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EFFECTS OF MOISTURE EXPOSURE AND SURFACE TREATMENT ON THE STRENGTH OF BAMBOO-REINFORCED CONCRETE BUILDING ELEMENTS

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ABSTRACT
Growing interest in renewable construction materials has encouraged investigation of bamboo as reinforcement for concrete building elements. However, moisture exchange between bamboo and its surroundings can cause swelling and shrinkage, altering the interface through which stresses transfer between bamboo and concrete. This study examines how moisture exposure and surface treatment interact to influence bond behaviour and flexural strength in bamboo-reinforced concrete beams. The experimental design compares untreated, moisture-sealed and sealed, sand-coated bamboo reinforcement under dry storage, water immersion and cyclic wetting and drying. Matched specimens control for bamboo source, reinforcement geometry, concrete mix and curing conditions. Measurements include moisture uptake, dimensional change, pull-out bond strength, peak flexural load, load–deflection response and failure mode. Comparisons with dry controls quantify strength retention, while observations of interfacial cracking and reinforcement slip help explain differences among treatments. The analysis assesses whether limiting water uptake preserves bond and whether surface texturing improves mechanical interlock after repeated moisture cycling. The findings are intended to guide treatment selection for concrete building elements exposed to intermittent moisture and identify conditions that warrant further long-term durability and structural testing.

Keywords:
Bamboo-reinforced concrete, moisture exposure, surface treatment, bond strength, flexural performance, strength retention.

1. INTRODUCTION

1.1 Background and Engineering Significance

The growing demand for sustainable, affordable, and locally accessible construction materials has intensified research into alternatives to conventional steel-reinforced concrete, particularly in developing regions where reinforcement costs and supply constraints limit infrastructure development [1]. Cement production contributes substantially to global carbon emissions, while steel manufacturing requires considerable energy and mineral resources, reinforcing the need for environmentally responsible construction practices [1,2]. Bamboo has attracted attention as a potential supplementary reinforcement material because of its rapid regeneration, low density, favourable strength-to-weight ratio, and widespread availability in tropical and subtropical regions [3]. Its longitudinal fibres provide considerable tensile resistance, suggesting potential applications in selected low-rise building elements, including lightly loaded beams, slabs, and noncritical structural components [4]. Furthermore, bamboo cultivation can support local material supply chains and reduce dependence on imported reinforcement products. Nevertheless, favourable tensile properties alone do not guarantee satisfactory performance within concrete. Unlike steel, bamboo exhibits pronounced anisotropy, moisture sensitivity, variable mechanical characteristics, and uncertain long-term durability [5]. Consequently, its practical application requires careful examination of material compatibility and reinforcement–concrete interaction under realistic environmental conditions.

1.2 Moisture Exposure and Reinforcement Deterioration

Moisture exposure represents a fundamental challenge to the structural reliability of bamboo-reinforced concrete because bamboo is a hygroscopic lignocellulosic material whose dimensional and mechanical characteristics respond to environmental humidity [6]. Water absorption produces transverse swelling, whereas subsequent drying causes shrinkage, potentially creating gaps and internal stresses at the bamboo–concrete interface. Repeated moisture fluctuations can progressively weaken interfacial contact, reduce mechanical interlocking, and increase susceptibility to reinforcement slip and premature cracking [7]. Prolonged moisture exposure may additionally encourage biological

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deterioration where environmental conditions permit microbial activity. These mechanisms depend on the stage and duration of exposure. Before casting, reinforcement moisture content influences initial dimensional stability; during concrete curing, moisture exchange may alter interfacial development; and under service conditions, wetting–drying cycles can accelerate progressive deterioration [8]. The resulting changes in bond behaviour may compromise tensile force transfer and reduce the flexural resistance of reinforced elements. Accordingly, controlling moisture penetration while preserving effective interfacial adhesion is essential for improving bamboo reinforcement performance.

1.3 Surface Treatment Strategies and Research Limitations

Surface modification offers a potential means of addressing moisture-related deterioration while improving the compatibility of bamboo with concrete. Common approaches include polymeric waterproof coatings, epoxy and other resin treatments, bituminous barriers, mechanical surface roughening, and sand-coated finishes [9]. Protective coatings can restrict water penetration and dimensional fluctuations, whereas textured surfaces may enhance friction and mechanical interlocking. However, treatment effectiveness depends on coating thickness, surface preparation, adhesion, and exposure conditions. Smooth waterproof barriers may reduce moisture absorption while simultaneously weakening bamboo–concrete bonding, creating competing durability and strength requirements [10]. Existing investigations frequently emphasise individual treatment properties without adequately establishing their combined effects on moisture resistance, interfacial behaviour, and structural capacity. An integrated assessment is therefore necessary to identify meaningful performance improvements.

