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Silane-Grafted Bamboo Fiber and SiC Dispersion-Strengthened Epoxy Composites: Mechanical Performance and Hygrothermal Durability

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ABSTRACT

Recently, Biocomposites are gaining rapid industrial application due to their unlimited structural integrity and environmental sustainability. In this study, the mechanical and hygrothermal performance of epoxy matrix biocomposites reinforced with chemically modified bamboo fibers and dispersion-strengthened with silicon carbide (SiC) particulate fillers is investigated. Bamboo fibers were subjected to sequential surface treatments comprising alkaline mercerization with 0.1 N NaOH and silane coupling using the Gelest hydrolysis method, yielding four composite typologies: untreated bamboo–epoxy (UBE), NaOH-treated bamboo–epoxy (NBE), NaOH–silane-treated bamboo epoxy (NSBE), and SiC-filled NaOH–silane-treated bamboo–epoxy (NSBES). Composite laminates were fabricated by hand lay-up with compression consolidation and post-cured at 80°C. Tensile, flexural, and moisture absorption tests were conducted in accordance with ASTM D3039, ASTM D790, and ASTM D570 standards, respectively. Under dry conditions, alkali treatment (NBE) raised peak tensile strength by 23.97% over untreated composites at an optimal 15 vol% fiber loading, while combined NaOH–silane treatment (NSBE) further improved it by 39.96% to 64.8 MPa. The addition of 10 vol% SiC to the NSBE system (NSBES) yielded a peak tensile strength of 89.6 MPa, representing a 38.27% gain attributable to dispersion-strengthening mechanisms that impede matrix crack propagation. Flexural strength similarly peaked in the NSBES system, with SiC raising it by 67.32% at 10 vol% bamboo fiber loading compared to unreinforced composites. Under moisture-saturated conditions, NSBES retained the best hygrothermal stability, recording a wet tensile strength of 74.3 MPa surpassing even the dry UBE baseline of 46.3 MPa and the lowest saturation moisture content (W% = 0.92%). Moisture absorption kinetics followed a dual Fickian/non-Fickian diffusion regime, with the diffusion coefficient decreasing systematically across the treatment hierarchy. These results demonstrate that the synergistic combination of silane grafting and SiC dispersion strengthening yields high-performance, moisture-resistant natural fiber composites well-suited to structural, automotive, marine, and construction applications where both mechanical integrity and environmental durability are required.

Keywords:
Silane coupling,
Dispersion strengthening,
Tensile,
Flexural,
Moisture,
Biocomposite.

INTRODUCTION

Despite the advent of polymeric fibers that entered the market with exceptional qualities, the year 2009 was globally designated the International Year of Natural Fibers (Asim et al., 2015), an event that revitalized the prominence of plant-based reinforcements across several industries. This renewed interest is driven by the judicious exploitation of forest and agricultural residues, accelerated in part by growing environmental degradation. Reports (Subagyo and Chafidz, 2018) indicate that annual global production of steel, plastics, and lignocellulosic fibers stands at approximately 0.7, 0.1, and 4.0 billion tonnes (BT) respectively. This underscores the growing global demand for, and relevance of, natural fibers within contemporary environmental sustainability discourse. Moreover, forest and agricultural products collectively account for three-fifths of that lignocellulosic output. This also shows the extent to which customer demands, corporate environmental policies, and research and development have compelled industries to embrace environmental stewardship. Ranging from socio-economic to environmental considerations, natural fibers have proven to be competitive alternatives to Kevlar, aramid, carbon, and glass fibers, which are among the highest-ranking synthetic reinforcements. These plant-based fibers have remained indispensable due to their unique qualities such as affordability, availability, design flexibility, machinability, non-toxicity, low weight, exceptional specific strength with absolute biodegradability, prospects of energy recovery after shelf life, lower costs of production and disposal. They are also health-friendly and eco-friendly, available, reusable, and recyclable, collectively offering a lower carbon footprint and substantial decrease in depleting forest reserves (Asim et al., 2015; Manjit and Mridul, 1994; Dhakal et al., 2007). Hence, to sustain the atmospheric carbon budget and other environmental resources, attention to exploit eco-friendly alternatives that can be reduced, reused and recycled at the end of their life cycle becomes a global priority to both the industrial and research communities.

Modern research and industrial development have also shown that natural fibers can exhibit superior flexibility, stiffness, modulus, and elongation at break compared to the synthetic fibers that dominate in high-mechanical-strength applications. It has also been established (Asim et al., 2015) that polymeric matrices of petroleum origin are non-biodegradable, but reinforcing them with natural fibers improves their degree of biodegradability. In addition, while synthetic fibers offer superior tensile strength and physical properties, natural fibers exhibit higher inherent elasticity and stiffness. Enhancing the mechanical performance of natural fibers therefore represents a viable pathway toward establishing them as credible alternatives to synthetic reinforcements in polymeric matrices.

