tau \, . \, p \, . \, la \quad (1)$$

where, P = pull-out force applied through the UTM [N]; τ = bond stress [MPa]; l_a = embedment length [mm] of a bamboo bar; and p = perimeter of bamboo [mm]

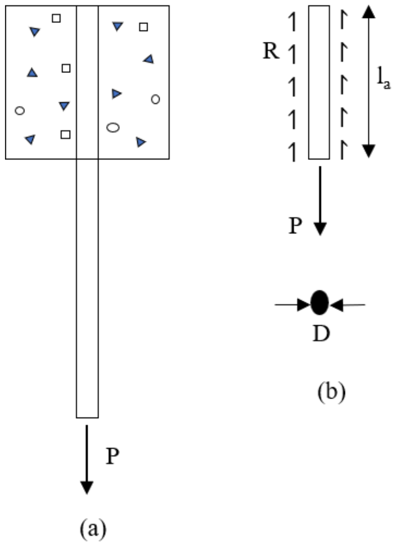

Fig. 6. Schematic representation of (a) Pull-out sample (b) Forces related to bond

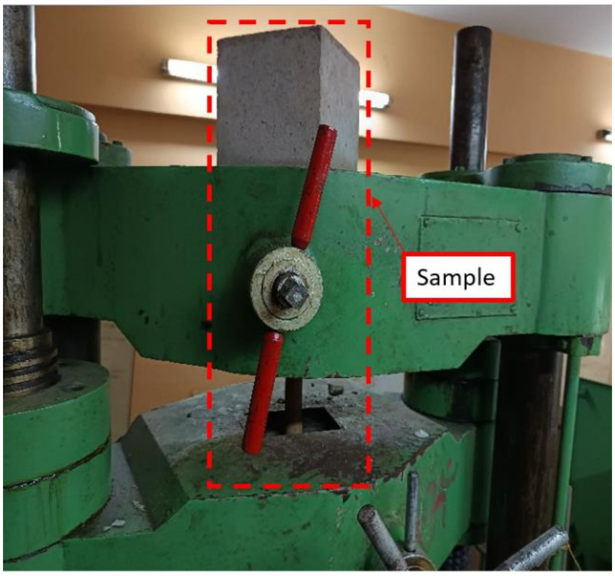

Fig. 7. Pull-out sample placed inside UTM

3. Results and Discussion

3.1 Water Absorption of Bamboo

The water absorption test results indicated that untreated specimens exhibited the highest rate of water absorption, particularly within the first two days.

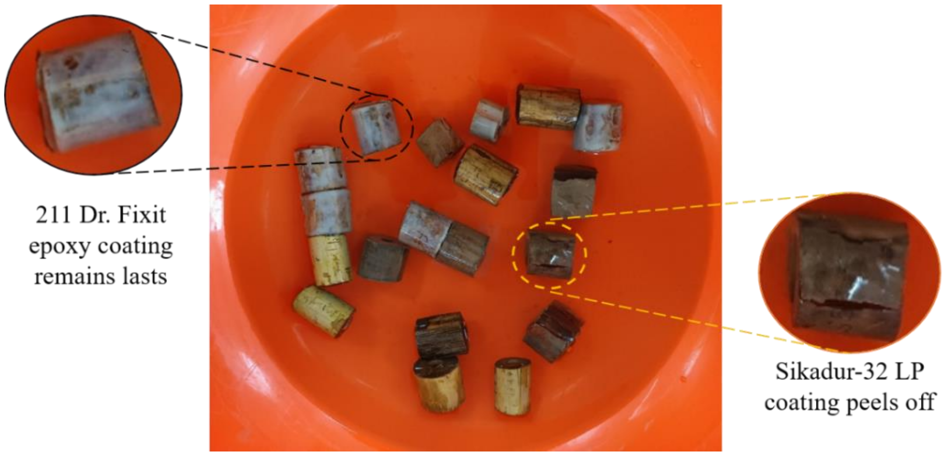

Fig. 8. Bamboo samples immersed in water for water absorption test

After this initial period, the absorption rate significantly decreased. In contrast, specimens coated with SD showed low water absorption during the first five days; however, this rate increased sharply afterward. This sudden increase is attributed to the peeling of the coating layer due to prolonged water immersion, as illustrated in Figure 8, which suggests that the SD bonding agent is less effective in providing long-term water resistance. Conversely, the DF-coated specimens absorbed the least amount of water throughout the entire test period, likely because the coating remained intact, demonstrating its superior efficiency. The water absorption results are presented in Figure 9.