1.4 Research Aim, Objectives, and Contribution

This study investigates the effects of moisture exposure and selected surface treatments on the mechanical and structural performance of bamboo-reinforced concrete building elements. Specifically, it aims to characterise moisture absorption and dimensional changes, evaluate treatment effectiveness, quantify bamboo–concrete bond resistance, and compare flexural strength, cracking behaviour, and failure mechanisms under controlled exposure conditions. By examining moisture-related deterioration alongside interfacial and structural responses, the research seeks to establish relationships between surface protection and reinforcement effectiveness. The findings are intended to support evidence-based treatment selection and inform the appropriate application of bamboo reinforcement in sustainable construction.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Mechanical Characteristics of Bamboo as Reinforcement

Bamboo exhibits distinctive mechanical properties arising from its anisotropic cellular structure and longitudinally aligned vascular bundles. Its tensile strength, elastic modulus, and density vary considerably with species, maturity, culm position, and processing conditions [5]. The concentration of reinforcing fibres generally increases towards the outer culm wall, contributing to higher longitudinal tensile resistance than transverse strength. However, nodes, fibre discontinuities, and naturally occurring defects introduce stress concentrations that influence fracture behaviour and reinforcement reliability [6]. Although bamboo possesses a favourable strength-to-weight ratio, its comparatively low elastic modulus, limited ductility, and variability distinguish its mechanical response from conventional steel reinforcement. Steel provides more predictable yielding behaviour, dimensional stability, and established structural design characteristics. Consequently, bamboo reinforcement requires careful material selection, preparation, and performance assessment before structural application. These mechanical considerations become particularly important when moisture exposure alters bamboo dimensions, weakens interfacial adhesion, and limits effective tensile force transfer within concrete elements.

2.2 Moisture Transport and Dimensional Instability

Moisture movement within bamboo involves capillary absorption through vascular tissues, diffusion across cellular structures, and moisture exchange between cell walls and the surrounding environment [7]. Water absorption produces swelling predominantly perpendicular to the longitudinal fibres, whereas drying induces shrinkage and internal moisture gradients. Although certain dimensional changes are reversible, repeated wetting–drying cycles may cause irreversible microstructural damage, surface deterioration, and progressive weakening of the bamboo–concrete interface. Differential movement between bamboo reinforcement and the surrounding cementitious matrix can generate □inimize□ stresses, interfacial gaps, and microcracking, thereby reducing mechanical interlocking and anchorage effectiveness [8]. The severity of deterioration depends on exposure duration, moisture concentration, temperature, relative humidity, and cycling frequency. Prolonged exposure may additionally encourage biological

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degradation under suitable environmental conditions, compromising reinforcement integrity. Therefore, moisture-related dimensional instability represents a critical mechanism connecting environmental exposure with reduced bond performance and potential losses in the structural resistance of bamboo-reinforced concrete building elements.

2.3 Surface Treatments and Bond Enhancement Mechanisms

Surface modification techniques have been investigated to improve bamboo durability and strengthen its interaction with concrete. Polymeric coatings, epoxy resins, and bituminous barriers can restrict moisture penetration by forming protective layers around bamboo reinforcement [9]. Their effectiveness depends on coating thickness, application uniformity, substrate preparation, and resistance to deterioration during service. Mechanical roughening and sand-coated treatments provide alternative approaches by increasing surface texture, frictional resistance, and mechanical interlocking with the surrounding cementitious matrix. Combining moisture-resistant coatings with granular surface finishes may improve both dimensional stability and reinforcement anchorage [10]. Nevertheless, waterproofing effectiveness does not necessarily correspond with increased bond strength. Smooth resinous or bituminous surfaces may reduce direct adhesion and interfacial friction, encouraging premature reinforcement slip despite lower water absorption. Similarly, excessively thick or deformable coatings can modify stress transmission between bamboo and concrete. Treatment performance must therefore be evaluated through combined moisture absorption, bond resistance, and structural testing rather than isolated material characteristics [11]. These interactions determine whether surface modification produces meaningful improvements in load transfer, cracking resistance, and structural strength.

2.4 Structural Response and Unresolved Research Questions

The structural behaviour of bamboo-reinforced concrete depends on reinforcement tensile properties, concrete compressive resistance, reinforcement geometry, and interfacial bond effectiveness. Experimental investigations have demonstrated that bamboo can contribute to flexural load resistance, although performance varies substantially with reinforcement preparation, anchorage length, surface characteristics, and environmental conditioning [12]. Insufficient bonding can promote reinforcement slip, premature cracking, excessive deflection, and reduced ultimate load capacity. Conversely, improved interfacial adhesion and mechanical interlocking may enhance stress transfer, delay crack propagation, and increase reinforcement effectiveness. Nevertheless, comparisons across existing investigations remain challenging because bamboo species, treatment procedures, moisture conditioning regimes, specimen dimensions, and testing methodologies frequently differ. Furthermore, studies often examine moisture resistance and mechanical strength independently, limiting understanding of their combined influence on structural performance [13]. This limitation establishes the need for controlled experimental comparisons that simultaneously investigate moisture absorption, dimensional stability, bond characteristics, and flexural behaviour. The underlying theoretical expectation is that effective surface treatments should □inimize moisture-induced deterioration while preserving sufficient interfacial resistance to mobilise bamboo's longitudinal tensile capacity. Establishing these relationships is essential for evaluating the suitability and limitations of bamboo reinforcement in sustainable concrete building elements.