Natural fibers are generally derived from minerals, animals and plant sources. Asbestos is a popular example of mineral reinforcement in composites but is in restricted usage due to their carcinogenic properties. Silk from spiders, wool from sheep, and hair from goats, camels, and horses are common animal-derived fibers. Plant fibers available in commercial quantities include bamboo, hemp, jute, ramie, kenaf, plantain, flax, pineapple, cotton, and date palm. Additional plant-derived sources include banana, sisal, coir, rice husk, cork etc while synthetic fibers include polymeric, glass, and carbon fibers, as well as Kevlar. When compared to their moderate mechanical properties, the low density of most natural fibers which ranges between 1.15–1.6 g/cm^3 offers a high specific strength and modulus. This strength-to-weight advantage enables natural fibers to compete effectively with synthetic alternatives (Sanal and Verma, 2017; Rambabu et al., 2019). Table 1 presents the mechanical properties of bamboo, glass, and carbon fibers, highlighting bamboo's potential as a substitute for synthetic fiber reinforcements.

Table 1: Mechanical properties of Bamboo, Glass and Carbon fibers, (Vaisanen et al., 2017).

Fiber	Density (g/cm^3)	Tensile strength (MPa)	Specific strength (MPa cm^3/g)	Elastic modulus (GPa)	Specific modulus (GPa cm^3/g)
Bamboo	0.6-1.1	140-230	600	11-17	48-89
Glass	2.6	2200-3600	850-1300	65	27
Carbon	1.4-1.8	3000-4000	1710	250-500	164-171

In order to meet broader industrial design requirements, this study seeks to further exploit the low density of bamboo fibers to improve their comparable specific strength and superior specific modulus relative to glass fiber. To achieve these objectives, the study aims to investigate surface modifications that will increase the fiber aspect ratio and fiber–matrix interfacial bonding, while reducing the high degree of moisture affinity inherent to bamboo fibers, all of which are expected to yield improved mechanical properties. In addition, previous studies by Santhosh and Bhanuprakash (2017) have shown that a 10% SiC filler content improved tensile strength by 2.53 times. In alloys, what interstitial atoms do to host atoms during solid solution strengthening is analogous to what particulate fillers such as silicon carbide, alumina, perlite, fly ash, and clay do in composites. In a crystal lattice, interstitials create local lattice distortions that impede dislocation movement, thereby reducing plastic deformation and increasing strength. On this basis, this study examines the role of SiC as a dispersion-strengthening filler in supplementing the mechanical properties of bamboo fiber in an epoxy resin matrix. Additionally, the necessity of assessing the thermal compatibility of the fiber, filler, and matrix to ensure adequate thermal stability during composite processing and service life is also a stated objective of this study. This is important because a composite becomes unserviceable if it oxidizes or decomposes at or below its intended service temperature.

MATERIALS AND METHODS

Materials

Extraction and Surface reconstruction of Fibers

Mature bamboo plants were harvested from the University of Port Harcourt Botanical Gardens and cut at their nodal positions. The sheaths and branch stubs were removed, the green outer skin was scraped off, and the culm was split lengthwise into 16 bamboo splints. With the lacunae exposed, the nodal diaphragms were excised and the internal skin scraped off to reveal the dense bamboo tissue. The bamboo pieces were then stripped into thin slices of no more than 5 mm to form bamboo chips. To achieve a higher aspect ratio, bamboo fibers were extracted from the culm by removing non-cellulosic organic matter. The beneficial effect of a high aspect ratio in increasing fiber flexibility defined as the ability to bend extensively without fracture is expressed mathematically in equation (5). A physicochemical approach was adopted as the retting method, in which wet ball milling of the bamboo chips was preceded by alkaline treatment. Alkaline treatment has been recommended (Esen et al., 2017) as a simple and economical method for increasing fiber aspect ratio, improving mechanical properties, and enhancing surface roughness and fiber–matrix adhesion. In this study, a stock solution of 18.94 N NaOH was prepared from a molar mass of 40 g/mol at a concentration of 50% w/w. From this, a 0.1 N working solution was prepared by adding 1.05 mL of the stock solution to 50 mL of deionized water and adjusting the volume to 200 mL with deionized water. The bamboo chips were immersed in the 0.1 N NaOH solution for three days at room temperature, during which the NaOH dissolved the lignin binders into soluble salts that were readily rinsed out of the fiber bundle, exposing the cellulosic fibers. The sodden chips were first rinsed in dilute HCl to neutralize residual NaOH, then washed repeatedly in a water bath until the pH of the wash water reached 7.0. The softened chips were processed in a wet ball mill and subsequently rinsed in a warm water bath to remove residual lignin fragments and other organic matter, yielding the bamboo fibers. The extracted fibers were combed with a blunt metal brush and sun-dried in still air before being cut to a mean length of 20 cm. The processed fibers were stored in a silica-gel-laden desiccator to maintain a moisture-free surface prior to use.

