



Studies on influence of seashell-based filler on water absorption behaviour of bamboo-epoxy composite: mechanical and fractured surface characterization

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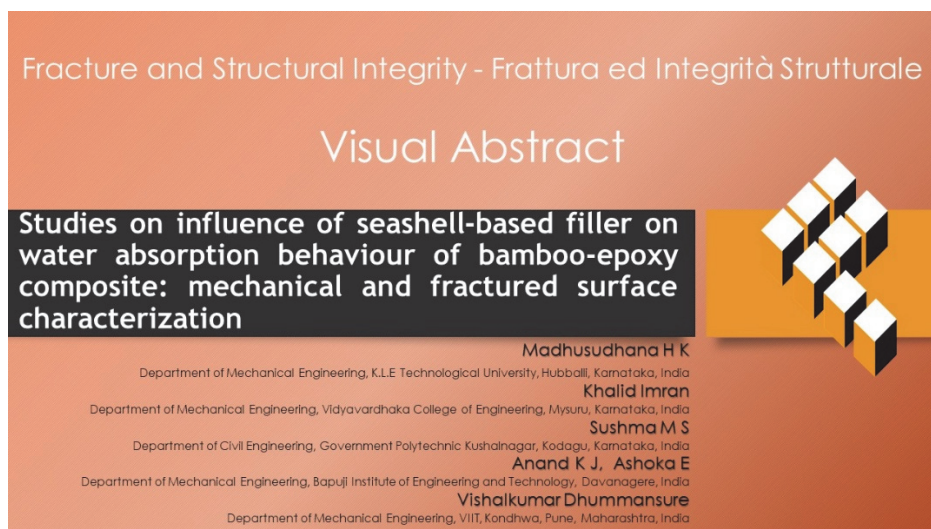
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KEYWORDS. Bamboo Composites, Hybrid Composites, Biofiller, Seashell, Moisture Absorption, Mechanical Properties.



INTRODUCTION

Natural fiber composites have gained increasing attention as sustainable and cost-effective alternatives to synthetic counterparts due to their renewability, low density, and satisfactory mechanical properties. Among them, bamboo is particularly attractive because of its abundance, rapid growth, and high strength-to-weight ratio, making it a promising alternative to synthetic fibers in lightweight structural applications [1,2]. However, a major drawback of natural fibers, including bamboo, is their hydrophilic nature, which makes them highly susceptible to moisture absorption. The hydroxyl groups in cellulose and hemicellulose facilitate water uptake, leading to fiber swelling, poor interfacial adhesion with hydrophobic matrices, microcracking, and degradation of mechanical properties under humid or wet conditions. These effects are more pronounced at higher fiber contents and prolonged water exposure, which significantly reduce their key mechanical properties, especially the tensile and flexural strength. This moisture sensitivity has been widely recognized as a critical challenge limiting the broader application of bamboo composites in structural and outdoor environments [3,4]. To address this issue, researchers have explored various strategies, including fiber surface treatments, and hybridization with synthetic fibers and fillers [5]. Chemical treatments such as alkali and silane modification improve fiber–matrix bonding and reduce water uptake, resulting in enhanced strength retention under aging conditions. One of the widely researched surface modification approach is treatment of bamboo fibers with NaOH. Several studies have demonstrated that NaOH treated bamboo fiber reduce the hydrophilic contents in bamboo and enhance fiber–matrix bonding, leading to reductions in water uptake [6–8]. While chemical treatments can reduce hydroxyl groups and improve adhesion, they offer only partial resistance under prolonged exposure. A more effective approach involves hybridization with other fibers, where bamboo fibers are combined with less hydrophilic reinforcements such as glass or carbon fibers [9]. Studies consistently show that hybrid bamboo-glass composites exhibit reduced water absorption and better mechanical performance compared to non-hybrid composites [10–12]. Kudva et al. [13] combined chemical surface treatment with hybridization, treating bamboo fibers with NaOH and KMnO_4 , and reinforced them with carbon fibers. NaOH-treated hybrids showed lower moisture uptake (4.1%) than KMnO_4 -treated ones (5.6%) and better retention of tensile and flexural properties under aging.

Studies have shown that incorporating filler particles into the polymeric matrix reduces voids and enhances interfacial bonding, thereby improving the properties of composites. The effectiveness of fillers depends upon their type, loading, and particle size [14]. Larger particles often reduce the homogeneity, act as stress concentrators, and lead to poor stress transfer within the matrix. Conversely, smaller particles provide a higher surface area, which enhances interfacial bonding and improves the properties of composites. However, excessively fine particles are prone to agglomeration.

In natural fiber composites, inclusion of particulate fillers has been widely reported as an effective strategy to mitigate the moisture-induced degradation of the mechanical properties. Fillers occupy micro-voids, act as barriers to water diffusion, and improve interfacial adhesion, leading to enhanced strength retention under wet conditions [5]. For bamboo composites, several studies have highlighted the role of fillers in improving the durability and performance under moisture exposure. Tahir et al. [15] reported that when bamboo–epoxy composites were incorporated with silicon carbide (SiC), a significant reduction in water uptake was observed. Composite with 6 wt% SiC exhibited the lowest water absorption due to reduced void content. A. Gupta [16] observed that the addition of ceramic fillers Al_2O_3 and SiC reduced water absorption from 9.2% in unfilled bamboo composites to 6.8% in filled bamboo composites after prolonged immersion. Sugiman et al. [17] incorporated nano- CaCO_3 in bamboo fiber unsaturated polyester composites. It was found that nano- CaCO_3 reduced equilibrium water uptake by 16.2% and mitigated tensile and flexural strength degradation to 37% and 42%, respectively. These works consistently establish fillers as effective means of enhancing moisture resistance and mechanical retention in wet conditions. However, most of these fillers are either synthetic or industrially processed, which limits their cost-effectiveness and sustainability. In recent years, research focus has shifted towards using fillers derived from industrial and agricultural waste for improving composite performance while supporting circular economy goals. Such fillers not only improve properties but also enable waste valorization. Studies on the inclusion of non-conventional fillers like industrial waste cenosphere, agro wastes such as coconut shell powder, and eggshell incorporated in natural fiber composites have been documented. The findings from these studies demonstrated that these waste fillers positively influenced the characteristics of composites, where mechanical properties were improved [18–20]. H. Jena et al. [21] reported that adding cenosphere to bamboo–epoxy composites reduced water absorption, with maximum reduction observed at 3 wt% (21% in distilled water and 32% in seawater). Similarly, A. Gupta [22] demonstrated that cenosphere fly ash and cement bypass dust (CBPD) fillers improved both water and chemical resistance of bidirectional bamboo–epoxy composites. Chakkour et al. [23] reported that the addition of montmorillonite (MMT) and eggshell powder fillers significantly reduced water uptake by filling micro voids and creating diffusion barriers. Highest water uptake of 16.4% was observed in unfilled composites, while addition of 3 wt% MMT and eggshell powder reduced the water absorption to 10.2% and 12.2% respectively.