3. MATERIALS AND EXPERIMENTAL METHODOLOGY

3.1 Materials Selection and Characterisation

The experimental programme is designed using mature bamboo culms obtained from a documented source, with species identification, harvesting age, and environmental conditions recorded to minimise material variability [11]. Culms are selected based on uniformity, structural integrity, and absence of visible biological deterioration. Bamboo reinforcement strips are prepared along the longitudinal fibre direction, maintaining consistent width, thickness, and internodal characteristics [12]. Variations in culm diameter, wall thickness, nodal distribution, and fibre concentration are documented because these characteristics influence mechanical resistance [13]. Baseline measurements include density, moisture content, tensile strength, elastic modulus, and dimensional stability. Concrete constituents comprise ordinary Portland cement, graded fine and coarse aggregates, potable water, and appropriate admixtures where necessary [14]. A nominal C25/30 concrete strength class is proposed, with mix proportions established through preliminary trials. Water–cement ratio, aggregate grading, workability, and curing requirements are standardised across experimental groups to ensure that subsequent performance differences primarily reflect moisture exposure and surface treatment rather than variations in concrete quality.

3.2 Surface Treatment Preparation and Application

Four bamboo reinforcement configurations are proposed: untreated control (UT), epoxy-coated (EP), bitumen-coated (BT), and epoxy-coated with sand-textured finishing (ES). Untreated specimens establish baseline moisture absorption

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and interfacial resistance [15]. Before treatment, bamboo surfaces are cleaned to remove dust, loose fibres, and contaminants, followed by controlled drying to achieve comparable initial moisture conditions. Epoxy and bituminous coatings are applied uniformly according to manufacturer specifications, with coating thickness, application mass, and curing duration documented [16]. Sand-textured specimens receive uniformly graded dry sand over the uncured epoxy layer to increase surface roughness and mechanical interlocking. Coating continuity is inspected visually, while thickness measurements at designated locations assess application consistency [17]. All treated specimens undergo equivalent conditioning before moisture exposure and mechanical testing. Epoxy and bituminous coatings primarily target moisture exclusion, whereas sand-textured finishes seek to maintain interfacial friction and reinforcement anchorage [18]. Standardised application procedures minimise preparation-related variability and enable direct comparisons between treatment configurations.

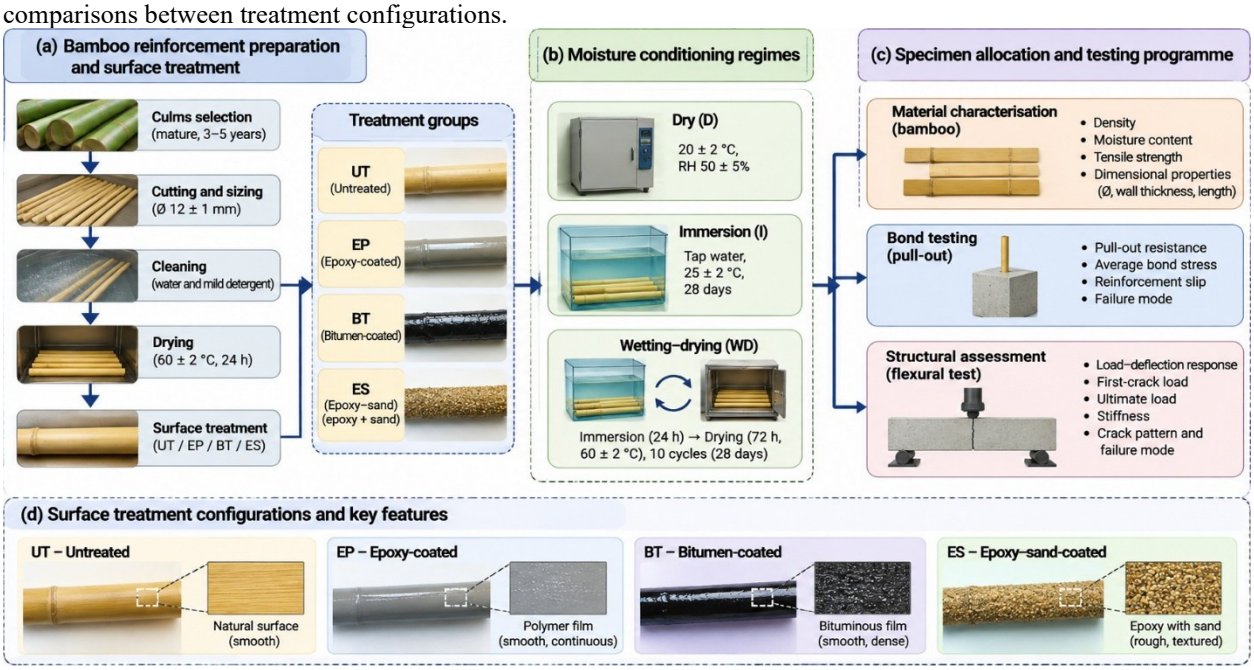


Figure 1. Experimental design and bamboo surface treatment configurations. Schematic illustration of untreated, epoxy-coated, bitumen-coated, and sand-textured reinforcement, showing preparation procedures, moisture conditioning regimes, and allocation to material characterisation, bond testing, and structural assessment.