Surface preparation of Fillers

Silanol surface deposition following the Gelest method was used to prepare the SiC particulate surfaces. Ethanol and water in the ratio of 19:1 were mixed and the aqueous solution adjusted to pH 4.5 by the dropwise addition of acetic acid. With gentle stirring for 5 minutes, silane at 2% of the solution volume was added to hydrolyze it into silanol. The SiC particles were added and stirred for 3 minutes, then rinsed twice in ethanol, and the deposited silane layer was allowed to cure at room temperature under ambient Port Harcourt humidity for 24 hours. The prepared particulate fillers were stored in a dry, airtight jar ready for use.

Preparation of epoxy and hardener

The epoxy resin used in this study was a 1 kg pack of "Epochem 105" purchased from GZ Industrial Supplies, First Artillery Junction, Port Harcourt, Nigeria. It is a clear, colourless, heavy-duty, high-quality adhesive for composites. It is also solvent-free when used as an unpigmented binder, offering outstanding resistance to water and a wide range of domestic and commercial chemicals. The epoxy comes with a 1 kg curing catalyst, "Epochem 205" as a fast-drying and medium-viscosity epoxy curing agent. To obtain a rigid, high-strength, moisture-resistant solid with excellent bonding qualities, the two components were combined in a 250 mL beaker and mixed using a mechanical shear stirrer for up to 120 minutes at room temperature to yield a homogeneous mixture. The resin-to-hardener ratio was 5:1; the mixed system gels between 9–12 minutes and attains maximum strength within 4 days. In addition, this resin has low volatility and mild odour, providing safe handling characteristics. Furthermore, Epochem resin offers excellent wetting and filler-settling resistance.

Production of Biocomposites

The conventional hand lay-up method supplemented with compression molding was used to fabricate the composite samples using an Aluminum mold of 150 × 140 × 40 mm^3 dimension. The processed Bamboo fibers were cut into the mold dimension with a tolerance of 5mm from each end. Silicon spray was applied as a mold-releasing agent and was left for 30 minutes to dry before the Epoxy-Hardener mixture was poured into the mold gently to avoid bubble formation. After an even spread of the Epoxy-Hardener mixture as a matrix blend within the mold, a layer of processed Bamboo fiber was laid in unidirectional orientation and a gentle squeezing was done using a hand roller to disperse the fibers within the matrix and to expel interfacially entrapped voids and air bubbles. It has been established that fiber length is a critical factor in determining composite strength; in this study, maximum fiber length up to the mold length was used. The factor varied in this study was the fiber volume fraction, starting with 5 vol%. Subsequent layers at 10%, 15%, and 20% volume fractions were sandwiched by topping up the matrix volume and squeezing with the hand roller to impregnate the new fiber layer and expel voids and air. Having established 15% as the optimal fiber volume fraction, this loading was held constant to investigate the dispersion-strengthening effect of SiC fillers on the bamboo–epoxy composites. SiC particles were incorporated into the epoxy matrix mixture at filler volume fractions of 5%, 10%, 15%, and 20% at a constant 15% bamboo fiber loading. An unreinforced reference sample (Ref), containing neither fiber nor SiC filler, was tested alongside all other composites.

Several samples were produced under four typologies:

i. UBE (Untreated Bamboo fiber in Epoxy Resin),
ii. NBE (NaOH-treated Bamboo fiber in Epoxy Resin),
iii. NSBE (NaOH-Silane-treated Bamboo fiber in Epoxy Resin),
iv. NSBES (NaOH-Silane-treated Bamboo fiber in Epoxy Resin SiC-strengthened),

Each composite slab was cured for 24 hours and consolidated under a 5 kg static load applied to the top of the mold. After removal from the mold, post-curing was carried out at 80ºC for 120 minutes, in preparation for tensile and flexural (three-point bending) tests.

Methods

To investigate the effect of SiC dispersion strengthening on bamboo fiber-reinforced epoxy composites, fabricated samples were subjected to three characterisation tests: tensile strength, flexural strength, and moisture absorption.

Tensile strength behaviour

Tensile tests, measuring the force required to deform composite samples and the associated elongation at fracture, were conducted in accordance with ASTM D3039. Tests were performed in triplicate and mean values reported. Strain was measured using a video extensometer on a 30 kN capacity Tinius Olsen Universal Testing Machine-H10KS at a crosshead speed of 10mm/min.

Flexural strength behaviour

The maximum deflection of a composite is easily measured using the three-point bending test conducted in line with ASTM D 790 protocol. This flexural strength, modulus of rupture or bend strength is an intensive property that determines its tendency to bend extensively before deformation. It also shows the maximum allowable stress the composite can carry before failure as well as the fiber-matrix interfacial shear strength.