Literature review revealed that existing research has frequently focused on hybridization with synthetic fillers with few studies reported on industrial/agro waste. Studies on incorporating bio waste-derived fillers, especially seashell filler remain comparatively scarce. Seashells, an abundant byproduct of the seafood industry, are primarily composed of calcium carbonate (CaCO_3) and offer distinctive advantages. Calcium carbonate possesses high surface hardness, low solubility in water, and excellent compatibility with polymer matrices. Seashell bio fillers have gained attention as a cost-effective and eco-friendly alternative to ceramic fillers. A recent study showed that by combining bamboo fibers with seashell fillers, a synergistic effect can be achieved to improve the mechanical properties in bamboo-epoxy composites [24]. Motivated by these observations, this study aims to propose a remedial strategy for reducing moisture uptake in bamboo fiber composites by introducing seashell biofiller into the epoxy matrix. The primary objective of this work is to evaluate the moisture absorption behavior of bamboo fiber composites under water immersion and explore the potential of seashell waste-derived bio-fillers' effect on moisture resistance and mechanical properties. Hybrid bamboo composites with varied seashell filler contents were fabricated via compression molding technique. Moisture absorption behaviour of the developed bamboo-epoxy composites was evaluated using a water immersion test. Tensile and flexural tests on water-soaked specimens were conducted as per ASTM standards to assess the effect of moisture on mechanical behaviour. Fractographic analysis using SEM micrographs was performed on fractured tensile samples to understand the effect of water ingress on the structural integrity of composites.

MATERIALS AND METHODS

Materials and specimen preparation

To fabricate the composites, bamboo fiber was used as the primary reinforcement in an epoxy matrix, while waste seashells were processed into particulate filler. Tab. 1 provides the details of the materials used in the present study.

Material	Details
Fiber-Bamboo mat	Twill weave, 150 gsm
Matrix-Epoxy	Lapox L12 Epoxy with K6 Hardener, (Resin-to-hardener ratio-10:1)
Filler-Seashell	Clamshell powder, Particle size range: 50–75 μm

Table 1: Materials details.

Bamboo fibers were sourced from Sreenath weaving Industry (Rajasthan, India), while epoxy with hardener was procured from Yuje Enterprises (Bengaluru, India). Biofiller was synthesized internally from discarded clamshells. The clamshells are collected from the seashores of coastal Karnataka, India. Initially, these collected clamshells were cleaned thoroughly with running tap water to remove dirt, then kept in hot water to remove any residual organic matter. After the cleaning, the shells were dried in a hot-air oven to eliminate residual moisture. The dried shells were then crushed using a mechanical jaw crusher. The coarse shell particles were then subjected to grinding using a ball mill to achieve fine particulates, and the resulting powder was sieved to obtain particles suitable for composite fabrication. The particle size in the range 50–75 μm was obtained through sieve analysis. This size range was selected based on the previous findings to provide a balance between surface area and dispersion [24,25]. The sieved filler was then stored in an airtight polythene bag to avoid moisture absorption prior to its incorporation into the bamboo-epoxy composite system. Fig. 1 shows the synthesized clamshell filler.

Energy-dispersive X-ray Spectroscopy (EDX) was used to determine the elemental composition of processed clamshell powder. Fig. 2 presents EDX analysis of the prepared clamshell powder. As observed from the elemental composition, Calcium (Ca) is the major component, dominating the composition at 50 wt%, underscoring the significant presence of calcium in the clamshell powder, which is primarily composed of calcium carbonate (CaCO_3). Oxygen (O) and Carbon (C) are the other major constituents detected due to the presence of carbonate groups in calcium carbonate, highlighting the substantial contribution to the overall molecular structure. This elemental analysis provided essential insights into the chemical stability of the filler and aligns strongly with the expected characteristics of a CaCO_3 -dominant shell material.



Figure 1: Clamshell powder.

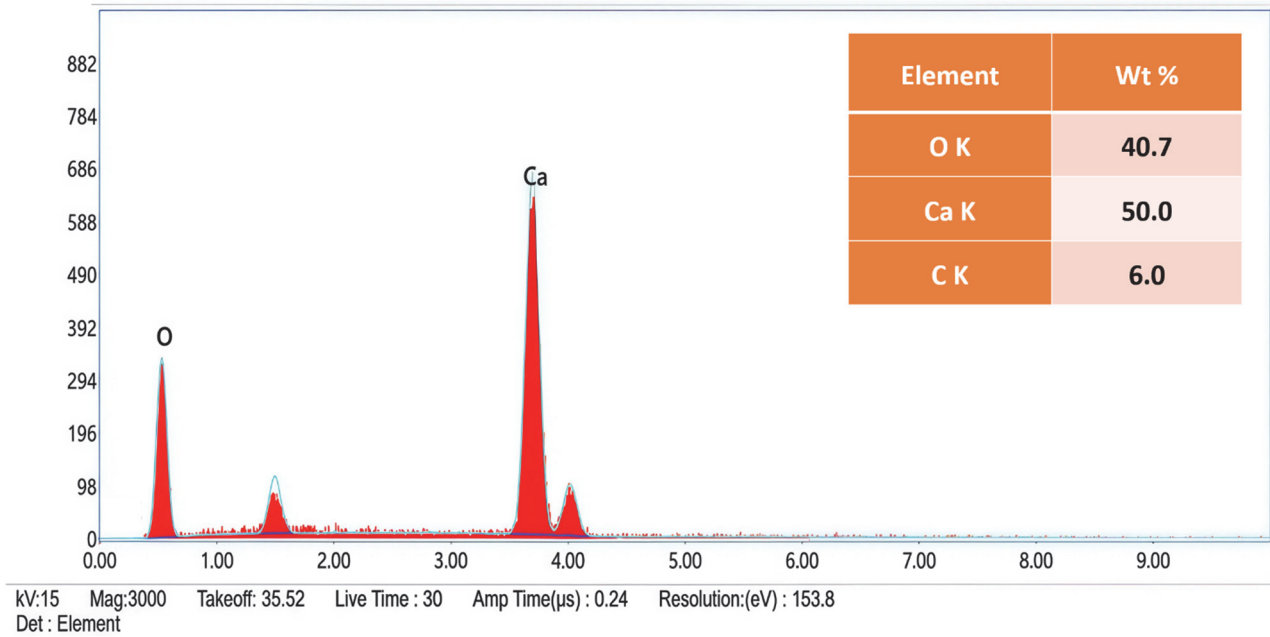


Figure 2: EDX of clamshell powder.

