UDK 625.821.5:666.982.7
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
Mater. Tehnol.

ENHANCING THE DURABILITY AND MECHANICAL PERFORMANCE OF BAMBOO FIBER-REINFORCED CONCRETE THROUGH MAGNESIUM HYDROXIDE MODIFICATION UNDER WET-DRY CYCLES

IZBOLJŠANJE TRAJNOSTI IN MEHANSKIH LASTNOSTI BETONA OJAČANEGA Z BAMBUSOVIMI VLAKNI PREKO MODIFIKACIJE Z MAGNEZIJEVIM HIDROKSIDOM V MOKRO-SUHIH CIKLUSIH

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Prejem rokopisa – received: 2025-04-22; sprejem za objavo – accepted for publication: 2025-08-22

doi:10.17222/mit.2025.1439

This study systematically investigates the effects of different treatment methods (untreated and magnesium hydroxide [$Mg(OH)_2$] treated fibers) and varying fiber dosages (0, 1.2, 1.8, 2.3 and 2.8) % on the mechanical properties and durability of bamboo fiber-reinforced concrete (BFRC). Compressive, tensile, and flexural strength tests were conducted before and after 16 wet-dry cycles, and scanning electron microscopy (SEM) was used to analyze the microstructure of bamboo fibers and their interfacial bonding mechanisms, establishing the durability of BFRC. The results indicate that as the bamboo fiber content increases, the compressive strength of BFRC decreases, while the tensile and flexural strengths reach their optimal values at a 2.3 % fiber content. Untreated bamboo fibers contain surface impurities, leading to weak interfacial bonding with the cement matrix, whereas $Mg(OH)_2$-treated fibers exhibit a cleaner surface and significantly enhanced interfacial adhesion. After 16 wet-dry cycles, BFRC with untreated fibers showed a flexural strength loss of 11.5–12.7 %, compared to 17.4 % for plain concrete. BFRC with $Mg(OH)_2$-treated fibers further reduced the loss to 8.2–8.9 %, confirming the treatment's effectiveness. This study provides new insights into the development of high-durability and sustainable bamboo fiber-reinforced composites and establishes a theoretical foundation for their application in civil engineering.

Keywords: bamboo fiber, SEM, magnesium hydroxide, durability, mechanical properties

Avtorji v članku opisujejo sistematično študijo vpliva različnih dodatkov bambusovih vlaken v z njimi ojačanem (armiranem) betonu (BFRC; angl.: bamboo fiber-reinforced concrete), na njegove mehanske lastnosti in trajnost. BFRC so armirali z različno količino (0 %, 1,2 %, 1,8 %, 2,3 % in 2,8 %) neobdelanih in z magnezijevim hidroksidom [$Mg(OH)_2$] obdelanimi bambusovimi vlakni. Avtorji so določili tlačno, natezno in upogibno trdnost na izdelanih preizkušancih iz BFRC, ki so bili neobdelani in/ali obdelani s šestnajstimi (16) mokrosuhimi ciklusi. Sledile so še analize mikrostrukture bambusovih vlaken in njihove medmejne vezave s cementno matrico, s pomočjo vrstičnega elektronskega mikroskopa (SEM), ki naj bi pomagale osvetliti korelacije trajnosti BFRC. Rezultati raziskave so pokazali, da se z naraščajočo vsebnostjo bambusovih vlaken zmanjšuje tlačna trdnost BFRC, medtem ko natezna in upogibna trdnost dosežeta svoja optimalna nivoja pri vsebnosti bambusovih vlaken 2,3%. Neobdelana bambusova vlakna vsebujejo površinske napake in nečistoče, kar poslabšuje medmejno vezavo vlaken s cementno matrico. Bambusova vlakna obdelana z $Mg(OH)_2$ imajo bolj čisto površino, kar pomembno izboljša medmejno adhezijo. Po obdelavi BFRC s 16-timi mokrosuhimi ciklusi je prišlo od 11,5% do 12.7%-nega padca upogibne trdnosti BFRC v primerjavi s 17,4%-nim padcem pri nearmiranim betonu. BFRC z vlakni obdelanimi z $Mg(OH)_2$ pa je bilo zmanjšanje upogibne trdnosti le od 8,2 % do 8,9 %-no, kar je upravičilo učinkovitost uporabe postopka obdelave bambusovih vlaken. S to študijo so avtorji postavili teoretične temelje izdelave visoko kvalitetnega trajnostnega betona, armiranega z obdelanimi bambusovimi vlakni za civilno uporabo.