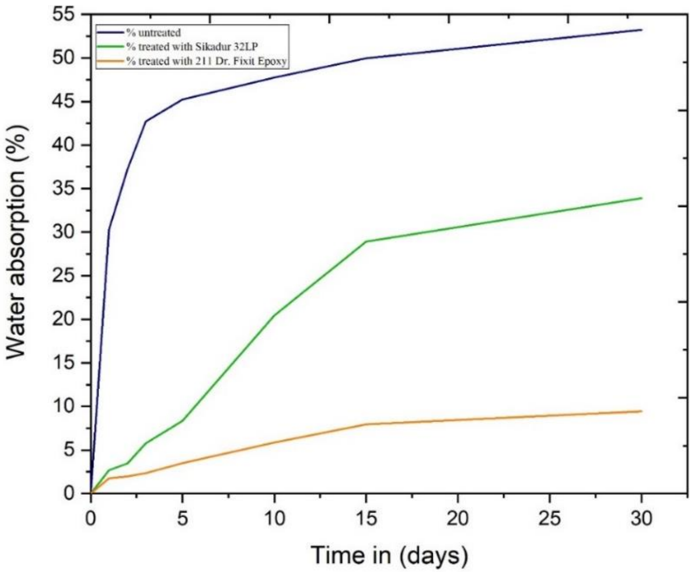

Fig. 9. Water absorption of different bamboo samples

3.2. Effect of Chemical Surface Treatment on Bond Strength

The untreated bamboo specimens exhibited the lowest bond strength, with an average value of 0.59 MPa. Both chemical treatments significantly enhanced the bond strength compared to untreated samples. For specimens treated with SD, a bond strength of 0.81 MPa was observed, resulting in an average increase of approximately 1.39 times compared to untreated bamboo. In contrast, DF-treated specimens exhibited an average bond strength of 0.97 MPa, approximately 1.65 times higher than that of untreated bamboo and 1.19 times greater than the SD-treated specimens. This enhancement can be attributed to the higher shear strength of the DF bonding agent, as indicated in its technical data sheet.

The findings indicate that chemical treatments play a crucial role in enhancing bond strength by establishing a stronger adhesive bond between bamboo bars and concrete, with DF treatment providing the best results. However, it was observed that the bonding agent layer detaches from the bamboo in the slippage portion, suggesting that the applied pull-out load exceeded the adhesive bond's resistance at the bamboo surface. Post-failure analysis revealed that the coating remained adhered to the concrete, indicating a stronger bond with the concrete than with bamboo. This suggests that the failure likely occurred at the weaker bamboo-adhesive interface due to inadequate adhesion.

3.3. Effect of Mechanical Surface Treatment on Bond Strength

In this study, various mechanical treatments were examined to assess their effect on bond strength during pull-out tests. Figures 10 and 11 illustrate the average load versus slip behavior for bamboo samples (B1 to B6) and (B7 to B12), respectively. The results indicate that among the (B1 to B6) group, sample (B2) achieved the highest bond strength of 2.17 MPa, which is 3.7 times greater than that of the untreated (B0) sample and 2.66 times higher than the (B1) sample. Additionally, samples B1, B3, B4, B5, and B6 showed bond strength improvements of 38%, 194%, 253%, 118%, and 182%, respectively, compared to the untreated (B0) sample. Among the (B7 to B12) group, sample (B8) exhibited the highest bond strength at 2.56 MPa, which is 4.38 times greater than the (B0) sample and 2.65 times higher than the (B7) DF-treated sample. Similarly, samples B7, B9, B10, B11, and B12 showed improvements of 65%, 237%, 328%, 163%, and 311%, respectively, relative to the untreated bamboo.