To investigate the effect of clamshell filler incorporation, two categories of composite were prepared: bamboo composite without filler and with filler. The unfilled base composite (without filler) was prepared with bamboo-epoxy in a 35-65 wt.% ratio. Hybrid bamboo-epoxy composites were prepared by maintaining a 35 wt% bamboo fiber content. The clamshell filler was incorporated into the epoxy matrix at different loadings, with the epoxy proportion adjusted accordingly. Tab. 2 provides the details of all the composite compositions. For fabricating these bamboo composite panels, hand lay-up process followed by the compression molding technique is used. Post-curing, the composite panels were demolded, and specimens were prepared for further testing in accordance with ASTM standards. Fig. 3 illustrates the steps involved in the fabrication of bamboo composites.

Sl. No.	Bamboo fiber wt %	Epoxy wt %	Clamshell wt %	Description
1	35	65	0	Unfilled composite
2	35	62	3	Filled composites
3	35	59	6	
4	35	56	9	

Table 2: Details of composite combinations.

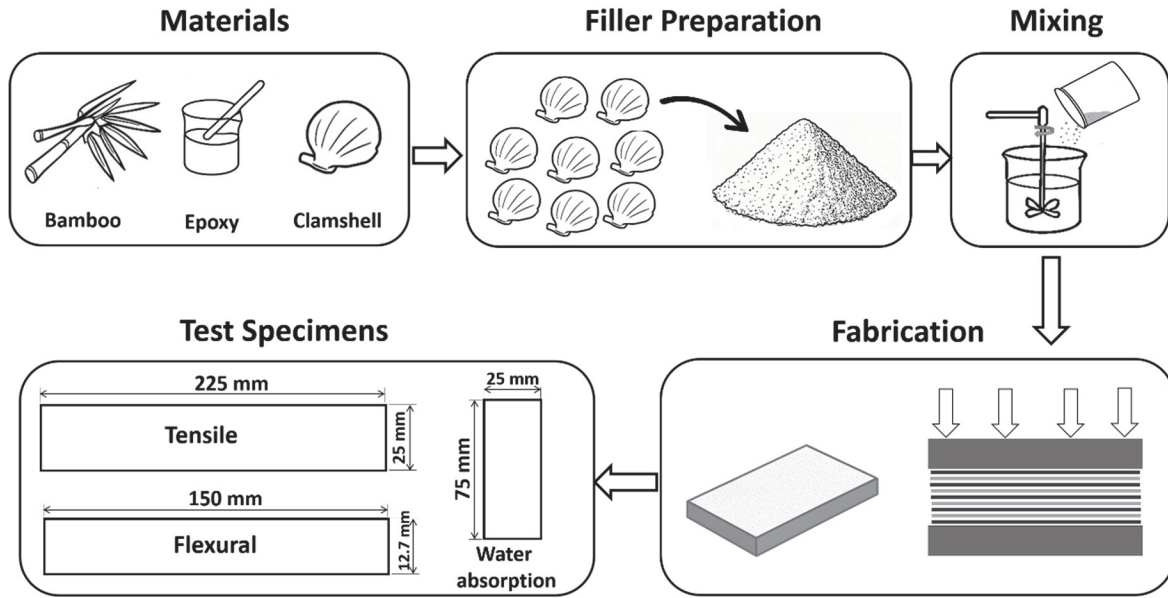


Figure 3: Composite fabrication.

Water absorption test

Understanding how composites behave when exposed to water over extended periods is critical for bamboo fiber composites used in environments where exposure to moisture is expected. The water absorption test is an important aspect of composite characterization studies. The tests help determine the composite's ability to resist moisture uptake. In the present work, water absorption characteristics studies were conducted following the ASTM D570 standard by immersing samples in fresh water at room temperature.

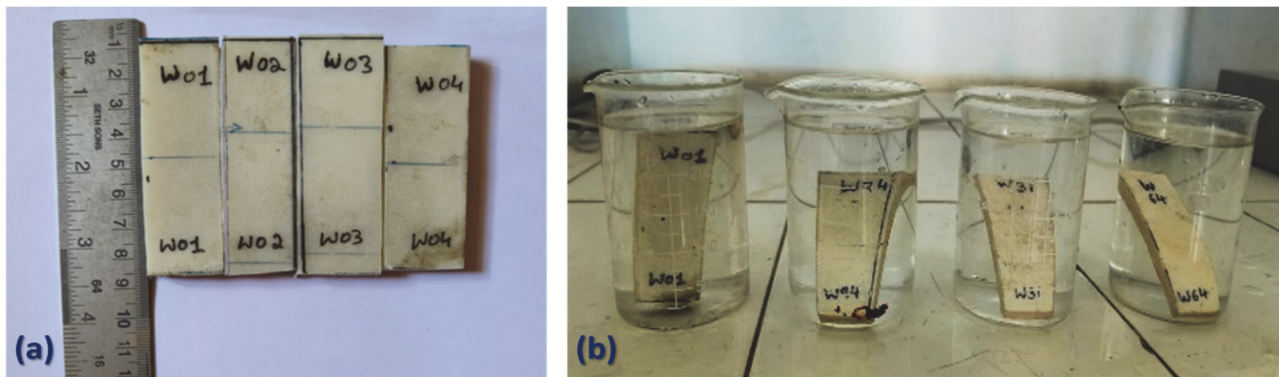


Figure 4: (a) Water absorption test specimens (b) Specimens immersed in water.

For water absorption testing, specimens of size $75 \times 25 \times 6$ mm were used. For each composite composition, the water absorption test was performed on a set of 3 samples, and average values were considered for the result analysis. Fig. 4 (a) shows prepared specimens. Prior to the test, the samples were dried in an oven at 70°C for 24 h to remove any additional moisture on their surfaces, and the initial weight (W_i) of the sample was noted using a digital weighing machine (0.1 mg accuracy). Then they were immersed in a glass container filled with tap water at room temperature ($25 \pm 2^\circ\text{C}$), as shown in Fig. 4 (b). After 24 h, each sample was removed from the water, wiped off the surface using a dry cloth, and weighed immediately. The weight measurements were taken periodically at time intervals of 24 h, up to water saturation in all the composites had been noticed. The saturation level of absorption is considered when, for 3 successive days, the weight change readings of the sample obtained were less than 0.1% [23]. The moisture absorption (%) of each specimen was evaluated by considering the weight gain attained at each time interval. The weight gain (in percentage) for each sample was calculated using the formula:

$$W_g = \frac{(W_t - W_i)}{W_i} \times 100 \quad (1)$$

where W_g is the weight gain in percentage, W_i is the initial dried weight of the sample, and W_t is the weight measured at a given time interval.