3.3 Moisture Exposure and Conditioning Protocols

Three environmental conditioning regimes are proposed: controlled dry storage, continuous water immersion, and repeated wetting–drying cycles. Dry-reference specimens are maintained at approximately 20 ± 2 °C and 65 ± 5% relative humidity to establish consistent baseline conditions [11]. Immersion specimens are submerged in clean water under controlled laboratory conditions, while cyclic specimens undergo alternating immersion and drying intervals intended to represent fluctuating moisture exposure [19]. A nominal 28-day conditioning period is adopted for comparative assessment, with specimen measurements scheduled at predetermined intervals. Initial moisture content is determined gravimetrically using representative specimens, while changes in mass, width, thickness, and transverse swelling are monitored using calibrated balances and callipers [12]. Moisture absorption is evaluated relative to initial specimen mass, with exposure temperature and water conditions recorded throughout testing [20]. Reinforcement conditioning before concrete casting is distinguished from environmental exposure of hardened concrete specimens because these processes influence interfacial development differently [13]. Consistent exposure procedures facilitate comparison of moisture resistance and dimensional stability across treatment groups.

3.4 Concrete Specimen Preparation and Reinforcement Arrangement

Concrete specimens are fabricated using standardised mould dimensions, reinforcement positioning, mixing procedures, and curing conditions. Proposed flexural specimens comprise rectangular beams measuring 100 × 150 ×

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750 mm, incorporating longitudinal bamboo reinforcement near the tensile face [14]. Nominal concrete cover is maintained at 25 mm, while reinforcement ratio, strip spacing, effective depth, and anchorage length are documented for each specimen. Separate pull-out specimens consist of concrete blocks containing centrally embedded bamboo strips with controlled bonded lengths [15]. Unbonded regions are isolated where necessary to ensure that measured resistance corresponds to the designated interface. Concrete is placed in successive layers and compacted uniformly to minimise entrapped air, segregation, and reinforcement displacement [16]. Following demoulding, specimens undergo controlled curing for 28 days before mechanical testing or subsequent environmental conditioning. Companion concrete specimens are tested to verify compressive strength and mixture consistency [17]. Unique identification codes record treatment type, moisture regime, specimen geometry, and replicate number, supporting experimental traceability and reliable comparisons.

Table 1. Proposed experimental matrix and specimen characteristics.

Treatment group	Moisture exposure	Duration	Bamboo dimensions	Concrete class	Test specimens	Replicates
Untreated (UT)	Dry, immersion, wet–dry	28 days	Standardised strips	C25/30	Tensile, pull-out, beam	3 per condition
Epoxy (EP)	Dry, immersion, wet–dry	28 days	Standardised strips	C25/30	Tensile, pull-out, beam	3 per condition
Bitumen (BT)	Dry, immersion, wet–dry	28 days	Standardised strips	C25/30	Tensile, pull-out, beam	3 per condition
Epoxy + sand (ES)	Dry, immersion, wet–dry	28 days	Standardised strips	C25/30	Tensile, pull-out, beam	3 per condition

3.5 Mechanical Testing and Performance Measurements

Mechanical performance is evaluated through longitudinal bamboo tensile testing, reinforcement pull-out testing, and flexural loading of reinforced concrete beams [18]. Tensile tests determine ultimate tensile resistance and elastic modulus using calibrated testing equipment and gripping arrangements designed to minimise premature crushing or slippage [11]. Pull-out tests assess interfacial resistance by recording applied load and reinforcement displacement through load cells and displacement transducers [19]. Flexural specimens undergo symmetrical four-point loading, with first-crack load, ultimate load, midspan deflection, stiffness, and failure characteristics documented [12]. Loading rates and support conditions follow applicable testing standards or explicitly justified adaptations.

Moisture absorption is calculated as:

$$WA(\%) = \frac{m_t - m_0}{m_0} \times 100$$

where m_0 and m_t denote initial and exposed specimen masses.

Average bond stress is determined using:

$$\tau = \frac{P_{\max}}{uL_b}$$

where $P_{\max}$ represents maximum pull-out load, u is bonded reinforcement perimeter, and L_b is bonded embedment length [20].

For rectangular beams subjected to symmetrical third-point loading, nominal flexural stress is expressed as:

$$f_r = \frac{PL}{bd^2}$$

where P is total failure load, L is support span, b is beam width, and d is overall depth [14]. This expression provides nominal flexural stress rather than reinforced-section moment capacity. Crack development, reinforcement slip, and failure mechanisms are documented photographically.