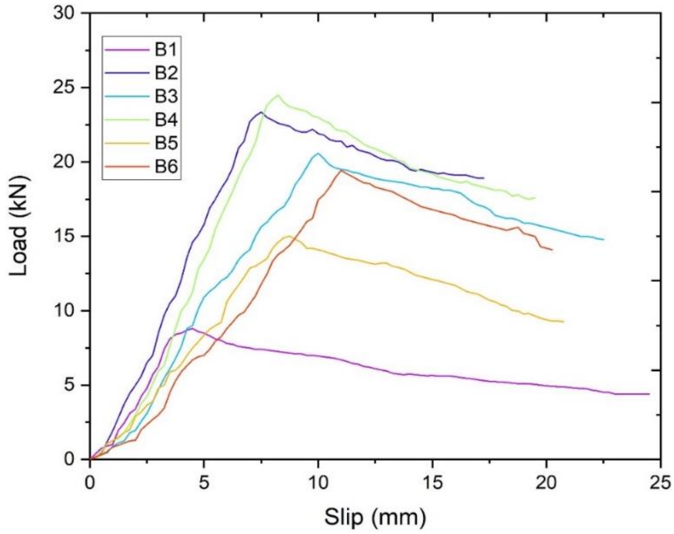

Fig. 10. Load-slip curve for SD-treated bamboo samples

Table 4. Experimental results of pull-out tests of bamboo specimens.

Sample ID	Treatment Provided		Average peak load [N]	Avg. Bond Strength [MPa]	Increase in Bond strength	Failure mode
	Chemical	Mechanical				
B0	-	-	6200	0.59	1	Bamboo Slippage
B1	SD	-	8800	0.81	1.39	Bamboo Slippage
B2	SD	Steel wire	24500	2.17	3.7	Bond failure with concrete spalling
B3	SD	PVC clamp	20580	1.73	2.95	Bamboo Slippage
B4	SD	Sand coated	23356	2.07	3.53	Bamboo Slippage
B5	SD	Hose clamp	15026	1.28	2.18	Bamboo Slippage
B6	SD	Steel wire mesh	19436	1.65	2.82	Bamboo Slippage
B7	DF	-	10472	0.97	1.65	Bamboo Slippage
B8	DF	Steel wire	28950	2.56	4.38	Bond failure with concrete spalling
B9	DF	PVC clamp	23560	1.97	3.38	Bamboo Slippage
B10	DF	Sand coated	28346	2.51	4.29	Bond failure with concrete spalling
B11	DF	Hose clamp	18150	1.54	2.63	Bamboo Slippage
B12	DF	Steel wire mesh	22700	2.41	4.11	Bamboo Slippage

Overall, both chemical and mechanical treatments significantly improved bond strength, with the DF and steel wire combination (B8) showing the most substantial enhancement. Sample B8 exhibited superior bond strength due to the confining effect of the wire wrapping, which increased shear force transfer between the bamboo and concrete while minimizing slippage during the pull-out test. This confinement led to greater resistance to debonding. Notably, the sand-sprinkled sample (B10) achieved nearly identical average bond strength, only 2% lower than that of sample B8, indicating a minimal difference. The increased bond strength in sample B10 is attributed to the roughened surface texture created by the sand particles, which enhanced frictional resistance and mechanical interlocking with the surrounding concrete, thereby improving adhesion and load transfer. Additionally, both B8 and B10 samples displayed stiffer initial sliding stages in their load-slip curves, suggesting a stronger bond between bamboo and concrete, as shown in Figure 11.