When a homogeneous composite sample treated as an elastic, slender rectangular beam of height h and width b is subjected to a bending moment M through a radius of curvature R, a flexural rigidity EI is developed. This gives rise to a tensile or compressive stress σ at a distance y from the neutral plane, where the second moment of area I is taken about the neutral axis. The flexural rigidity (EI) is directly proportional to the second moment of area I; substituting the elastic modulus E as the proportionality constant gives:

$$MR \propto I \quad (1)$$

Showing that:

$$MR = EI \quad (2)$$

Meanwhile:

$$Mh = I\sigma \quad (3)$$

For a cylindrical beam, the second moment of inertia I = $\left(\pi d^4/_{64}\right)$

Then the flexibility:

$$\text{F} = \frac{1}{MR} = \frac{1}{EI} = \frac{1}{\left[E\left(\pi d^4/_{64}\right)\right]} = \frac{64}{E\pi d^4} \quad (4)$$

$$\therefore \text{F} = \frac{64}{E\pi d^4} \quad (5)$$

Hence, Flexibility (F) and diameter (d) are inverse functions of each other and this shows that at constant stiffness (E) and length (L), by reducing the diameter of fibers to achieve higher aspect ratio (Length/diameter) increases the flexibility or slenderness of a fiber which is its ability to bend without breaking. This formed the background of this study where surface treatments have been aimed at increasing the aspect ratio to achieve improved mechanical properties.

For a rectangular beam as used in this flexural test:

$$\text{I} = \left(bh^3/_{12}\right) \quad (6)$$

From equation (1) through (5):

$$\frac{M}{I} = \frac{E}{R} = \frac{\sigma}{h}$$

This shows that:

$$\sigma = \frac{\text{Mh}}{I} \quad (7)$$

In a three-point bending test, the Applied force (F) is maximum at the midpoint hence effective force becomes F/2 and this midpoint effect acts at a rectangular length of the beam y = L/2 leading to the bending moment:

$$M = \frac{F}{2} \times \frac{L}{2} = \frac{FL}{4} \quad (8)$$

From these equations:

$$\sigma = \frac{\text{Mh}}{I} = \left[\left(\frac{FL}{4}\right)h \Big/ \left(bh^3/_{12}\right)\right] \quad (9)$$

Hence,

$$\sigma = \frac{3FL}{2bh^2} \quad (10)$$

This shows that, in a three-point deflection test of a rectangular composite beam, the flexural strength σ is obtained using Equation (10), where F is the maximum load recorded at failure, L is the specimen length between the two support points, and b and h are the specimen width and thickness, respectively.

Samples were made out of each fiber typology in triplicates so that an average result can be reported at point of failure. The flexural test was conducted using a 30 kN load cell applied at crosshead speed of 2 mm/min. A span of 48 mm, maintaining a span to depth ratio of 16:1, was used in the 30 kN load cell with the load placed midway between the supports.

Moisture Absorption Test

The epoxy hardener is hygroscopic and the bamboo fiber reinforcement is inherently hydrophilic; these characteristics, along with other compositional attributes, elevate the moisture uptake of the fabricated composite. Absorbed water promotes microcrack development and fiber swelling, leading to dimensional instability and other detrimental effects on the composite's service performance.

A prediction of the diffusion and permeability rates of the composite was conducted using a water absorption test in accordance with ASTM D570 at room temperature. The kinetics of water absorption was investigated by recording the average increase in moisture absorptions of three samples after their immersion in distilled water. Rectangular samples of 23 × 24 × 24 mm dimension in line with ASTM D 5229-04 were sealed at their lateral faces to reduce capillary absorption of water. These samples were oven-dried for 24 hours at 60°C to ensure complete, uniform dryness and were periodically weighed until negligible mass change was recorded. Their initial dry weights (W_d) were recorded using a four-digit electronic weighing balance. Water absorption was monitored for up to 28 days until negligible mass change was observed in all samples immersed in a shallow basin of distilled water. After each soaking interval, samples were retrieved and surface-dried with an absorbent cloth before wet-weight (W_w) measurement.

Experimentally, the percentage moisture content (W%) were calculated using equation (11):

$$W\% = \frac{Weight\ gain\ (\Delta W)}{Initial\ weight} \times 100 = \left(\frac{W_w - W_d}{W_d}\right) \times 100 \quad (11)$$

where W% is the percentage moisture content, W_w is the wet weight (g) after a soaking time (t) and W_d is the initial dry weight (g).