Mechanical tests

This work examines the effect of moisture absorption on the mechanical properties of hybrid bamboo composites. Fig. 5 shows prepared specimens for mechanical testing. For tensile testing, rectangular coupons with dimensions of $225 \times 25 \times 6$ mm were prepared. For flexural testing, specimens with dimensions of $150 \times 12.7 \times 6$ mm were used, with a 16:1 span-to-depth ratio. The test specimens were first immersed in water for a specific time period to absorb moisture. Then, tensile and flexural tests were conducted on water-soaked specimens adhering to the ASTM standards. For testing these water-aged samples, UTM (Zwick Roell- Z020, 20 kN load cell) was employed. Tensile testing was performed as per the ASTM D3039 standard. For flexural testing 3-point bending setup was used as per the ASTM D790 standard. For each composition, tensile and flexural tests were performed on a set of four samples, and results are reported as mean \pm SD.

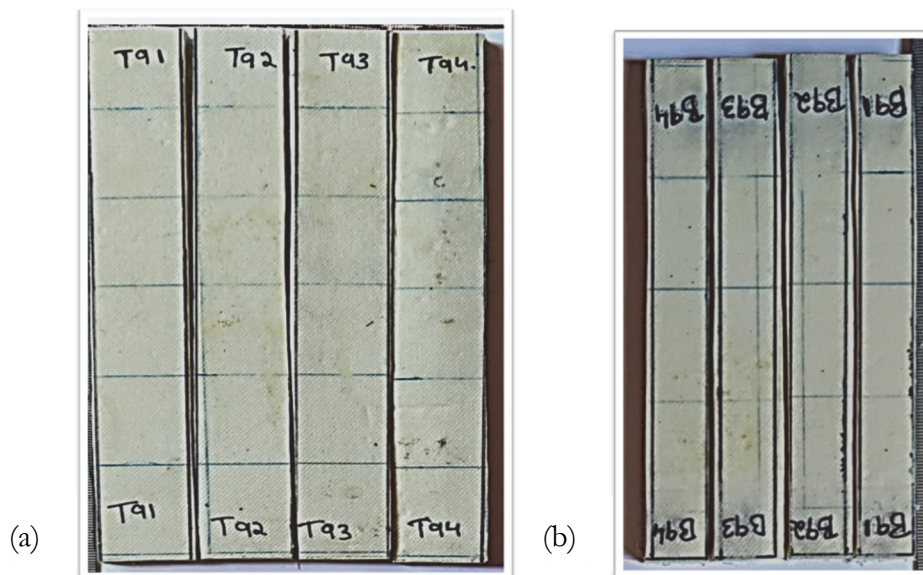


Figure 5: (a) Tensile test specimens (b) Flexural test specimens.

RESULTS AND DISCUSSIONS

Moisture absorption results

The moisture absorption characteristics of bamboo composites immersed in water are analyzed by plotting graphs for water absorption (weight gain %) against the immersion time (hours), as shown in Fig. 6. The graph shows that for all composite samples, there is a rapid increase in water uptake during the initial period of immersion. However, after a while, this uptake slows down and eventually reaches a saturation level in absorption. The unfilled bamboo composite exhibited a weight gain of 5.85%, while composites with 3, 6, and 9 wt% clamshell filler showed lower weight gains of 4.53%, 4.07% and 4.95% respectively. This reduction in weight gain achieved with clamshell filler inclusion demonstrates the effectiveness of filler particles in creating the barrier effect, which restricts moisture diffusion and thereby enhances the moisture resistance of composites. From Fig. 6, it can be observed that the unfilled bamboo composite showed the highest absorption, while the composite having 6 wt% filler exhibited the lowest absorption. The base composite without filler exhibits the highest moisture absorption due to the hydrophilic nature of bamboo fibers, which increases the water absorption rate in a humid environment. In the case of hybrid composites, moisture absorption decreased with an increase in clamshell filler content. It can be observed that, inclusion of clamshell filler consistently reduced moisture absorption. The addition of 3% clamshell filler reduces moisture absorption to 4.53%. With 6% filler, moisture absorption further

decreases to 4.07%. This indicates enhanced resistance to moisture ingress due to the increased filler content, improving the composite's hydrophobicity. But at 9% filler loading, there is a slight increase in moisture uptake, indicating possible micro-void formation due to filler agglomeration. Overall, the composites with filler show lower moisture absorption, as the filler content effectively blocks water pathways, enhancing the composite's resistance to moisture. Clamshell filler acts as a barrier, reducing water uptake by the bamboo fibers. Also, clamshell fillers reduce the voids and gaps where water can infiltrate and limit water ingress, thereby minimizing water absorption.

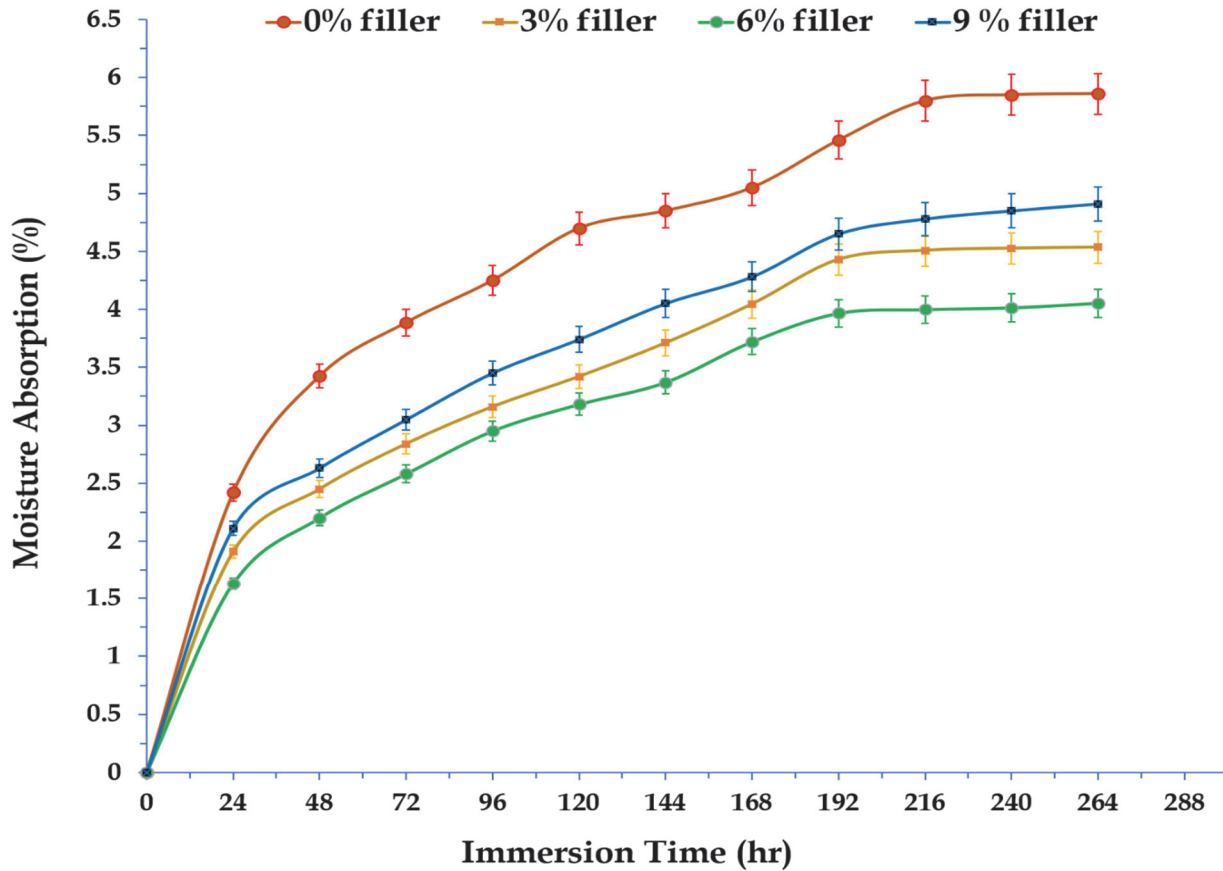


Figure 6: Moisture absorption results of bamboo-epoxy composites.