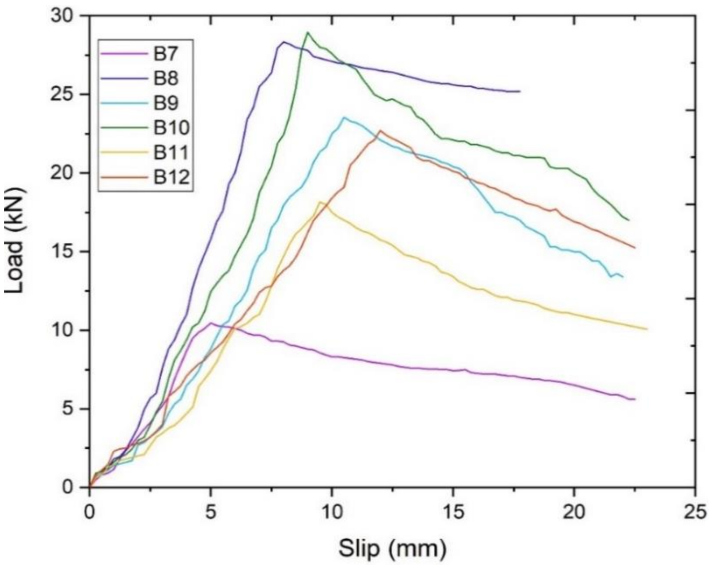

Fig. 11. Load-slip curve for DF-treated bamboo samples

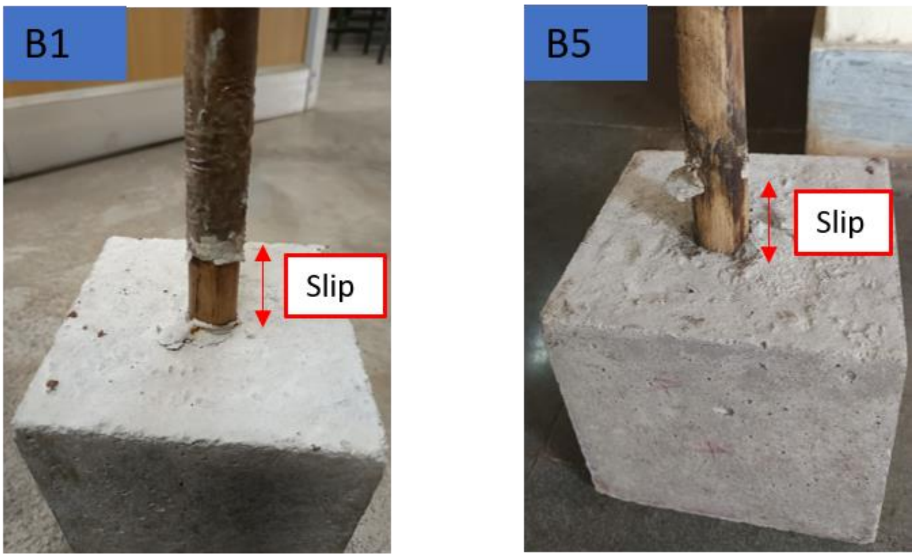

Fig. 12. Bond failure due to slippage of bamboo

Fig. 13. Bond failure with concrete spalling

3.4. Effect of Surface Treatment on Failure Mode

The failure modes observed during the pull-out tests were classified as either bond failure with concrete spalling or slippage of the bamboo, as shown in Table 4. The untreated sample (B0) and most of the treated samples (B1, B3, B4, B5, B6, B7, B9, B11, B12) exhibited failures due to slippage of the bamboo, as illustrated in Figure 12, resulting in lower bond strength. This slippage indicates that the applied force exceeded the adhesive and frictional resistance provided by the treatments.

In contrast, samples B2, B8, and B10, treated with steel wire and sand particles in addition to bonding agents, exhibited bond failures characterized by concrete spalling, as shown in Figure 13. These treatments significantly enhanced bond strength, enabling efficient load transfer from bamboo to concrete. This failure mode may be attributed to high shear stress concentrations around the embedded bamboo. It suggests that while the bond strength between bamboo and concrete was sufficient to transfer loads, the surrounding concrete could not withstand the resulting stresses, leading to spalling. Consequently, these treatments not only enhance bond strength but also shift the failure mode from bamboo slippage to concrete spalling, indicating a stronger bond between bamboo and concrete.

4. Conclusions

In this research, thirty-nine bamboo bars were embedded in concrete cube specimens and subjected to pull-out tests. A detailed comparison was made to assess the effects of chemical and mechanical treatments on the load-slip curve, bond strength, and failure modes of the pull-out samples. The following conclusions were drawn:

- The newly proposed DF bonding agent was found to be more effective in reducing water absorption and thereby improving bond strength compared to untreated and SD-treated samples.
- Mechanical treatments like steel wire, PVC clamp, sand particles, hose clamp, and steel wire mesh showed improved bond strength with both bonding agents.
- The bond strength of the B8 sample was the highest at 2.56 MPa, followed by the B10 sample at 2.51 MPa, while the B0 sample measured the lowest value of 0.59 MPa.
- The failure mode in the B2, B8, and B10 samples shifted from bamboo slippage to concrete spalling. This transition indicates that the applied treatments significantly improved the bond strength, surpassing the tensile capacity of the surrounding concrete.
- The B10 sample required less preparation time, was eco-friendly, and more economical than the B8 sample, with a bond strength reduction of less than 2 percent.
- Samples B8 and B10 exhibited stiffer initial sliding stages in the load–slip curves compared to other specimens, indicating a stronger bond. The highest slip at peak load was observed in the B0 sample, while the lowest occurred in the B8 sample.