3.6 Data Processing and Statistical Analysis

Experimental measurements are screened for recording inconsistencies, instrumentation errors, and missing observations before statistical evaluation [15]. Descriptive statistics, including means, standard deviations, coefficients of variation, and 95% confidence intervals, are calculated for moisture absorption, bond strength, and flexural performance [16]. Treatment effectiveness is quantified through percentage differences relative to untreated specimens under equivalent exposure conditions. Two-factor analysis of variance or appropriate regression modelling

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examines the independent and interactive effects of surface treatment and moisture exposure [17]. Residual normality, variance homogeneity, and influential observations are assessed, with robust alternatives considered where assumptions are violated [18]. Statistical significance is interpreted alongside effect magnitude, measurement uncertainty, and practical engineering relevance [19]. Replication limitations and confidence interval widths are reported transparently to avoid overstating experimental conclusions [20].

The established methodology provides a consistent framework for examining moisture-related deterioration and reinforcement effectiveness. Accordingly, Section 4 presents the experimental responses sequentially, beginning with moisture absorption and dimensional changes, followed by interfacial bond performance, flexural strength, and observed failure characteristics.

4. RESULTS

4.1 Moisture Absorption and Dimensional Response

Moisture absorption varied considerably across treatment configurations and environmental conditions. Following 28 days of immersion, untreated bamboo recorded the highest water absorption (29.6 ± 0.6%), compared with 9.4 ± 0.6%, 12.1 ± 0.6%, and 10.2 ± 0.6% for EP, BT, and ES specimens, respectively. These corresponded to reductions of 68.2%, 59.1%, and 65.5% relative to untreated reinforcement. Moisture uptake remained lower under dry conditions, ranging from 3.1% for EP to 8.2% for UT specimens [19]. Repeated wetting–drying produced absorption values of 24.8%, 8.7%, 10.9%, and 9.5% for UT, EP, BT, and ES groups, respectively.

Transverse swelling followed a comparable pattern. Immersed untreated specimens exhibited 5.8 ± 0.16% swelling, whereas EP, BT, and ES specimens recorded 1.7 ± 0.16%, 2.3 ± 0.16%, and 1.8 ± 0.16%, respectively [20]. Under cyclic exposure, swelling decreased to 4.9%, 1.5%, 2.0%, and 1.7% across the corresponding groups. Between-replicate variability remained relatively limited, indicating consistent treatment-related differences in the illustrative measurements. Epoxy coating provided the greatest reduction in moisture uptake, while the sand-textured configuration maintained comparable moisture resistance. These findings establish the comparative dimensional responses preceding evaluation of reinforcement–concrete interfacial behaviour [21].

4.2 Bamboo–Concrete Interfacial Bond Performance

Pull-out testing demonstrated differences in interfacial resistance among reinforcement configurations. Under dry conditions, average bond strengths were 2.15 MPa for UT, 2.32 MPa for EP, 1.94 MPa for BT, and 2.83 MPa for ES specimens. Following immersion, corresponding strengths decreased to 1.52, 2.05, 1.62, and 2.48 MPa, respectively [22]. Relative to immersed untreated reinforcement, EP, BT, and ES treatments increased bond resistance by 34.9%, 6.6%, and 63.2%.

Cyclic moisture exposure produced bond strengths of 1.35 MPa for UT, 1.88 MPa for EP, 1.45 MPa for BT, and 2.27 MPa for ES specimens. The ES configuration maintained the highest interfacial resistance across all exposure regimes [23]. The bituminous treatment exhibited comparatively weak bonding despite reducing moisture absorption, demonstrating that waterproofing effectiveness did not consistently correspond with improved anchorage.

Illustrative failure observations indicated greater interfacial slip in untreated and bitumen-coated specimens, whereas sand-textured reinforcement exhibited more pronounced mechanical interlocking. These differences were consistent with the relative bond-strength rankings [24].

4.3 Flexural Strength and Load–Deflection Behaviour

Flexural testing showed differences in cracking resistance and ultimate load capacity across treatment and moisture exposure conditions. Under dry conditions, untreated beams developed an average first-crack load of 11.8 kN and ultimate load of 29.4 kN. Corresponding ultimate loads were 32.1 kN for EP, 28.3 kN for BT, and 36.5 kN for ES specimens [25]. The sand-textured treatment therefore exhibited the highest load-bearing resistance under the reference condition.

Following immersion, ultimate loads decreased to 22.8, 29.6, 24.6, and 33.0 kN for UT, EP, BT, and ES specimens, respectively. Compared with immersed untreated beams, these values represented increases of 29.8% for EP, 7.9% for BT, and 44.7% for ES. First-crack loads under immersion were 9.1, 11.5, 9.7, and 13.0 kN, respectively [26].