Composite Material	Filler	Filler wt. %	Reduction in water uptake (%)	Reference
Bamboo-Epoxy	Clamshell	6	30.4	Present work
Bamboo-Epoxy	Al ₂ O ₃	10	25.6	[16]
Bamboo-Epoxy	SiC	10	22.0	[16]
Bamboo-Epoxy	Cenosphere	3	21.0	[21]
Bamboo-Epoxy	MMT	3	37.8%	[23]
Bamboo-Epoxy	Eggshell	3	25.7%	[23]

Table 3: Comparison of water absorption reduction in bamboo composites.

The reduction in water absorption achieved in similar experimental conditions/environment for hybrid bamboo composites with different fillers is provided in Tab. 3 for comparative analysis. As seen in Tab. 3, the bamboo-epoxy composite with clamshell filler achieved a 30.4 % reduction in water uptake, which was higher than reported with ceramic filler Al₂O₃



(25.6%), SiC (22%), and industrial waste cenosphere (21%). Eggshell filler, which also has a high CaCO₃ content, exhibited comparable performance (25.7%), while MMT provided a higher reduction (37.8%).

Moisture absorption effect on mechanical properties

The results of tensile and flexural tests conducted on wet samples to investigate the effect of filler on the mechanical properties of bamboo composites are presented in Tab. 4. The findings show that after prolonged moisture uptake exposure, the composites' tensile and flexural strengths significantly declined. However, hybrid bamboo composites with clamshell filler showed enhanced strength compared to the unfilled base composite.

Clamshell wt%	Tensile Strength (MPa)	Tensile Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0	18.7± 0.8	390±13	40±1.6	1.95±0.11
3	26.4±1.1	435±17	53.5±1.9	2.30±0.12
6	31.5±1.4	470±20	61±2.3	2.55±0.15
9	25.6±1.3	425±15	48.2±2.1	2.20±0.12

Table 4: Tensile and flexural test results.

Fig. 7 shows the result of the tensile test. It can be observed that the base composite (without filler) has the lowest tensile strength of 18.7 MPa and modulus of 390 MPa, indicating a substantial weakening of the composite structure in wet conditions. When incorporated with clamshell filler, the adverse effect of moisture absorption was minimized, where the composites exhibited improved retention of tensile strength in wet conditions. For hybrid bamboo composites, a 6% filler addition provided the best overall tensile strength retention in wet conditions, exhibiting a maximum strength of 31.5 MPa and a modulus of 470 MPa. The addition of 9% resulted in the decline of strength, but still showed improved moisture resistance compared to the unfilled composite. A similar trend was reported for bamboo fiber-unsaturated polyester composites with nano-CaCO₃ filler, where up to 3 wt% improved tensile strength, while higher loading showed a lesser effect [17]. A similar pattern has been noted in the behavior of the water-soaked bamboo composite under flexural loading, as depicted in Fig. 8. The flexural strength of composites with clamshell filler was higher than that of the base composite, indicating improved moisture resistance and enhanced strength retention with filler inclusion. The unfilled base composite had the lowest strength of 40 MPa and modulus of 1.95 GPa, a significant reduction in flexural property due to moisture absorption, signifying its high sensitivity to moisture. Among all samples, adding 6% filler was more effective in enhancing flexural strength and showed the best retention of strength in wet conditions. Flexural strength of 61 MPa and modulus of 2.55 GPa were achieved for this configuration. Further addition of 9% filler resulted in a decline in strength retention, indicating that a higher filler content was not beneficial.

Compared to nano-CaCO₃ filler, the clamshell inclusion was more effective in retaining strength under wet conditions. In bamboo composites, nano-CaCO₃ filler addition improved the tensile strength by 42%, and flexural strength by 15.8% [17], whereas the addition of 6 wt% clamshell filler improved tensile strength by 68.4% and the flexural strength by 52.5%. This superior performance can be attributed to the inherent characteristics of the clamshell particles and their effective interaction with the bamboo fibers and the epoxy matrix. As clamshell fillers are less hygroscopic compared to bamboo fibers, they absorb less moisture. The presence of filler creates stronger interfacial bonding. Further, they act as a physical barrier and mitigate the effects of micro gaps and voids, thereby reducing the pathways for water penetration. Consequently, lower water uptake limits the epoxy plasticization and minimizes fiber swelling, leading to reduced degradation of mechanical properties under humid conditions.

To analyse the extent of degradation of mechanical properties under humid conditions, the results of the present study were compared with the mechanical properties of unaged bamboo-epoxy composites reported in the earlier work by the co-author Anand K J et.al [24]. In that study, bamboo composites were fabricated using the same constituent materials and similar processing parameters, and tensile and flexural tests were conducted on dry specimens (unaged). Fig. 9 presents a comparison of the tensile strength and the flexural strength of water-aged bamboo-epoxy composites with the corresponding unaged samples (dry conditions). As seen from the comparison graph, in the wet condition, the bamboo composites demonstrated a lower range of strength properties in comparison to the dry samples. However, for both conditions, when the clamshell filler was incorporated, the bamboo composite strength properties were enhanced.