Ključne besede: bambusova vlakna, vrstična elektronska mikroskopija (SEM), magnezijeb hidroksid, trajnost, mehanske lastnosti

1 INTRODUCTION

With the increasing scarcity of global resources and worsening environmental issues, the development of sustainable construction materials has become a key focus in the field of building materials.[1] Bamboo fiber, as a natural, renewable, and environmentally friendly reinforcement material, exhibits excellent specific strength, toughness, and biodegradability, making it widely applicable in construction, transportation, and packaging industries. Incorporating bamboo fiber into cement-based composites not only enhances toughness and crack resistance but also reduces the carbon footprint, promoting the advancement of green construction.[2,3] However, in practical engineering applications, buildings and infrastructure are often exposed to wet-dry cycling conditions, which significantly impact structural integrity and long-term performance of materials.[4] Therefore, examining the structural behavior of bamboo fiber-reinforced

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cementitious composites (BFRCs) subjected to cyclic wet-dry conditions is of great significance for improving their engineering applicability and extending their service life.[5]

The existing studies on BFRCs primarily examine how fiber content, dimensions, and surface modifications influence specific mechanical characteristics.[6,7] For instance, Vinod et al.[8] reported that bamboo fiber substantially enhances the fracture mitigation capacity of cementitious materials. Su et al.[9] found that an optimal fiber content of 1.5 % enhances flexural strength, while Teixeira et al.[10] observed that a fiber length of 20 mm increases compressive strength by approximately 12 %. In China, Pan et al.[11] demonstrated that bamboo fiber improves the flexural strength of cement mortar but has limited influence on the compressive strength. Rasheed et al.[12] revealed that alkaline modification of bamboo fibers promotes stronger matrix-fiber bonding, resulting in significantly improved material resilience under environmental exposure. Additionally, Purnell[13] systematically investigated the deterioration mechanisms of BFRCs under wet-dry cycles, while Patel et al.[14] analyzed strength variations under different cycle numbers, reporting a 15 % reduction in compressive strength after ten cycles. However, most of these studies focus on the reinforcing effects of bamboo fiber in cementitious matrices, whereas the interfacial degradation mechanisms, microstructural evolution, and durability performance of BFRCs under wet-dry cycling remain inadequately explored.[15,16] Moreover, conventional alkali treatment methods have been widely used, but this study proposes a novel magnesium hydroxide ($Mg(OH)_2$) treatment, which is a milder and more effective approach for enhancing fiber-matrix bonding, an area that remains underexplored.[17,18]

The innovative aspects of this study include: introducing $Mg(OH)_2$ treatment as an alternative surface modification method for bamboo fibers; systematically evaluating its reinforcing effect under wet-dry cycling and comparing it with untreated fibers; investigating the evolution of multiple mechanical properties, including compressive, tensile, and flexural strength at different wet-dry cycle stages, providing a comprehensive understanding of the optimal fiber content and modification approach. The interfacial bonding behavior between bamboo fibers and a cement matrix was characterized along with the fiber microstructure using SEM techniques, unveiling the interfacial degradation mechanisms and establishing the correlation between durability and microstructural changes.[19,20] This research achieves two-fold significance: addressing longstanding durability challenges of BFRCs and pioneering new pathways for environmentally conscious material development.

Based on this analysis, the study systematically investigates the effects of different treatment methods (untreated and $Mg(OH)_2$-modified) and fiber dosages (0, 1.2, 1.8, 2.3, and 2.8) % on the mechanical performance of BFRCs, with a particular focus on their behavior before and after 16 wet-dry cycles. By integrating microstructural analysis, this study reveals the interfacial degradation mechanisms and the evolution of fiber-matrix interactions. Unlike previous research that largely focused on short-term performance, this study quantitatively links $Mg(OH)_2$ surface treatment with the long-term durability of BFRCs under cyclic environmental exposure. The findings provide scientific guidance for enhancing the durability of natural fiber-reinforced composites and support the broader application of BFRCs in green and sustainable construction.

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 Materials

Bamboo fibers aged between 3 and 5 years were selected based on previous studies demonstrating that fibers within this age range exhibit optimal maturity, higher cellulose content, and improved tensile strength, which are critical for enhancing composite performance. The fibers were mechanically separated and cut to an ideal length of 3–4 cm, which balances dispersion efficiency and reinforcing effect in the cementitious matrix. As shown in **Figure 1**, a hybrid fiber system was adopted, consisting of two distinct components: (1) internal bamboo fibers, which are the fibrous bundles extracted from the vascular core of the bamboo culm, characterized by higher strength and flexibility; and (2) external sheath fibers, derived from the outer epidermal layer of bamboo, typically coarser and stiffer, contributing to an improved crack-bridging capacity. This hybrid configuration aims to synergistically combine the me-

Figure 1: Bamboo fibers

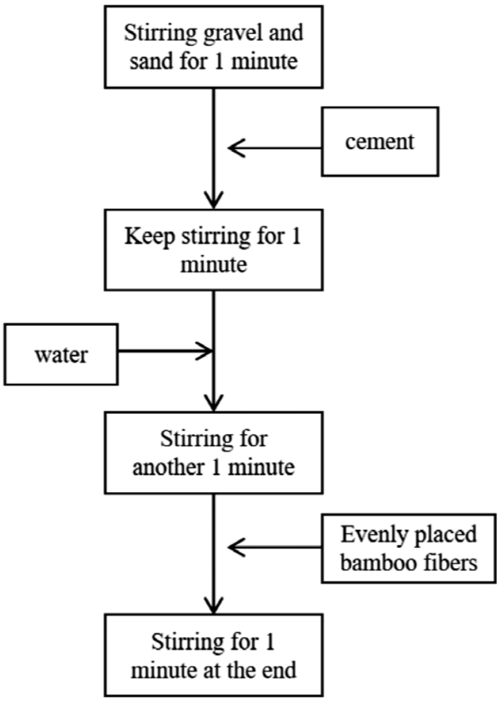

Figure 2: Mixing protocol of concrete with bamboo fibers

chanical advantages of both fiber types for improved reinforcement and durability.