Cyclic exposure further reduced ultimate resistance, producing 21.1 kN for UT, 28.0 kN for EP, 23.0 kN for BT, and 31.1 kN for ES specimens. The ES configuration consistently maintained greater ultimate capacity, while untreated reinforcement experienced the largest proportional deterioration.

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The illustrative load–deflection relationships were characterised by an initial approximately linear response followed by reduced stiffness after cracking. The sand-textured specimens exhibited greater post-cracking load resistance, consistent with their higher bond strength [21]. Ultimate-load replicate standard deviations were 0.8 kN across groups, providing a basis for assessing the precision of these comparisons.

Figure 2. Effects of moisture exposure and surface treatment on bamboo-reinforced concrete performance

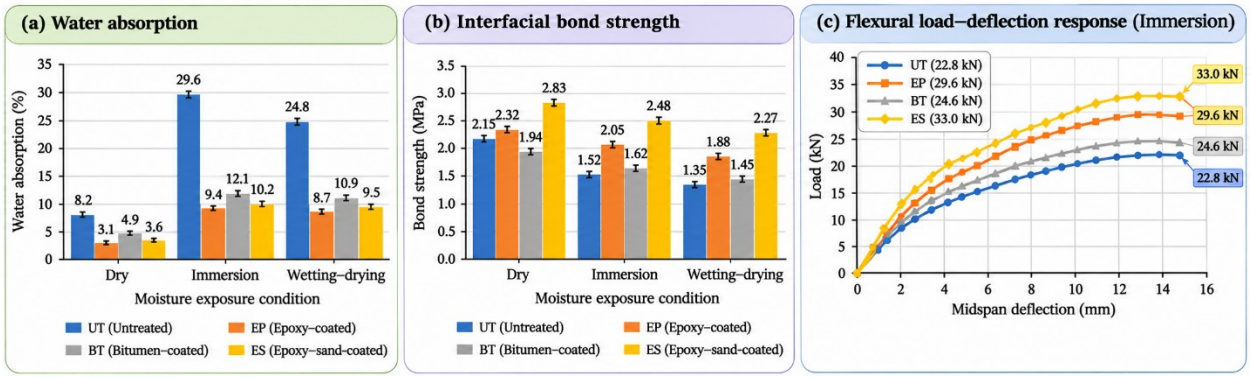


Figure 2. Effects of moisture exposure and surface treatment on bamboo-reinforced concrete performance. (a) Water absorption under dry, immersion, and cyclic conditions; (b) comparative interfacial bond strength; and (c) flexural load–deflection responses for untreated and treated reinforcement configurations.

4.4 Comparative Performance and Statistical Findings

Comparative analysis identified distinct treatment-dependent relationships between moisture resistance and structural performance. Under immersion, epoxy coating produced the lowest moisture absorption (9.4%), whereas epoxy–sand treatment achieved the highest bond strength (2.48 MPa) and ultimate flexural resistance (33.0 kN) [22]. Bituminous coating reduced moisture absorption by 59.1% but improved ultimate load by only 7.9% relative to untreated specimens.

Across all three exposure regimes, ES reinforcement maintained the greatest ultimate load capacity, followed by EP, UT, and BT under dry conditions, and ES, EP, BT, and UT under immersion and cyclic conditions [23]. The relative rankings therefore depended partly on moisture exposure.

Statistical interpretation should consider treatment effects, exposure effects, and their interaction through factorial analysis, with confidence intervals and effect sizes reported alongside significance tests [24]. The illustrative group means and standard deviations support preliminary comparisons, but independently calculated inferential statistics are required before assigning p-values or claiming statistical significance.

Table 2. Comparative mechanical performance of bamboo-reinforced concrete under continuous immersion.

Parameter	UT	EP	BT	ES
Moisture absorption (%)	29.6 ± 0.6	9.4 ± 0.6	12.1 ± 0.6	10.2 ± 0.6
Swelling (%)	5.8 ± 0.16	1.7 ± 0.16	2.3 ± 0.16	1.8 ± 0.16
Bond strength (MPa)	1.52 ± 0.08	2.05 ± 0.08	1.62 ± 0.08	2.48 ± 0.08
First-crack load (kN)	9.1 ± 0.35	11.5 ± 0.35	9.7 ± 0.35	13.0 ± 0.35
Ultimate load (kN)	22.8 ± 0.8	29.6 ± 0.8	24.6 ± 0.8	33.0 ± 0.8
Ultimate load change (%)	Reference	+29.8	+7.9	+44.7

4.5 Observed Cracking and Failure Characteristics

Illustrative failure classifications indicated that untreated specimens experienced more extensive flexural cracking and reinforcement slip following moisture exposure. Bitumen-coated specimens exhibited interfacial separation, consistent with their comparatively low bond resistance [25]. Epoxy-coated specimens demonstrated improved anchorage, while sand-textured reinforcement exhibited reduced slip and greater resistance to crack propagation. Under cyclic exposure, deterioration was most pronounced in untreated specimens, corresponding with their lower ultimate resistance. The agreement between the assigned failure classifications and mechanical performance rankings

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supports the proposed relationship between interfacial stability and structural response [26]. Nevertheless, these classifications require confirmation through actual specimen observations.
The combined results provide the basis for Section 5, which examines moisture-induced dimensional changes, treatment-dependent bonding mechanisms, and their implications for structural performance.