This study investigated the short-term bond behavior of treated bamboo in concrete, limited to 28-day results. Future research should examine long-term performance under varying environmental exposure conditions and concrete ages to better evaluate durability. Such investigations will contribute to the effective use of bamboo as a sustainable reinforcement material in construction.

References

[1] Bertolini L, Elsener B, Pedeferri P, Redaelli E, Polder RB. Corrosion of steel in concrete: prevention, diagnosis, repair. John Wiley & Sons; 2013. https://doi.org/10.1002/9783527651696
[2] wold steel Association world steel. Sustainability Indicators 2023 report. 2023;(November):1-9.
[3] Abdalla JA, Hawileh RA, Bahurudeen A, Jyothsna G, Sofi A, Shanmugam V, et al. A comprehensive review on the use of natural fibers in cement/geopolymer concrete: A step towards sustainability. Case Stud Constr Mater [Internet]. 2023;19(June):e02244. https://doi.org/10.1016/j.cscm.2023.e02244
[4] Cavalieri F, Bellotti D, Caruso M, Nascimbene R. Comparative evaluation of seismic performance and environmental impact of traditional and dissipation-based retrofitting solutions for precast structures. J Build Eng. 2023;79(September). https://doi.org/10.1016/j.jobe.2023.107918

[5] Nascimbene R, Bianco L. Cyclic response of column to foundation connections of reinforced concrete precast structures: Numerical and experimental comparisons. Eng Struct [Internet]. 2021;247(September):113214. https://doi.org/10.1016/j.engstruct.2021.113214
[6] Cavalieri F, Bellotti D, Nascimbene R. Seismic vulnerability of existing precast buildings with frictional beam-to-column connections, including treatment of epistemic uncertainty. Bull Earthq Eng [Internet]. 2023;21(2):1117-38. https://doi.org/10.1007/s10518-022-01574-x
[7] Bala A, Gupta S. Engineered bamboo and bamboo-reinforced concrete elements as sustainable building materials: A review. Constr Build Mater [Internet]. 2023;394(March):132116. https://doi.org/10.1016/j.conbuildmat.2023.132116
[8] de Sousa Leite L, Souza MT, da Silva EJ, Benvenuti T, de Castro Pessôa JR, Amado FDR. Assessing the flexural strength of reinforced concrete beams with bamboo splints co-assembled to steel rebars under three- and four-point flexural strength testing. Case Stud Constr Mater. 2024;20(February):1-15. https://doi.org/10.1016/j.cscm.2024.e02933
[9] Tariq M, Haydar S, Khushnood RA, Haq EU, Hameed A, Khan N. Advancing sustainable construction: Experimental study of concrete beams reinforced with chemically treated bamboo and enhanced interfacial bonding using nanotechnology. J Build Eng. 2025;99(November 2024). https://doi.org/10.1016/j.jobe.2024.111552
[10] Karakus-Zambak O, Celik OC. Behavior of bamboo reinforced concrete (BRC) beams under monotonic and dynamic loads. Constr Build Mater [Internet]. 2025;458(October 2024):139683. https://doi.org/10.1016/j.conbuildmat.2024.139683
[11] Scurlock JMO, Dayton DC, Hames B. Bamboo: An overlooked biomass resource? Biomass and Bioenergy. 2000;19(4):229-44. https://doi.org/10.1016/S0961-9534(00)00038-6
[12] Mishra M, Kumar MK, Maity D. Experimental evaluation of the behaviour of bamboo-reinforced beam-column joints. Innov Infrastruct Solut [Internet]. 2019;4(1):11-5. https://doi.org/10.1007/s41062-019-0237-9
[13] Archila H, Kaminski S, Trujillo D, Zea Escamilla E, Harries KA. Bamboo reinforced concrete: a critical review. Mater Struct Constr [Internet]. 2018;51(4). https://doi.org/10.1617/s11527-018-1228-6
[14] Puri V, Chakrabortty P, Anand S, Majumdar S. Bamboo reinforced prefabricated wall panels for low cost housing. J Build Eng [Internet]. 2017;9:52-9. https://doi.org/10.1016/j.jobe.2016.11.010
[15] Harelimana V, Zhu J, Yuan J, Uwitonze C. Investigating the bamboo as alternative partial replacement of steel bars in concrete reinforcement members. Struct Des Tall Spec Build. 2022;31(6):e1921. https://doi.org/10.1002/tal.1921
[16] Kankam JA, Perry SH. Variability of bond strength between bamboo and concrete. ACI Mater J. 1989;86(6):615-8. https://doi.org/10.14359/2290
[17] Ghavami K. Bamboo as reinforcement in structural concrete elements. Cem Concr Compos. 2005;27(6):637-49. https://doi.org/10.1016/j.cemconcomp.2004.06.002
[18] Kute SY, Wakchaure MR. Performance Evaluation for Enhancement of Some of the Engineering Properties of Bamboo as Reinforcement in Concrete. J Inst Eng Ser A. 2014;94(4):235-42. https://doi.org/10.1007/s40030-014-0063-1
[19] Agarwal A, Nanda B, Maity D. Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. Constr Build Mater. 2014 Nov 30;71:610-7. https://doi.org/10.1016/j.conbuildmat.2014.09.011
[20] Mali PR, Datta D. Experimental study on improving bamboo concrete bond strength. Adv Concr Constr. 2019;7(3):191-201.
[21] Muhtar, Dewi SM, Wisnumurti, Munawir A. Enhancing bamboo reinforcement using a hose-clamp to increase bond-stress and slip resistance. J Build Eng [Internet]. 2019;26:100896. https://doi.org/10.1016/j.jobe.2019.100896
[22] Qaiser S, Hameed A, Alyousef R, Aslam F, Alabduljabbar H. Flexural strength improvement in bamboo reinforced concrete beams subjected to pure bending. J Build Eng [Internet]. 2020;31(February):101289. https://doi.org/10.1016/j.jobe.2020.101289
[23] Mondal B, Maity D, Patra PK. Bond Behavior between Bamboo and Normal-Strength Concrete: Experimental and Numerical Investigation. Pract Period Struct Des Constr. 2022;27(3):1-11. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000715
[24] Sivakumar R, Ganesan R, Latha A, Moolchandani K, Sharma AK, Mishra SRK, et al. Experimental Analysis on the Feasibility of Bamboo Reinforcement in Concrete Mix Design and Comparison with Steel Reinforced Concrete. Adv Mater Sci Eng. 2023;2023. https://doi.org/10.1155/2023/6931291
[25] Sakaray H, Togati NVVK, Reddy IVR. Investigattion on properties of bamboo as reinforcing material in concrete. Int J Eng Res Appl. 2012;2(1):77-83.
[26] Tazowar M, Farhan A, Siddique A, Ahmed I. A novel approach for enhancing the bond performance of bamboo reinforced concrete by surface treatment and corrugation. Constr Build Mater [Internet]. 2023;409(September):133728. https://doi.org/10.1016/j.conbuildmat.2023.133728