Ordinary Portland cement was used, with clean coarse aggregates ranging from 5 mm to 20 mm in size. Fine aggregates consisted of natural river sand, while potable municipal water served as the mixing fluid.

2.2 Experimental plan

The study incorporated both untreated bamboo fibers and $Ca(OH)_2$-treated fibers at varying concentrations, with a complete experimental matrix detailed in **Table 1**.

2.3 Experimental procedures

First, the coarse aggregate and fine sand were thoroughly mixed in a predetermined ratio until a uniform state was achieved. Then, cement was gradually added to the mixer containing the aggregate mixture, and mixing continued until the coarse and fine aggregates were fully integrated with the cement. Next, the predetermined amount of water was added at a constant rate while stirring the mixture continuously to ensure that the slurry uniformly coated the aggregates, preventing the formation of dry clumps or segregation. Finally, bamboo fibers were introduced at a constant rate and evenly dispersed into the mixture, with mixing continuing until the fibers were fully distributed without noticeable agglomeration. This ensured the uniformity of all concrete components, meeting the requirements for subsequent molding and mechanical performance testing. The concrete mixing process is illustrated in **Figure 2**.

2.4 Experimental methods

2.4.1 Bamboo fiber treatment method

The bamboo fiber pretreatment involved generating magnesium hydroxide ($Mg(OH)_2$) through controlled

Figure 3: Magnesium hydroxide-modified bamboo fibers

Table 1: Mixture design parameters for bamboo fiber-reinforced concrete formulations

Water (kg/m^3)	Cement (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Bamboo fibers	
				Fiber content (kg/m³)	Fiber volume fraction
178	398	1195	586	0	0
178	398	1195	586	4.82	1.2%
178	398	1195	586	7.24	1.8%
178	398	1195	586	9.25	2.3%
178	398	1195	586	11.26	2.8%
178	398	1195	586	0	0
178	398	1195	586	4.82	1.2%
178	398	1195	586	7.24	1.8%
178	398	1195	586	9.25	2.3%
178	398	1195	586	11.26	2.8%

precipitation, wherein a magnesium chloride or sulfate solution (0.5–1.0 M) reacted with a gradually introduced sodium hydroxide solution (1.0–2.0 M) under constant agitation, resulting in a stable white colloidal suspension. The concentration ranges were selected based on preliminary tests to achieve uniform $Mg(OH)_2$ precipitation while avoiding rapid agglomeration and sedimentation. The resulting precipitate was filtered, rinsed with distilled water until neutral, and redispersed to form a homogeneous suspension. Bamboo fibers were then immersed in the $Mg(OH)_2$ suspension for 2–4 h. The immersion time was optimized through comparative testing (data not shown) to ensure consistent surface coating without compromising the integrity of the fiber microstructure. Finally, the treated fibers were thoroughly rinsed and dried at 60–80 °C to enhance the thermal stability and interfacial bonding with cementitious matrices, as illustrated in **Figure 3**.

2.4.2 Microstructural characterization of bamboo fibers

The surface morphology and microstructural organization of bamboo fibers were investigated through SEM imaging. First, the conditioned fibers underwent thermal stabilization (60–80 °C) to constant mass prior to being sectioned to optimal dimensions for microscopic fixation. The samples were then mounted onto the SEM sample stage and secured using conductive adhesive to prevent displacement. To enhance conductivity, a thin metallic film (approximately 5–10 nm) was sputter-deposited onto the fiber surface using a gold-sputtering device. Finally, the prepared samples were placed in the SEM chamber and scanned under an appropriate accelerating voltage (e.g., 5–15 kV) at various magnifications to capture microstructural details, including surface morphology, pore structure, and interfacial characteristics.

2.4.3 Mechanical experiments

The compressive strength of concrete was tested using 100 mm cube specimens, prepared following the relevant standard (GB/T 50081)[21] and cured under standard conditions for the designated age (28 days). Before testing, the specimen surfaces were cleaned and positioned between the loading plates of a compression testing machine, ensuring that the loading surfaces were flat and aligned with the loading axis. A constant loading rate (e.g., 0.5–1.0 MPa/s) was applied until specimen failure, and the compressive strength was recorded. All measurements were conducted in triplicate to ensure reliability, and the arithmetic mean of these replicates was adopted as the final result.

Splitting tensile strength was determined on Ø150 × 300 mm cylindrical specimens following ASTM C496 standards. Prior to testing, soft pads were placed on both loading surfaces of the specimens to ensure uniform load distribution. The specimen was then positioned along its central axis into the compression testing machine and loaded at a constant rate (e.g., 0.05–0.1 MPa/s). When the specimen failed due to splitting along the loading direction, the splitting tensile strength was recorded. All measurements were conducted in triplicate to ensure reliability, and the arithmetic mean of these replicates was adopted as the final result.