RESULTS AND DISCUSSION

Tensile Strength

Effect of Fiber Volume Fraction and Surface Treatment (Dry Condition)

Figure 1 shows that the tensile strength response to increasing bamboo fiber fraction followed a consistent trend across all treatment typologies. For the UBE system, strength increased from 28.4 MPa (0% fiber reference) to a peak of 46.3 MPa at 15% fiber loading with a recorded 63% improvement. However, beyond 15%, strength declined to 43.1 MPa at 20% fiber fraction, indicating the onset of fiber agglomeration and inadequate matrix impregnation at higher loadings, consistent with established theory for short-fiber composites, Madhuri and Rao (2014).

However, the NaOH-treated NBE series showed significantly superior performance: peak tensile strength reached 57.4 MPa at 15% fiber, a 23.97% gain over neat epoxy at the same fiber loading. This improvement reflects the dual effect of alkaline delignification: (i) removal of waxy surface deposits and lignin binders exposing cellulosic microfibrils with superior specific strength, and (ii) the resulting increase in surface roughness amplified mechanical interlocking at the fiber-matrix interface, Diana and Ferreira, (2019).

Furthermore, the NSBE system, benefiting from both NaOH mercerization and silane coupling, achieved the highest tensile performance among all untreated and treated variants, recording a tensile strength of 64.8 MPa at 15% fiber loading a 39.96% improvement over the neat epoxy reference. This enhancement is attributable to the silane coupling agent forming covalent Si–O–C bonds between the functionalized fiber surface and the epoxide matrix, significantly reducing interfacial debonding susceptibility.

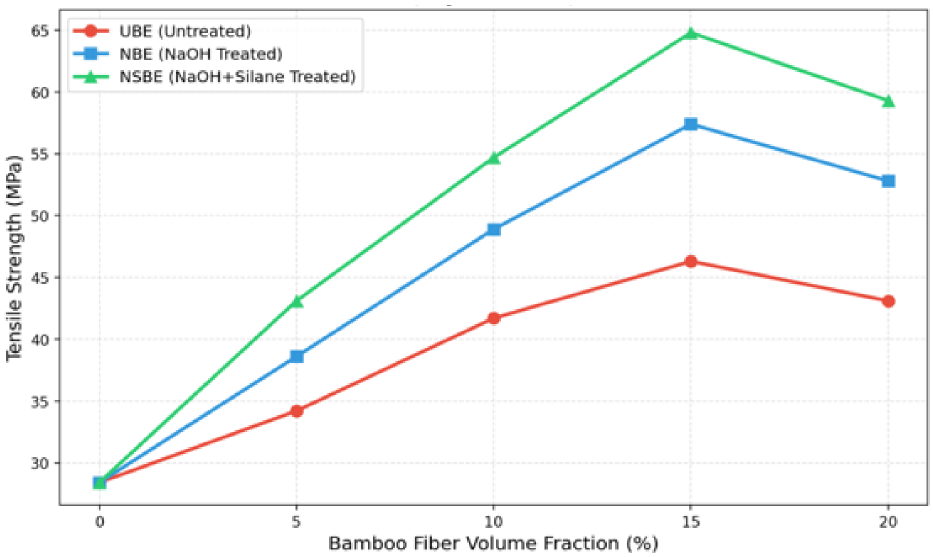

Figure 1: Tensile strength vs. bamboo fiber volume fraction under dry conditions for UBE, NBE, and NSBE composites

Effect of Fiber Volume Fraction and Surface Treatment (Wet/Moisture-Saturated Condition)

Under moisture-saturated conditions, all composite samples exhibited reduced tensile strength compared to dry counterparts. This is a well-documented behavior in natural fiber composites attributed to plasticization of the epoxy matrix, fiber swelling, and hydrolytic degradation of fiber-matrix interfacial bonds, (Dhakal et al., 2007; Muñoz and Garcia-Manrique, 2015).

From Figure 2, the UBE system registered the most severe strength reduction, with a peak wet tensile strength of 36.4 MPa compared to 46.3 MPa under dry conditions, representing a 27.20% reduction. The NBE system demonstrated improved moisture resistance with only a 24.51% strength loss between dry and wet conditions. Remarkably, the NSBE system exhibited superior hygrothermal stability, retaining strength with only a 19.56% reduction under moisture-saturated conditions.