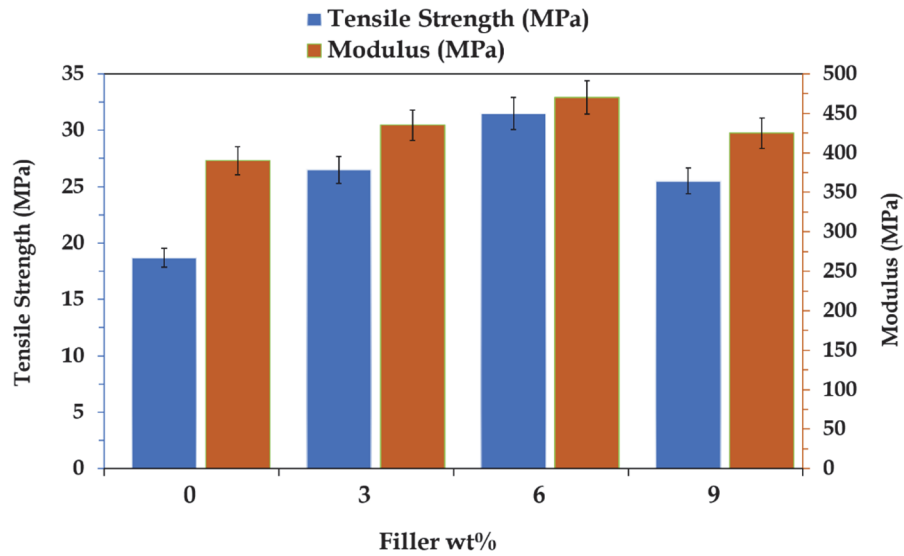


Figure 7: Tensile strength of bamboo composite wet samples

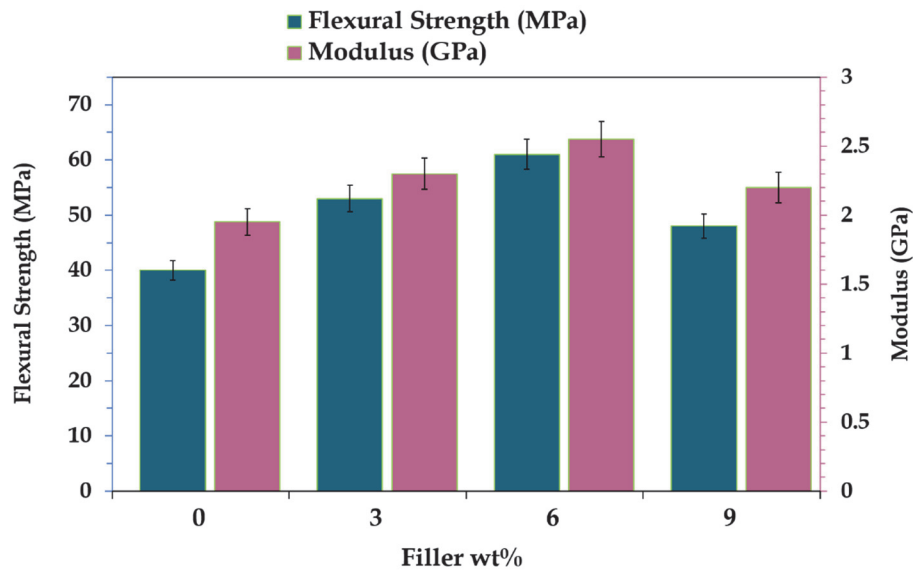
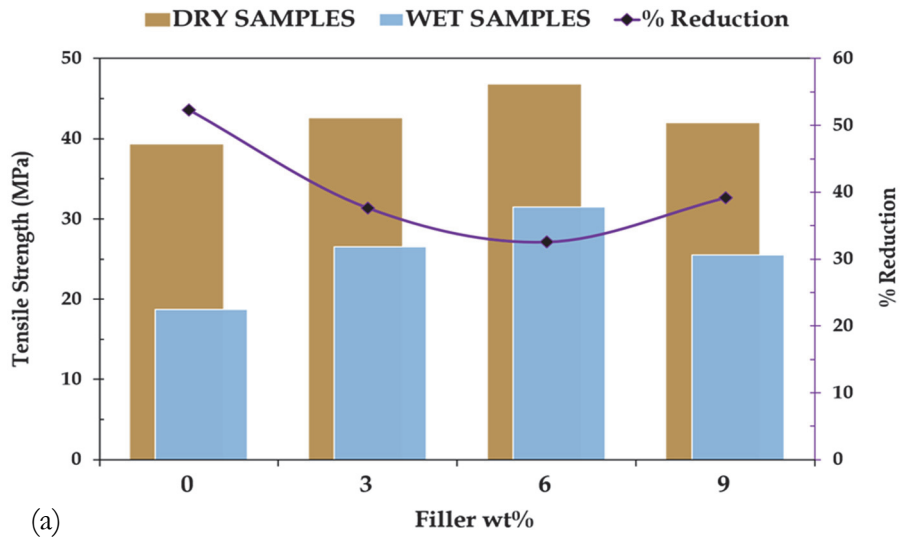


Figure 8: Flexural strength of bamboo composite wet samples



(a)

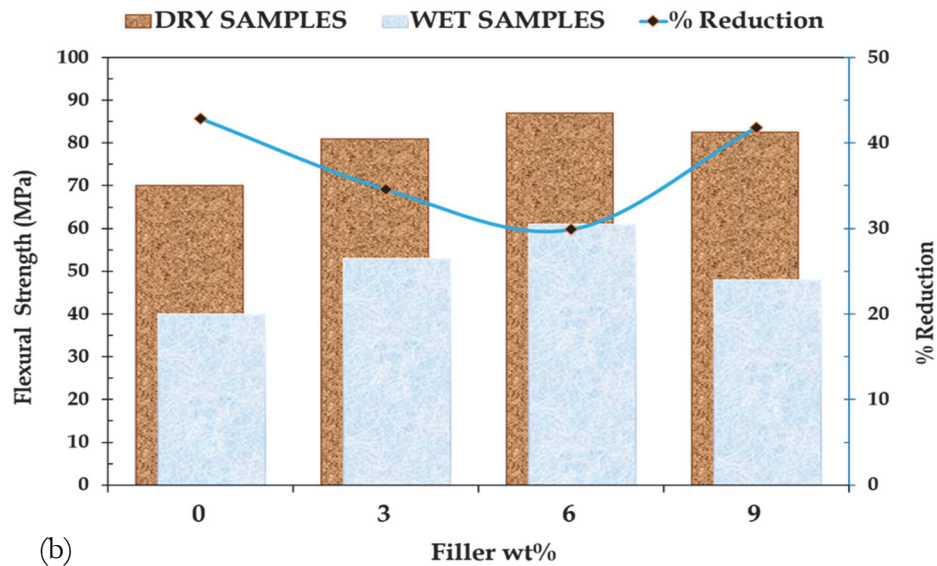


Figure 9: Comparison of results: (a) Tensile strength, (b) Flexural strength.

In wet conditions, for the composite without filler, a significant reduction of 52% in tensile strength (Fig. 9a) and 43% in flexural strength (Fig. 9b) was observed, indicating a substantial weakening of the composite structure due to moisture absorption. This significant reduction in strength was due to moisture absorption through the bamboo fibers' cell walls, causing them to swell and resulting in the weakening of the fiber-matrix interface, thereby reducing the effectiveness of stress transfer. Further, after prolonged exposure to moisture, the water absorption can cause hydrolytic degradation of a polymer matrix, breaking down the chemical bonds and compromising the composite's structural integrity. These adverse effects, lead to decreased load-bearing capacity of composites and overall strength declines severely in wet conditions. However, adding clamshell filler resulted in enhancing strength and reducing the adverse effects of water-soaking on mechanical properties. The addition of filler mitigated the moisture absorption impact, showing improved retention of strength. For bamboo composite with 6% clamshell filler demonstrated a higher retaining percentage of strength compared to 3%. However, 9% clamshell filler was less effective than 6% but still improved moisture resistance compared to 0% filler, suggesting an optimal filler content is between 3% and 6%. The addition of 6% filler provided the best overall strength retention in wet conditions, exhibiting 67.5% retention of tensile strength and 70% retention in flexural strength.