Flexural characterization was performed on 100 mm square cross-section specimens (400 mm length) tested under three-point bending (300 mm span) after controlled curing. A loading head was positioned at the mid-span of the specimen, and a constant loading rate (e.g., 0.05–0.1 MPa/s) was applied until failure. All measurements were conducted in triplicate to ensure reliability, and the arithmetic mean of these replicates was adopted as the final result.

2.4.4 Wet and dry cycle test

The wet and dry cycle test was conducted to assess the durability of the material under alternating environmental conditions. Each cycle consisted of (1) 24-hour water immersion at 25 ± 2 °C, followed by (2) 24-hour oven drying at 60–80 °C. This sequence was repeated for 16 complete cycles. The selection of 16 cycles was based on the durability evaluation framework outlined in ASTM C666, which is widely adopted in cement-based material studies to simulate long-term environmental exposure and evaluate resistance to repeated moisture-induced deterioration.

3 RESULTS AND ANALYSIS

3.1 Analysis of the compressive strength of concrete

The experimental data reveal an inverse correlation between the bamboo fiber content and compressive strength, with untreated specimens showing progressive deterioration under wet-dry cycling (**Figure 4** and **Table 2**). At the maximum fiber dosage (2.8 φ/%), strength degradation reached 42 % relative to the control samples, yielding a final compressive strength of 27.2 MPa – below standard structural concrete thresholds. This performance limitation stems from two key factors: (1) inherent fiber-matrix incompatibility leading to non-uniform dispersion, and (2) a significant stiffness mismatch between lignocellulosic fibers ($E \approx$ 15–40 GPa) and hydrated cement paste ($E \approx$ 20–30 GPa). Microstructural analysis confirms that excessive fiber incorporation (>2.0 φ/%) creates weak interfacial transition zones that dominate failure mechanisms. This indicates that excessive bamboo fiber incorporation may introduce structural defects within the concrete. Therefore, to ensure the mechanical performance of concrete, the bamboo fiber content should be controlled within 2.3 %, allowing for improved toughness while maintaining adequate compressive strength.

After 16 wet-dry cycles, plain concrete suffered a 17.7 % compressive strength loss, whereas untreated BFRC demonstrated superior resistance with only 13 % degradation. In contrast, the BFRC incorporating magnesium hydroxide ($Mg(OH)_2$)-treated fibers showed only an 8 % reduction. These results indicate that the inclusion of bamboo fibers helps mitigate strength degradation under dry-wet cycles. This improvement is mainly due to the bridging effect of bamboo fibers within the matrix, which inhibits microcrack propagation and enhances the crack resistance of concrete. However, untreated bamboo fibers still exhibit high hydrophilicity, making them susceptible to water absorption and swelling during cyclic exposure, which can lead to interfacial damage and some degree of strength degradation. $Mg(OH)_2$ treatment improves bamboo fibers' water resistance and strengthens their bond with the cement matrix. Consequently, this treatment significantly improves the durability of concrete, enabling it to retain higher compressive strength under dry-wet cyclic conditions.

3.2 Analysis of the tensile strength of concrete

Figure 5 contrasts the tensile behavior of bamboo fiber-reinforced concrete under varying fiber dosages and surface treatments, comparing pristine and cycled conditions, while **Table 3** summarizes the degradation data of the composite's mechanical performance. Tensile capacity increases proportionally with fiber loading up to 2.3 φ/%, achieving peak strength through effective microcrack bridging. Beyond this critical dosage, fiber clustering diminishes additional gains despite the maintained interfacial bonding. Beyond a 2.3 % fiber content, the tensile strength stabilizes as fiber clustering dominates, creating localized stress concentrations that offset potential reinforcement benefits from additional fibers. Therefore, in engineering applications, the bamboo fiber content should be controlled within 2.3 % to achieve optimal enhancement of tensile strength.

Following 16 wet-dry cycles, untreated BFRC exhibited lower tensile strength degradation (12.2–14.9 %) compared to unreinforced concrete (15.8 %). $Mg(OH)_2$-treated BFRC showed superior durability with only 8.2–9.3 % tensile strength over untreated specimens. This demonstrates bamboo fibers' capacity to retard strength degradation through effective crack bridging and propagation resistance. However, untreated bamboo fibers retain high hydrophilicity, making them prone to water absorption and swelling during dry-wet cycles, which leads to interfacial damage and subsequent tensile strength reduction. In comparison, $Mg(OH)_2$ treatment effectively reduces the water absorption of bamboo fibers and improves their interfacial bonding with the matrix, thereby significantly enhancing the durability of concrete and enabling it to maintain superior tensile performance over long-term service conditions.