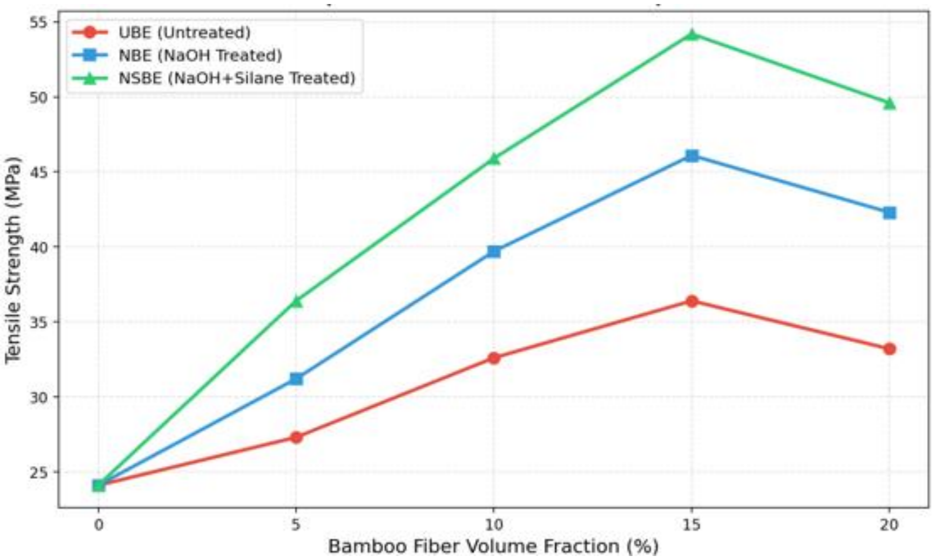

Figure 2: Tensile strength vs. bamboo fiber volume fraction under moisture-saturated conditions for UBE, NBE, and NSBE composites

The progressive improvement in wet retention across UBE → NBE → NSBE reflects the hydrophobicity introduced by NaOH and silane coupling. By substituting reactive surface hydroxyls with non-polar organosilane groups, moisture ingress pathways at the fiber surface are substantially reduced. These results were further reinforced by the moisture absorption data.

Dispersion Strengthening Effect of SiC Filler

Results from Figures 1 and 2 confirmed that all composite systems achieved maximum tensile strength at a bamboo fiber volume fraction of 15%, which was therefore adopted as the optimal bamboo content. Figure 3 shows that the addition of SiC filler to the optimized NSBE system (15% bamboo fiber) produced significant strength improvements consistent with dispersion strengthening mechanisms. The tensile strength of the NSBES system increased from 64.8 MPa (0% SiC) to a maximum of 89.6 MPa at 10% SiC loading, representing a 38.27% gain attributable to SiC dispersion. This enhancement is analogous to interstitial solid solution strengthening in metallic systems, wherein dispersed hard particles generate localized stress fields that obstruct matrix crack propagation and impose kinematic constraints on deformation (Santhosh and Nithyaprakash, 2017).

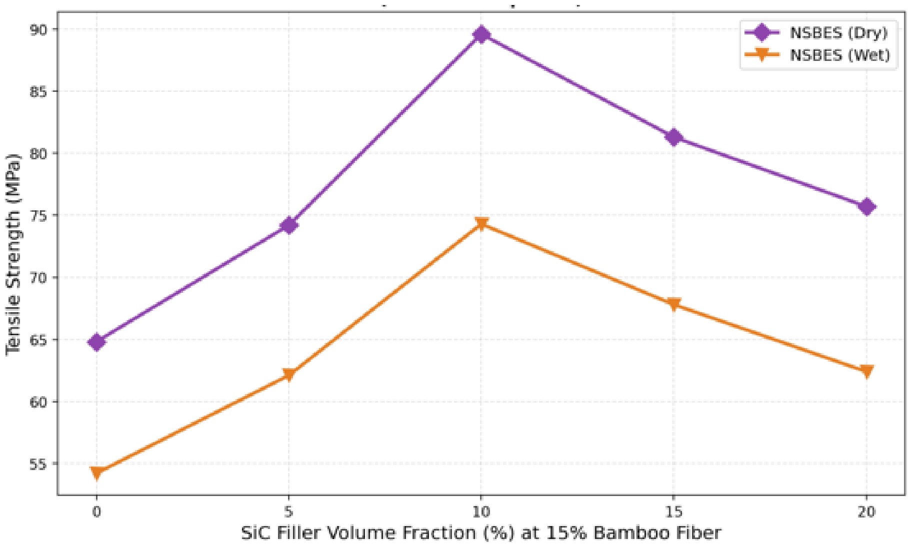

Figure 3: Tensile strength vs. SiC filler volume fraction for the NSBES composite system (dry and wet conditions) at 15% constant bamboo fiber loading

However, beyond 10% SiC, strength declined to 81.3 MPa (15% SiC) and 75.7 MPa (20% SiC), indicating the onset of particle agglomeration, stress concentration, and reduced matrix continuity at high filler fractions. This non-monotonic response strengthening followed by softening is a universal feature of particulate-reinforced polymer composites and confirms 10 vol% SiC as the optimal filler fraction for this system. The same trend was observed under wet conditions, with tensile strengths uniformly lower than their dry counterparts. Notably, under wet conditions, the NSBES system at 10% SiC achieved 74.3 MPa, outperforming even the dry NSBE composite without filler (64.8 MPa), confirming that SiC fillers effectively seal the internal porosity otherwise exploited by moisture ingress.