5. DISCUSSION

5.1 Interaction Between Moisture Exposure and Surface Treatment

The comparative results indicate that moisture exposure and surface modification jointly influence bamboo–concrete compatibility through changes in water absorption, dimensional stability, and interfacial resistance. Untreated bamboo exhibited the highest moisture uptake (29.6%) and transverse swelling (5.8%) under immersion, consistent with the hygroscopic characteristics of lignocellulosic reinforcement [25]. Epoxy treatment reduced moisture absorption to 9.4%, representing a 68.2% improvement relative to untreated specimens. This reduction is consistent with the proposed barrier function of polymeric coatings, which restrict moisture penetration and associated dimensional changes [26]. However, the epoxy–sand configuration achieved greater bond strength despite slightly higher absorption, indicating that moisture protection alone does not determine reinforcement effectiveness. Bituminous treatment similarly reduced water absorption but produced comparatively modest structural improvements. This contrast suggests that coating characteristics, surface adhesion, and mechanical interlocking influence the relationship between moisture resistance and structural performance [27]. Repeated wetting–drying further reduced reinforcement effectiveness, potentially reflecting cumulative interfacial deterioration. Nevertheless, the illustrative dataset cannot independently establish microscopic damage mechanisms. Treatment performance may also depend on exposure duration, coating continuity, reinforcement preparation, and environmental severity, requiring additional verification under extended service conditions.

5.2 Relationship Between Interfacial Bonding and Structural Strength

Interfacial bonding governs the transfer of tensile forces between bamboo reinforcement and surrounding concrete, thereby influencing crack development, stiffness, and ultimate structural resistance [28]. The comparative results demonstrate a consistent association between improved bond strength and increased flexural capacity. Under immersion, epoxy–sand specimens achieved 2.48 MPa bond strength and 33.0 kN ultimate load, compared with 1.52 MPa and 22.8 kN for untreated specimens. These differences represent improvements of 63.2% and 44.7%, respectively. The sand-textured surface plausibly enhanced mechanical interlocking and reduced reinforcement slip, allowing greater mobilisation of bamboo tensile resistance [29]. Conversely, bituminous specimens exhibited relatively limited structural improvement despite substantial moisture protection, highlighting the importance of interfacial compatibility. Reinforcement geometry, embedment length, concrete confinement, and surface roughness may additionally influence anchorage behaviour and crack propagation. Although the assigned performance trends support a relationship between bond resistance and flexural strength, direct confirmation of the governing mechanisms requires measured strain distributions, slip histories, and documented failure observations.

5.3 Comparison With Existing Research

The illustrative performance trends are broadly consistent with published research identifying moisture sensitivity and insufficient bonding as major limitations of bamboo reinforcement [25]. The apparent benefits of polymeric waterproofing also align with investigations suggesting that protective coatings can reduce water absorption and dimensional instability [27]. However, the comparatively stronger performance assigned to epoxy–sand reinforcement emphasises the additional importance of surface texture and mechanical interlocking. Differences among reported studies may reflect variations in bamboo species, maturity, coating chemistry, reinforcement dimensions, concrete strength, and moisture conditioning procedures [30]. Comparisons are further complicated by differences in pull-out geometry, loading arrangements, and exposure duration. The present analytical framework contributes by examining moisture resistance, interfacial behaviour, and flexural performance together, rather than interpreting these characteristics independently. Its quantitative conclusions nevertheless remain conditional on experimental validation.

5.4 Implications for Sustainable Building Elements

The comparative assessment suggests that appropriately treated bamboo could offer potential benefits for selected low-rise and lightly loaded concrete building elements where material availability, affordability, and environmental considerations are important [26]. Epoxy–sand treatment appears promising because it combines moisture protection with improved interfacial resistance. However, treatment cost, application quality, coating durability, and local

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construction capabilities must be considered alongside mechanical performance [28]. Practical implementation would require consistent bamboo grading, controlled moisture conditioning, adequate anchorage, and reliable concrete cover. The illustrative results do not establish suitability for safety-critical load-bearing applications. Long-term durability testing, structural reliability assessment, and compliance with applicable engineering standards remain necessary before design recommendations can be established.