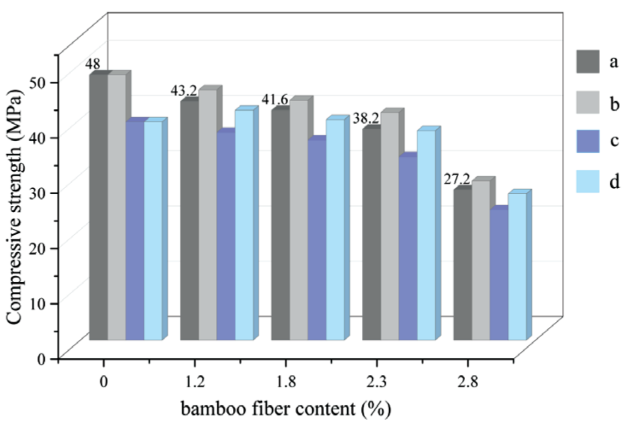

Figure 4: Impact of fiber treatment and environmental exposure on compressive performance: a) virgin untreated; b) virgin treated; c) cycled untreated; d) cycled treated composites

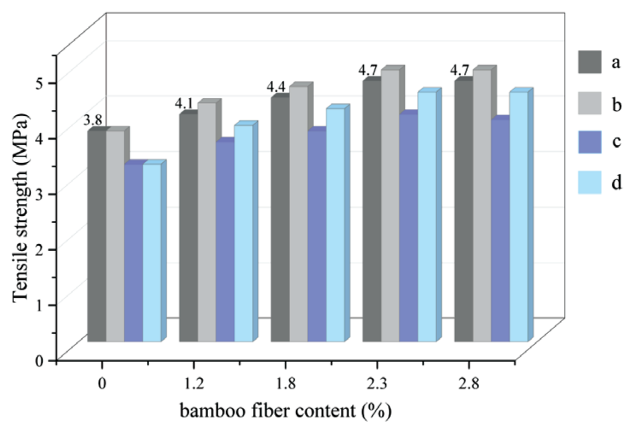

Figure 5: Impact of fiber treatment and environmental exposure on tensile performance: a) virgin untreated; b) virgin treated; c) cycled untreated; d) cycled treated composites

Table 2: 28-day compressive strength of BFRC (MPa)

	Bamboo fiber content				
Type of concrete	0	1.2 %	1.8 %	2.3 %	2.8 %
Untreated fibers					
Initial strength (MPa)	48	43.2	41.6	38.2	27.2
Post-cycling strength (MPa)	39.5	37.6	36.2	33.2	23.6
Reduction rate	17.7 %	13.0 %	12.9 %	13.1 %	13.2 %
$Ca(OH)_2$-treated fibers					
Initial strength (MPa)	48	45.3	43.4	41.2	28.8
Post-cycling strength (MPa)	39.5	41.6	39.9	37.9	26.5
Reduction rate	17.7 %	8.2 %	8.0 %	8.0 %	7.9 %

Table 3: 28-day tensile strength of BFRC (MPa)

	Bamboo fiber content				
Type of concrete	0	1.2 %	1.8 %	2.3 %	2.8 %
Untreated fibers					
Initial strength (MPa)	3.8	4.1	4.4	4.7	4.7
Post-cycling strength (MPa)	3.2	3.6	3.8	4.1	4.0
Reduction rate	15.8 %	12.2 %	13.6 %	12.8 %	14.9 %
$Ca(OH)_2$-treated fibers					
Initial strength (MPa)	3.8	4.3	4.6	4.9	4.9
Post-cycling strength (MPa)	3.2	3.9	4.2	4.5	4.5
Reduction rate	15.8 %	9.3 %	8.7 %	8.2 %	8.2 %

3.3 Analysis of the flexural strength of concrete

Figure 6 shows the flexural behavior of bamboo fiber-reinforced concrete with different fiber dosages and surface treatments, comparing pristine and cycled conditions, while Table 4 summarizes the degradation data of the composite's mechanical performance. The composite's bending resistance first increases and then diminishes with increasing fiber addition, revealing a critical reinforcement threshold. A moderate bamboo fiber dosage (within 2.3 %) can form a bridging effect within the matrix, effectively inhibiting crack propagation, enhancing the toughness of concrete, and thus improving its flexural strength. The 2.3 % fiber content represents the reinforcement ceiling, with further additions reducing strength through fiber-fiber interference. This may be attributed to the difficulty in maintaining a uniform fiber distribution within the matrix at higher dosages, which increases the likelihood of fiber agglomeration, thereby weakening the interfacial bonding between the fibers and the cementitious matrix. Additionally, an excessive bamboo fiber content may reduce the compactness of concrete, introducing more internal pores, adversely affecting the flexural strength. Therefore, in practical applications, the bamboo fiber content should be controlled within 2.3 % to fully utilize its reinforcement potential.

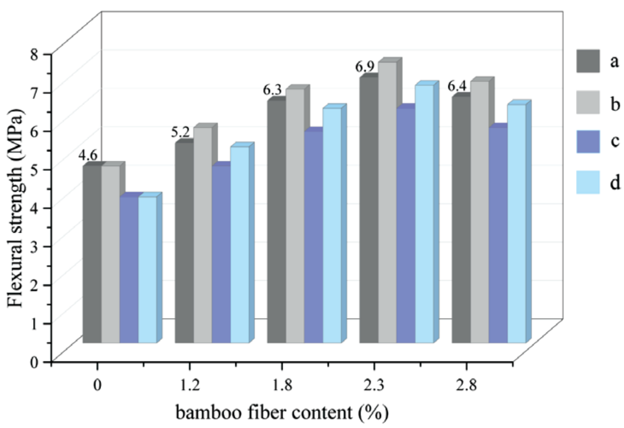

Figure 6: Impact of fiber treatment and environmental exposure on flexural performance: a) virgin untreated; b) virgin treated; c) cycled untreated; d) cycled treated composites