Flexural Strength

Flexural strength results in Figure 4 corroborated the tensile trends with notable additional insight. The three-point bending configuration imposes a combined tensile–compressive–shear stress state that is particularly sensitive to fiber–matrix interfacial quality and composite laminate uniformity. The UBE system peaked at 54.8 MPa (15% fiber), while the NBE system achieved 65.7 MPa, representing a 19.89% improvement over UBE at equivalent fiber loading. This confirms that alkali treatment not only improves tensile performance but also enhances interlaminar shear strength through improved matrix wetting and mechanical keying.

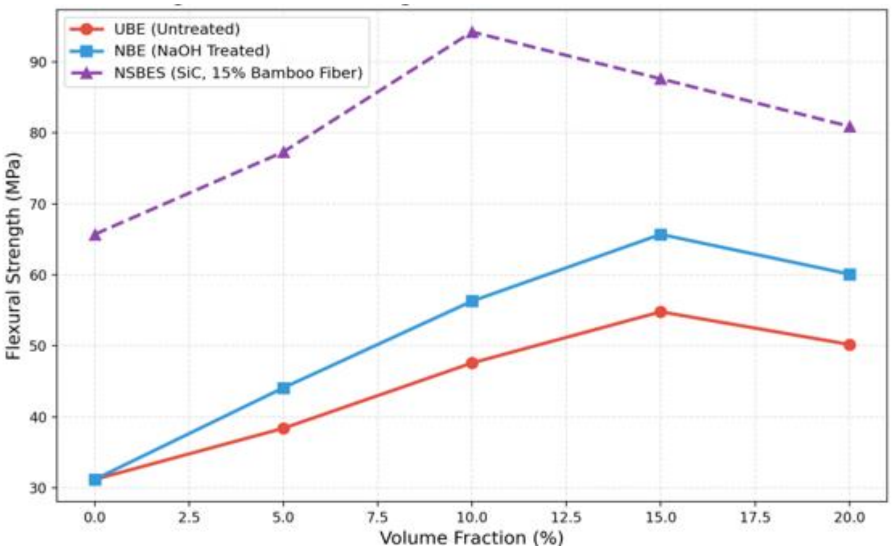

Figure 4: Flexural strength vs. volume fraction for UBE, NBE fiber composites and NSBES SiC-filler system

The SiC-loaded systems consistently recorded higher flexural strengths than the bamboo-reinforced composites without SiC. Specifically, SiC fillers raised flexural strength by 67.32% and 33.33% at the 10% and 15% bamboo reinforcement levels, respectively. SiC particles dispersed within the matrix between fiber layers acted as crack deflectors and load-transfer bridges, increasing the composite's resistance to interlaminar failure. These results indicate that for applications demanding high flexural strength, bamboo and SiC volume fractions of 10% and 15%, respectively, are optimal, while for high tensile strength applications, 15% of both bamboo fiber and SiC is recommended. The observed decline in flexural strength at 15% and 20% SiC fractions is attributed to inter-particle proximity effects that promote void nucleation under bending stress.

Moisture Absorption Behavior

The moisture absorption kinetics in Figure 5 revealed a characteristic Fickian diffusion response in the initial stage, transitioning to non-Fickian (anomalous) behaviour near saturation, consistent with the dual-mechanism absorption commonly reported for lignocellulosic fiber composites (Muñoz and Garcia-Manrique, 2015). Saturation was achieved earliest for the neat epoxy reference (percentage moisture content W% = 0.50%), confirming its more compact crosslinked network compared to all fiber-reinforced systems.

The UBE composite exhibited the highest moisture uptake (W% = 1.87% at saturation) and latest saturation point, reflecting the hydrophilic nature of untreated bamboo fibers and its associated interfacial voids that provide capillary moisture pathways. NaOH treatment (NBE) reduced saturation moisture content to 1.44%, while the addition of silane coupling (NSBE) further reduced it to 1.30%. The NSBES system incorporating both chemically treatment and SiC filler recorded the lowest moisture uptake (W% = 0.92%) and an early saturation point, demonstrating that SiC particles physically occupy internal voids that would otherwise serve as moisture reservoirs.