[27] Khatib A, Nounu G. Corrugated bamboo as reinforcement in concrete. Proc Inst Civ Eng Struct Build. 2017;170(4):311-8. https://doi.org/10.1680/jstbu.16.00067
[28] Wang G, Wei Y, Chen S, Zhao K, Zhou Z. Bond performance between surface-modified bamboo bars and concrete under pull-out loading. J Build Eng [Internet]. 2023;79(October):107920. https://doi.org/10.1016/j.jobe.2023.107920
[29] Terai M. Bond properties of bamboo reinforcement. J Build Eng [Internet]. 2024;86(February):108890. https://doi.org/10.1016/j.jobe.2024.108890
[30] IS 15912. Structural Design Using Bamboo - Code of Practice. Bur Indian Stand Dehli. (November).
[31] Dorjee S, Stapleton C, Chophel U, Tshering D, Samdrup T. Bambusa pallida (Poaceae: Bambusoideae), a new record for Bhutan. Bamboo Soc. 2020;30(July):1-5.
[32] 9096:2006 I. Preservation of Bamboo for Structural Purposes - Code of Practice. Bur Indian Stand. 2006;
[33] Bureau of Indian Standards. IS 10262: 2019- Concrete Mix Proportioning- Guidelines. Bur Indian Stand. 2019;Second Rev(January):1-40.
[34] Bureau of Indian Standards. IS 516 : 2021 - Hardened concrete - Methods of test. Bur Indian Stand [Internet]. 2021;516(March):1-20. Available from: www.standardsbis.in