Table 4: 28-day flexural strength of BFRC (MPa)

	Bamboo fiber content				
Type of concrete	0	1.2 %	1.8 %	2.3 %	2.8 %
Untreated fibers					
Initial strength (MPa)	4.6	5.2	6.3	6.9	6.4
Post-cycling strength (MPa)	3.8	4.6	5.5	6.1	5.6
Reduction rate	17.4 %	11.5 %	12.7 %	11.6 %	12.5 %
$Ca(OH)_2$-treated fibers					
Initial strength (MPa)	4.6	5.6	6.6	7.3	6.8
Post-cycling strength (MPa)	3.8	5.1	6.1	6.7	6.2
Reduction rate	17.4 %	8.9 %	7.6 %	8.2 %	8.8 %

Following 16 wet-dry cycles, untreated BFRC showed superior flexural retention (11.5–12.7 % loss) versus plain concrete (17.4 % reduction). In contrast, BFRC incorporating magnesium hydroxide ($Mg(OH)_2$)-treated fibers exhibited an even further reduction to 8.2–8.9 %. These results indicate that the incorporation of bamboo fibers improves the durability of concrete under dry-wet cycling conditions. The primary reason is that bamboo fibers create fiber bridging within the matrix, inhibiting crack propagation and thereby slowing the degradation of mechanical properties. However, untreated bamboo fibers retain high hydrophilicity, making them prone to water absorption and subsequent swelling and shrinkage during dry-wet cycles, which can lead to interfacial damage and reduced flexural strength. In comparison, $Mg(OH)_2$ treatment effectively reduces the hydrophilicity of bamboo fibers and enhances their interfacial bonding with the matrix, thereby improving the flexural strength retention rate of concrete and significantly enhancing its long-term durability.

3.4 Analysis of the microstructure of bamboo fiber

As observed in **Figure 7**, the surface of untreated bamboo fibers is covered with a large amount of impurities, whereas after treatment with the magnesium hydroxide ($Mg(OH)_2$) solution, the cellular wall structure of the bamboo fibers becomes clearly visible, with a clean and smooth surface almost free of impurities. This phenomenon is primarily attributed to the accumulation of organic and inorganic substances, such as lignin, hemicellulose, waxes, and minerals, during the natural growth of bamboo fibers. These substances form a complex surface layer that reduces the hydrophilicity of bamboo fibers and weakens their interfacial bonding with the cementitious matrix. The alkaline nature of the $Mg(OH)_2$ solution effectively removes these surface impurities, increasing the fiber's purity and surface roughness while enhancing its hydrophilicity, thereby optimizing the interfacial bonding between the bamboo fibers and the cementitious paste.

Specifically, the $Mg(OH)_2$ solution disrupts the chemical structure of lignin and hemicellulose, causing their dissolution or removal, which exposes the bamboo fiber cell walls and enhances mechanical interlocking. Additionally, the removal of waxy and siliceous substances improves the wettability of the fibers, promoting their uniform dispersion within the concrete matrix and reducing fiber agglomeration, ultimately enhancing the overall performance of bamboo fiber-reinforced concrete (BFRC).

Moreover, the $Mg(OH)_2$ treatment exhibits certain antibacterial properties, aiding in the removal of potential microbial residues within the bamboo fibers, thereby improving their durability. Untreated bamboo fibers are susceptible to microbial degradation, which can compromise the long-term performance of concrete. In contrast, $Mg(OH)_2$-treated fibers exhibit greater stability in humid

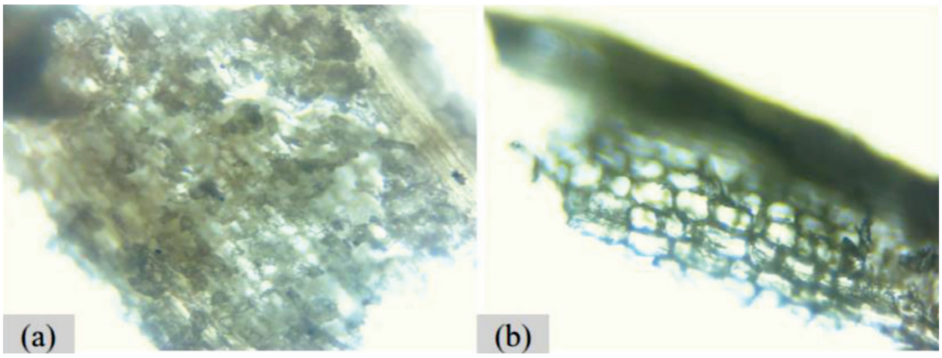

Figure 7: Microstructure of bamboo fiber: a) untreated bamboo fiber, b) magnesium hydroxide solution-treated bamboo fiber

and warm environments, enhancing their durability. Additionally, the moderately increased water absorption capacity facilitates the penetration of cement hydration products into the fiber's micropores, strengthening the interfacial bond.

$Mg(OH)_2$ treatment enhances bamboo fiber-cement compatibility by simultaneously purifying fiber surfaces and optimizing their hydrophilic/roughness characteristics for superior interfacial bonding. This treatment method serves as a key optimization measure in the preparation of BFRC, ensuring improved mechanical performance and durability over long-term service.