From the comparison graph, it was evident that clamshell filler addition at 3%, 6% and 9% reduced the degradation of mechanical properties. Tensile strength reduced by 37.8%, 32.5%, and 39%, while flexural strength declined by 34.6%, 30%, and 41.6%, respectively. The bamboo-epoxy composite with MMT filler (3 wt%) showed lower reductions, with tensile strength decreasing by 24.4% and flexural strength by 22.7% under wet conditions [23]. Although MMT demonstrated better moisture resistance and strength retention properties, the present study established that clamshell filler derived from waste seashells offers a sustainable and cost-effective alternative for enhancing the durability of bamboo composites under moisture exposure.

Fractography

In the current investigation, fractography is conducted for fractured wet samples. It provides critical insights into the moisture-induced degradation and failure mechanisms of composites. Figs. 10-12 present the SEM micrographs of water-soaked bamboo composite samples taken at different magnifications.

For the unfilled base composite, SEM micrographs of tensile fractured specimens is presented in Fig. 10. It can be seen that moisture absorption caused swelling of bamboo fibers and weakened the fiber-matrix interface, which reduces load transfer efficiency. As a result, fibers tend to pull out more easily under stress, contributing to lower mechanical properties. SEM micrographs shown in Fig. 10 (a) reveal moisture-induced matrix degradation, fiber pullout traces, void presence, and structural integrity loss, causing fibers to get separated from the matrix. A higher magnification image shows (Fig. 10 b) larger debonding around fibers, fiber breakage due to swelling, and increased fiber pull-out can be observed. This suggests that the load transfer between bamboo fibers and the epoxy matrix is insufficient, leading to early failure. This morphological study demonstrated the adverse effects of water soaking on the composite's structural properties.

Figs. 11 and 12 present SEM images of the composite with clamshell filler. When filler was added, it reduced moisture absorption and swelling. As seen in Fig. 11 (a), for composites with 3% filler, it was observed that some areas have pulled-out fiber bundle failures, indicating weakened fiber-matrix bonding, and there was matrix degradation occurred due to moisture. But it was less prevalent compared to the base composite, and due to filler inclusion, lesser fiber pullouts were observed, inferring better bonding and effective load transfer. Fig. 11 (b) displays fiber pullouts with more amount of resin on the fiber surface, indicating a modest increase in the strength of the composite.