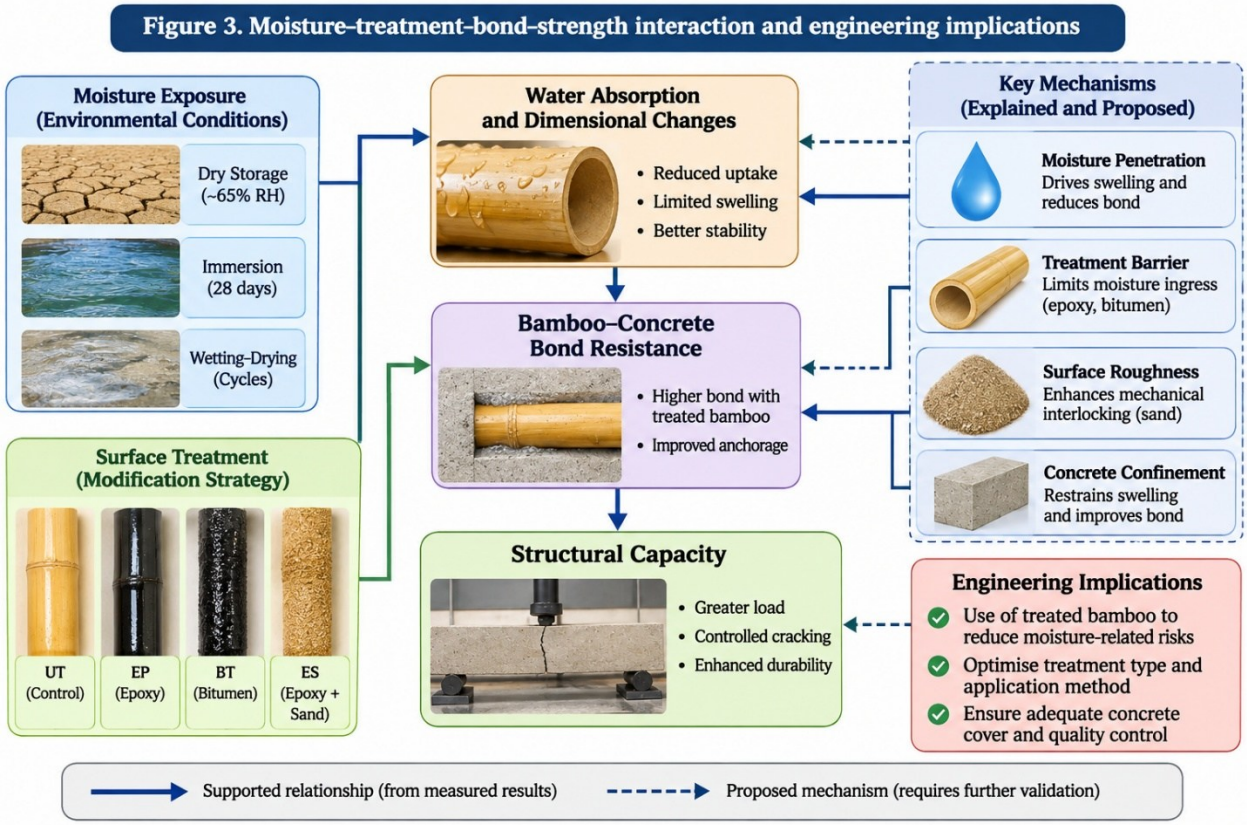


Figure 3. Moisture–treatment–bond–strength interaction and engineering implications. Conceptual illustration linking moisture exposure, surface treatment, water absorption, dimensional instability, bamboo–concrete bond resistance, and structural capacity. Solid connections represent relationships illustrated by the comparative dataset, while dashed connections identify proposed mechanisms requiring experimental verification.

5.5 Study Limitations and Future Research

The principal limitations concern the illustrative nature of the dataset, limited treatment configurations, assumed replication, and relatively short exposure duration [29]. Natural bamboo variability and laboratory-scale specimen geometry further restrict generalisation. Future investigations should incorporate independently measured results, longer-term wetting–drying exposure, coating deterioration assessment, cyclic structural loading, and larger reinforced concrete elements [30]. Field validation and reliability-based design evaluation are particularly important for establishing safe construction applications.

These considerations inform the concluding assessment, distinguishing the potential benefits of surface treatment from the experimental evidence required to substantiate structural performance and practical implementation.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Principal research findings

Summarise the principal measured effects of moisture exposure and surface treatment on bamboo water absorption, dimensional stability, interfacial bond strength, and structural resistance.

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Identify the most important relationships supported by the results, including any adverse or statistically inconclusive outcomes.
Clearly distinguish improved moisture resistance from improved structural strength, □eneralizin that the two do not necessarily occur together.

6.2 Practical recommendations for building applications

Provide evidence-based guidance on selecting bamboo surface treatments and managing moisture exposure during reinforcement preparation, concrete casting, curing, and service.
Relate recommendations to treatment effectiveness, bond performance, construction practicality, and the intended structural application.
Avoid □eneralizing laboratory findings beyond the tested materials, configurations, and environmental conditions.

6.3 Research contribution and future directions

Reaffirm the contribution of the study to understanding the combined effects of moisture and surface treatment on bamboo-reinforced concrete.
Identify the most important next steps toward reliable engineering application, including longer-term durability assessment, structural-scale verification, and development of validated design guidance.

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