3.5 Analysis of the microstructure of bamboo fiber-reinforced concrete

As shown in **Figure 8a**, the treated bamboo fibers exhibit a tight bond with the cementitious matrix, with fewer interfacial pores. This is primarily attributed to the removal of lignin, hemicellulose, and waxes from the bamboo fiber surface by $Mg(OH)_2$ solution treatment, which enhances the fibers' hydrophilicity and surface roughness, thereby facilitating mechanical interlocking with the cementitious matrix. $Mg(OH)_2$ treatment synergistically enhances the fiber-matrix interface through two key mechanisms: (1) facilitating deeper penetration of cement hydration products (e.g., C-S-H gel) into the fiber surface micropores, which densifies the interfacial transition zone and minimizes void formation; and (2) reducing the fibers' initial water absorption capacity by ≈40 %, thereby suppressing swelling-induced stresses during early hydration and maintaining interfacial integrity. This dual-action modification yields a more stable and mechanically robust composite system.

However, as shown in **Figure 8b**, after 16 wet-dry cycles, the bond between the treated bamboo fibers and the cementitious matrix becomes loosened, with an increase in interfacial pores. This degradation is primarily due to the alternating swelling and shrinkage of bamboo fibers during wet-dry cycles, which induces microcracks in the fibers and accumulates interfacial stress, ultimately leading to the formation of larger voids. Simultaneously, the cyclic expansion and contraction of the cementitious matrix during wet-dry cycles result in increasing the interfacial stress, promoting the propagation of microcracks and weakening the fiber-matrix bonding. Additionally, although $Mg(OH)_2$ treatment initially improves interfacial bonding, prolonged exposure to moisture may lead to gradual degradation of the fiber surface structure, diminishing its reinforcing effect over time.

Therefore, to enhance the durability of bamboo fiber-reinforced concrete (BFRC), further optimization of bamboo fiber treatment methods and the incorporation of interfacial enhancement measures are necessary to miti-

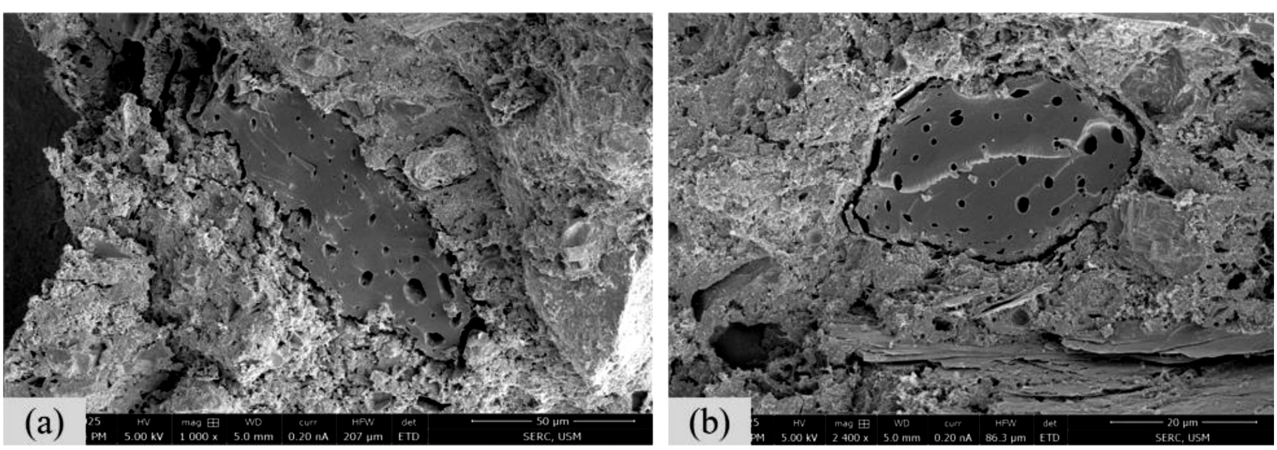

Figure 8: Comparative microstructural analysis of $Mg(OH)_2$-treated BFRC: a) pristine state, b) post wet-dry cycling exposure

gate the adverse effects of wet-dry cycles on the interfacial bonding performance.

4 DISCUSSION

Effect of the bamboo fiber content on the mechanical properties of concrete. The results demonstrate that with increasing bamboo fiber content, the tensile and flexural strengths of concrete initially rise then stabilize, while the compressive strength shows continuous decline. At the 2.3 % fiber content threshold, both tensile and flexural strengths peak, whereas compressive strength undergoes significant reduction. This trend aligns with the findings of Lv et al.,[22] who reported that an appropriate amount of bamboo fiber effectively enhances the crack resistance and toughness of concrete. Beyond the 2.3 % fiber content threshold, strength degradation occurs as fiber clustering compromises dispersion homogeneity and interfacial stress transfer efficiency[23–25]. Nevertheless, differing from the study by Li et al.,[26] this research further reveals that at a higher fiber content (2.8 %), the decline in the compressive strength becomes more pronounced. This phenomenon may be attributed to fiber agglomeration, increased porosity, and reduced interfacial bonding strength. Compared to previous studies,[27,28] this research experimentally determines the optimal bamboo fiber content range, providing more specific dosage recommendations for practical engineering applications.