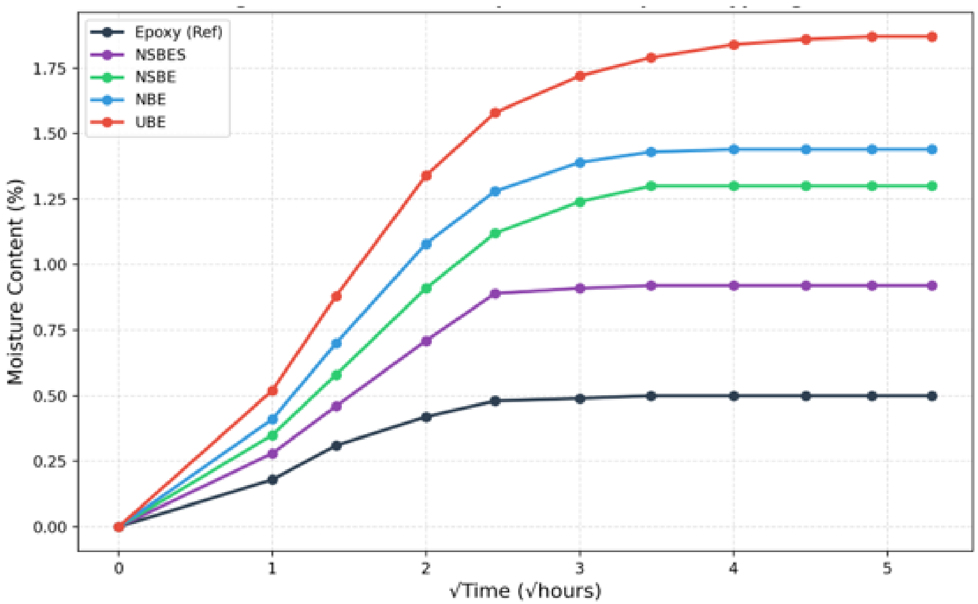

Figure 5: Moisture absorption kinetics (% moisture content vs. √time) for all composite typologies

In addition, the moisture absorption behavior of all the curves followed both Fickian and non-Fickian mechanisms in line with previous studies, (Venkateshwaran et al., 2011). The moisture absorption data follow the Fickian regime relating percentage moisture content W% and saturation time:

$$W(\%) = A\sqrt{t} \qquad (12)$$

where the diffusion coefficient A decreases systematically with treatment sophistication: A(UBE) > A(NBE) > A(NSBE) > A(NSBES). This hierarchy confirms the efficacy of the multi-stage treatment strategy in engineering composites with improved environmental durability.

CONCLUSION

This study has successfully demonstrated that the mechanical and hygrothermal performance of bamboo fiber-epoxy composites can be substantially enhanced through sequential surface treatment and particulate dispersion strengthening. The following specific conclusions are drawn from the experimental findings: Alkaline mercerization of bamboo fibers with 0.1 N NaOH effectively removed surface lignin, wax deposits, and amorphous hemicellulose, exposing cellulosic microfibrils of higher specific strength and increasing surface roughness for improved mechanical interlocking. This treatment alone raised peak dry tensile strength by 23.97% relative to untreated composites at the optimal fiber loading of 15 vol%, and reduced saturation moisture content from 1.87% to 1.44%. Subsequent silane coupling treatment (NSBE) introduced covalent Si–O–C bonds at the fiber–matrix interface, significantly reducing interfacial debonding susceptibility and moisture ingress pathways. Peak dry tensile strength reached 64.8 MPa, a 39.96% improvement over the epoxy reference, while saturation moisture content declined further to 1.30% and wet strength retention improved to 80.44% compared to 72.80% for untreated composites. SiC dispersion strengthening of the optimized NSBE system (NSBES at 10 vol% SiC) yielded the highest mechanical performance across all composite typologies: a peak dry tensile strength of 89.6 MPa (38.27% over NSBE without filler), a peak flexural strength 67.32% above the unreinforced baseline at 10 vol% fiber, and the lowest saturation moisture content of 0.92%. The wet tensile strength of NSBES at 10% SiC (74.3 MPa) surpassed the dry tensile strength of the untreated UBE composite (46.3 MPa), confirming that SiC particles effectively occlude internal porosity that would otherwise provide capillary pathways for moisture ingress. Moisture absorption kinetics for all composite typologies followed a combined Fickian and non-Fickian (anomalous) diffusion regime, consistent with previously reported behavior in lignocellulosic fiber composites. The diffusion coefficient A decreased systematically across the hierarchy A(UBE) > A(NBE) > A(NSBE) > A(NSBES), confirming the progressive efficacy of the multi-stage surface treatment and filler strategy in reducing moisture diffusivity. The NSBES composite system, combining the low density and renewability of bamboo with the crack-arresting capability of SiC, presents a compelling, cost-effective, and eco-friendly alternative to glass fiber–reinforced polymers for a broad range of industrial applications. These include lightweight structural panels in the automotive and aerospace sectors, building cladding and partition systems requiring moisture resistance, marine and offshore components exposed to humid environments, agricultural machinery enclosures, and packaging requiring structural integrity under ambient moisture conditions. Future work should focus on thermogravimetric analysis of the composite system, interlaminar shear strength characterization, and fatigue behaviour under cyclic hygrothermal loading to fully qualify the material for structural service.

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