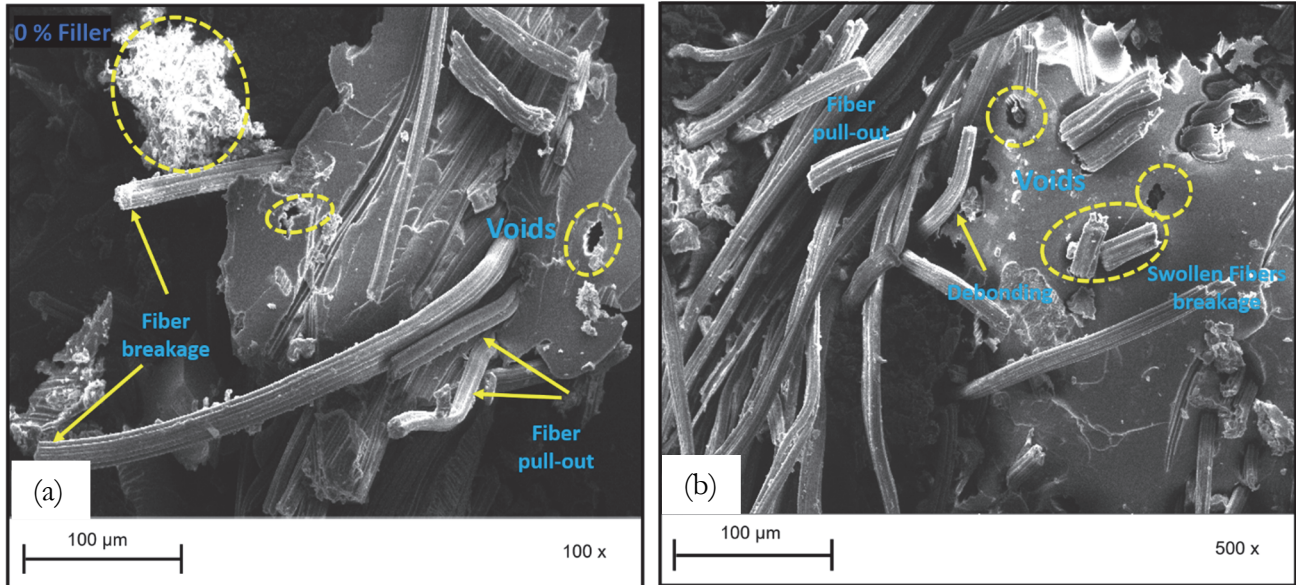


Figure 10: SEM micrographs of base composite: (a) 100X, (b) 500X

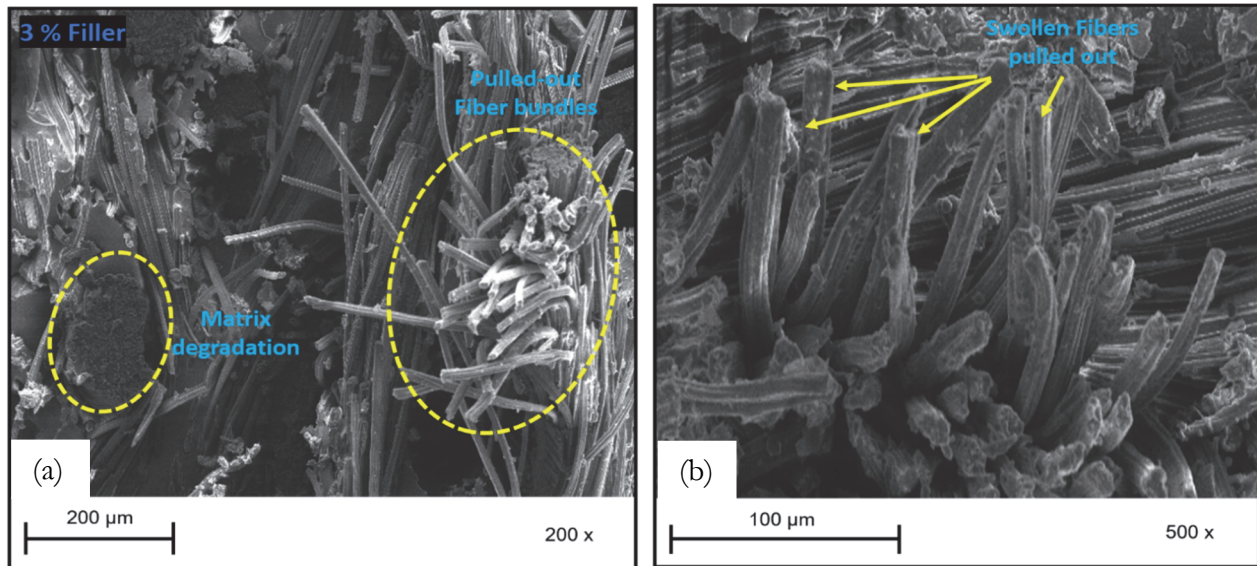


Figure 11: SEM micrographs of bamboo composite with 3 % filler: (a) 200X, (b) 500X

SEM micrographs of the bamboo composite with 6 % filler is presented in Fig. 12, which clearly shows improved interfacial bonding, and the composite exhibited better moisture resistance. The addition of clamshell particles created barriers for water molecules to infiltrate the matrix. Due to this, the resistance to water uptake significantly improved and enhanced load transfer efficiency. In Fig. 12 (a), fewer fiber pullouts can be seen, and moisture-induced matrix degradation was reduced. Fig. 12 (b), reveals uniform dispersion of filler particles that remain embedded in the matrix, indicating good adhesion, ensuring better wetting of fibers and strong interfacial bonding. This formed a smooth matrix interface, which

facilitates higher load-bearing capacity and better strength retention. Matrix cracking indicates moisture-induced internal stresses, and failure was mainly due to fiber breakage.

Overall, this morphological analysis explains the adverse effects of moisture absorption on the composite's structural properties and notable improvement in mechanical performance attained by the addition of clamshell filler to the bamboo-epoxy composite. This fractographic study is consistent with the results found in experimental investigations.

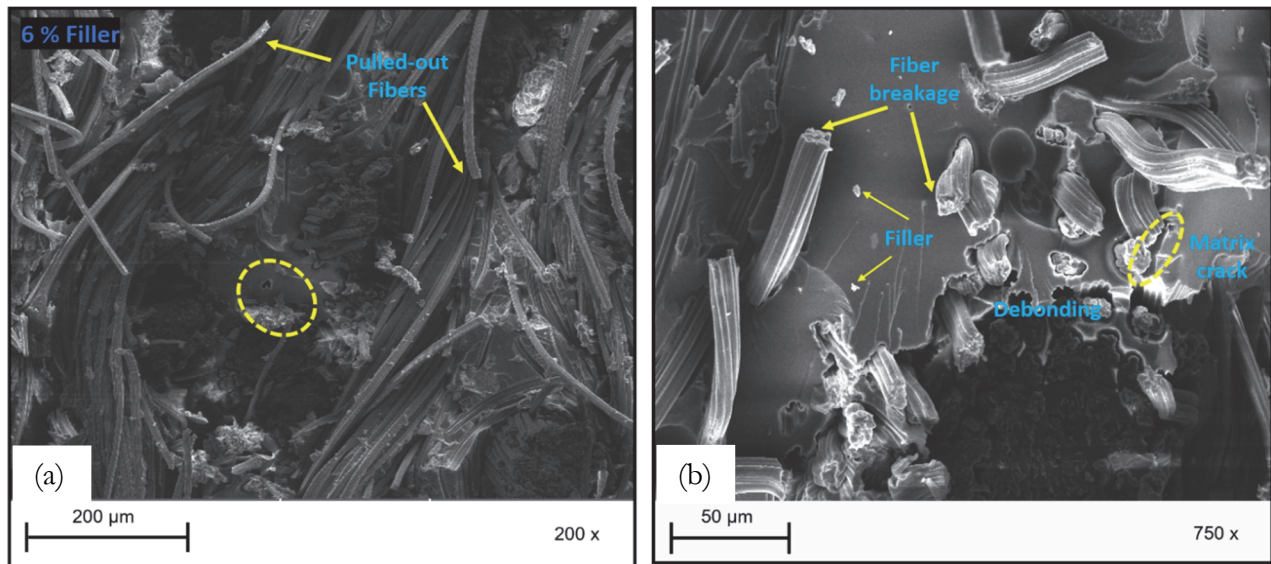


Figure 12: SEM micrographs of bamboo composite with 6 % filler: (a) 200X, (b) 750X.

CONCLUSIONS

This research was focused on mitigating the adverse effect of moisture absorption on the mechanical properties of bamboo-epoxy composites by incorporating particulate fillers derived from waste seashells. Water absorption test was conducted to analyse the moisture uptake behavior, and mechanical tests were conducted to evaluate the tensile and flexural properties after moisture conditioning. The main findings from the present study are as follows:

- Moisture absorption was significantly higher in unfilled bamboo composites, exhibiting highest absorption of 5.85%. Composite with clamshell filler exhibited significantly reduced absorption. Adding filler consistently reduced moisture absorption in bamboo composites, with most significant improvement achieved for 6 wt% filler, in which water uptake reduced by 30.4% compared to unfilled bamboo composites.
- Mechanical properties were significantly reduced in all samples due to moisture exposure, particularly in the unfilled bamboo composite, which had a severe degradation effect. The inclusion of filler reduced the moisture-induced degradation effect by reducing the water uptake and enhancing the retention of strength.
- Composites with clamshell fillers demonstrated improved moisture resistance due to better interfacial bonding, reduced water absorption, and improved stress distribution. The overall effects of filler incorporation facilitated the composite in maintaining mechanical properties under wet conditions.
- Bamboo composite with 6 wt% filler exhibited the most favorable balance between moisture resistance and strength improvement. Compared to unfilled wet samples, the tensile strength improved by 68.4% and the flexural strength by 52.5%.
- SEM analysis of wet samples highlighted the significant impact of moisture absorption on the bamboo fiber composites. Interfacial bonding between bamboo fibers and matrix degraded due to the water uptake, contributing to the loss of structural integrity and reduction in mechanical properties in wet conditions. The addition of filler reduced the hydrophilicity of the hybrid composite and altered the water absorption behavior. Filler presence minimized the moisture-induced degradation in the composite structure.

The findings from this study have given a brief understanding of clamshells as a sustainable filler to enhance the durability of bamboo composites, providing a green alternative to synthetic reinforcements while contributing to waste valorization. However, certain limitations to this study remain. The present study was restricted to a single particle size range and a



freshwater immersion test. Subsequent future work could focus on incorporating multiscale fillers combining micro and nano size particles, and extend the study to more aggressive environments such as saltwater and alkaline solutions.

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