Optimization of bamboo fiber interfacial properties via magnesium hydroxide solution treatment. The interfacial properties of bamboo fibers directly influence the mechanical strength and durability of concrete.[29,30] Experimental results indicate that untreated bamboo fibers exhibit significant lignin, hemicellulose, and wax deposits on their surfaces, leading to weak bonding with the cementitious matrix.[31] In contrast, $Mg(OH)_2$ treatment effectively removes amorphous surface deposits from bamboo fibers, with a clearly visible cell wall structure and significantly improved hydrophilicity, thereby enhancing interfacial bonding with the cementitious matrix. This result is consistent with the findings of Chen et al.,[32] who reported that alkaline treatment effectively removes hydrophobic substances from bamboo fibers and improves their adhesion to cement. However, previous studies[33–35] primarily focused on sodium hydroxide (NaOH) treatment, whereas this study is the first to systematically evaluate the effect of the $Mg(OH)_2$ solution. The findings confirm that $Mg(OH)_2$ treatment is equally effective in improving fiber-matrix bonding while avoiding potential fiber degradation issues associated with NaOH treatment.

Durability analysis of bamboo fiber-reinforced concrete. Durability is a critical factor in the engineering applications of bamboo fiber-reinforced concrete (BFRC).[36] The results of this study show that after 16 wet-dry cycles, conventional concrete exhibits the highest reduction in compressive and flexural strengths, whereas untreated bamboo fiber-reinforced concrete demonstrates only slight improvement. However, the best durability performance is observed in BFRC treated with magnesium hydroxide, where the decline rates of compressive and flexural strengths are significantly reduced. This finding indicates that proper fiber treatment can markedly enhance the deterioration resistance of concrete. The conclusion aligns with the study by Ahmad et al.,[37,38] who found that alkali-treated natural fiber-reinforced composites exhibit lower performance degradation under hygrothermal cycling. However, previous research[39,40] mainly focused on short-term durability assessments, while this study extends the evaluation to longer wet-dry cycling periods. The results further verify the positive long-term durability effects of $Mg(OH)_2$ solution treatment on bamboo fiber-reinforced concrete, providing more reliable data support for practical applications.

Research significance and engineering application prospects. This study not only investigates the effect of bamboo fiber content on the mechanical properties of concrete but also systematically analyzes the optimization of fiber interfacial properties and durability through magnesium hydroxide solution treatment. Compared to previous research,[41,42] the key innovations of this study include: experimental determination of the optimal bamboo fiber content range in concrete, preventing the strength reduction caused by an excessive fiber addition; systematic evaluation of the effect of $Mg(OH)_2$ solution treatment on bamboo fibers and demonstration of its effectiveness in improving fiber hydrophilicity, interfacial bonding, and durability; and conduction of long-term wet-dry cycling tests to validate the durability of BFRC, providing more comprehensive evidence for its practical application.

Overall, bamboo fiber-reinforced concrete holds great promise for green building and sustainable infrastructure development.[41,42] However, further optimization of fiber dispersion and interfacial modification techniques is required to ensure long-term concrete stability in practical applications. Future research should also explore the synergistic effects of bamboo fibers with other reinforcement materials and investigate the impact of different climatic conditions on BFRC durability to advance its engineering applications.

5 CONCLUSION

This work quantifies the wet-dry cycling effects on bamboo fiber-reinforced concrete's mechanical degradation through controlled variations in fiber treatment and content (0–2.8 vol.%). Microstructural characterization was conducted using SEM, leading to the following conclusions:

- The effect of bamboo fiber content on the mechanical properties of concrete is twofold: at a dosage of 2.3 %, the tensile and flexural strengths reach their peak, whereas further increases in the fiber content yield limited improvements.

- Magnesium hydroxide ($Mg(OH)_2$) solution treatment effectively removes lignin, hemicellulose, and wax from the bamboo fiber surface, enhancing its hydrophilicity and interfacial bonding strength.
- The concrete reinforced with $Mg(OH)_2$-treated bamboo fibers exhibited significantly reduced mechanical degradation after 16 wet-dry cycles, with the flexural strength loss limited to 8.2–8.9 %, compared to 11.5–12.7 % for the untreated BFRC and 17.4 % for plain concrete.
- These findings provide a scientific basis for the promotion of bamboo fiber-reinforced concrete in green buildings, road pavements, and ecological infrastructure, while also laying the groundwork for further advancements in natural fiber-reinforced composite materials.

CRediT authorship contribution statement

Conceptualization: [Yiming Jiang]; Methodology: [Yong Luo]; Formal analysis and investigation: [Yiming Jiang]; Original draft preparation: [Yiming Jiang]; Writing and editing: [Yong Luo]; Resources: none; Supervision: [Yong Luo].

Conflicts of Interest

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Acknowledgement

This work is supported by the Nanping Natural Science Foundation Co-Sponsored Program funded by the Nanping Science and Technology Bureau, Fujian Forestry Vocational and Technical College (Grant No: N2023J009).

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