Effect of Nano Silicon Carbide Particles on Epoxy Hybrid Composites Surface Morphological Behavior and Tensile Performance

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**Abstract:** This work assesses how the addition of nano silicon carbide (SiC) affects the mechanical and surface properties of epoxy composites reinforced with short bamboo fibers. Composites were produced by injection molding using an 10 wt% bamboo fiber fraction that had been treated with NaOH; samples contained varying nano SiC levels of 0, 3, 6, and 9 wt%. Moisture uptake, yield strength, tensile strength, and impact toughness were measured. Data show that tensile strength and impact toughness increase with higher nano SiC content, while moisture absorption decreases markedly. Scanning electron microscopy (SEM) photographs confirm tighter fiber–matrix bonding and reduced voids, which together bolster overall performance.

# Introduction

Evaluation of spectroscopic methods—FTIR, Raman, and XRD—focused on biofibre and biopolymer characterization within biocomposites. Notably, they reported that NaOH pre-treatment effectively de-lignifies and de-hemicelluloses the fibres, thereby reinforcing fibre-epoxy interfacial adhesion and yielding marked enhancements in mechanical properties. The authors conclude that such spectral techniques are indispensable for tailoring fibre-polymer compatibilities [1-4]. Likewise, [5-6] quantified the impact of naturally-occurring fillers—cellulose, lignin and starch—on epoxy matrix behaviour. Their results indicated that a 20–30 wt% proportion of wood flour simultaneously raises flexural modulus and reduces ductility. The study advocates for silanization treatments to mitigate filler agglomeration and to secure homogenous dispersion. Complementingly, [7-9]argued that moisture uptake—estimated at 25%—coupled with inherently weak fibre-epoxy bonding, constitutes the principal limitation of natural fibre composites. By incorporating 5 wt% nanoclay within a leveraged hybrid architecture, the tensile strength was improved by 15–20% and moisture uptake substantially curtailed, thereby adressing the identified weaknesses. Adding 3–6 wt% Al₂O₃ and SiC nanoparticles into carbon/epoxy laminates affected their mechanical properties. They recorded a 32% increase in flexural strength from the SiC particles, attributing it to efficient load transfer; however, adding more than 6 wt% led to agglomeration and the early formation of micro-cracks [10-12]. Hybrid composites containing both natural and synthetic reinforcing fibres. They demonstrated that jute–glass/epoxy hybrids yielded a 40% improvement in impact strength relative to pure jute laminates, a result of effective carrier effects. They also urged inclusion of full lifecycle assessments in future work to appraise the overall sustainability of such composites [13-15]. Laboratory work was showing that 1–3 wt% additions of nano-SiO₂ and TiO₂ into epoxy systems could raise fracture toughness by up to 50% via crack diversion mechanisms [16-19]. If the filler load exceeded that range, bulk viscosity and processing hurdles became significant; viscosity exceeded 1 000 mPa.s. In a directed comparison study, Bamboo–glass/epoxy hybrids outperformed composite bamboo/epoxy with a tensile strength of 68 MPa, contrasted to 45 MPa for the pure. Micro-mechanical simulations implicated improved fibre stiffness and refined stress transfer from the glass contribution [20-25]. Research [26]fabricated epoxy/SiC composites with thermal conductivity 1.5 higher than that of the unfilled epoxy. They achieved a uniform dispersion of SiC filler at loadings of 10–15 wt% using a proprietary in-situ triple-shaft static mixer, making the material applicable to thermal management in electronic modules. Research [27] demonstrated that the addition of 5 wt% oil-palm-derived cellulose nanofibrils elevated the storage modulus of an epoxy resin by 80% at 30 °C. Uniform dispersion, however, called for brief sonication owing to the nanofibrils’ high aspect ratio of approximately 50. Research [28-30] noted that kenaf/sisal/epoxy hybrid laminates reached a glass transition temperature 15 °C higher than that of single-fiber counterparts, a rise interpreted as the result of confined polymer chain movements; introduction of 3 wt% nanoclay subsequently improved the material's damping characteristics. Research [31-33] conducted a comprehensive review of hybrid composites, emphasizing a material cost reduction of 20% when compared with synthetic alternatives and identifying complications in fiber wetting, for which automated lay-up and tailored curing schedules were proposed. Research [34-35] outlined sustainable processing pathways—namely, solvent casting and compression molding—applied to starch/epoxy composites, yielding 90% biodegradability; to counter brittleness in the final blend, regulated quantities of glycerol were employed as a plasticizer. Using combining different nano-additives with epoxy, the mechanical and tribological properties of the polymer have been steered with impressive precision, as evidenced in recent reports. Research [36] investigated the role of different dimensional fillers, noting that a mere 0.5 wt% graphene provided a 120% rise in fracture toughness attributable to efficient crack-bridging, while 3 wt% SiO₂ mostly elevated hardness by 20%. Research [37] meanwhile integrated 2 wt% SiC into the epoxy matrix, which halved the wear rate because of a marked rise in surface hardness; the concurrent addition of a small quantity of MoS₂ effectually trimmed the friction coefficient by 35%, resulting in a distinct improvement in tribological efficiency. In a complementary work by Research [38, epoxy composites reinforced with untreated jute absorbed a full 12% of moisture in only 72 hours of immersion, provoking a 30% tensile strength reduction; the same fibers, when silane-modified, restricted the moisture ingress to 5%, thus stabilising mechanical properties. Farther afield, Research [39-40] provided a sweeping survey of kenaf-reinforced composites, asserting that a fill of 50 wt% kenaf afforded a peak flexural strength of 85 MPa, while strategic alkali scraping diminished fiber pull-out and secured long-term endurance. [49-50]

# Materials and Methods

This investigation employs an epoxy matrix augmented by natural fiber reinforcement and a nanoscale filler tailored to improve mechanical resilience and barrier to moisture ingress. The epoxy matrix is comprised of LY556, a thermosetting formulation recognized for its high tensile strength, outstanding chemical durability, and thermal steadiness. Curing is achieved by blending the resin with the hardener HY951 in a weight ratio of 10:1, a proportion selected to promote maximum cross-link density and cure homogeneity. To introduce tensile reinforcement, bamboo short fibers are introduced at a loading of 10 wt.%, with enhancement of the fiber surface achieved through a two-hour immersion in 5% sodium hydroxide at ambient temperature. The alkaline treatment serves to eliminate waxy and morphological contaminants, renders the fiber surface more competitive for chemical bonding, and diminishes the water-absorbing hydroxyl groups, thereby increasing fiber affinity for the resin and ensuring fine dispersion in the composite matrix.

Silicon carbide nanoparticles measuring 30 to 50 nanometers were selected as a secondary reinforcement, studied at four different weight fractions—zero, three, six, and nine percent. The choice of these specifically sized nanoparticles rests on three key properties: extreme hardness, exceptional capacity for load transfer, and outstanding thermal stability. Together, these traits provide measurable rises in mechanical strength, heightened resistance to impact, and lower permeability to moisture. Furthermore, such nanoparticles effectively limit the reach of micro-cracks and strengthen the bonding zone that separates the bulk matrix from the primary reinforcing constituents, leading to more durable composite structures.

The fabrication sequence was carefully designed to guarantee consistent reinforcement dispersion and maximize composite properties. Bamboo strands were immersed in an aqueous sodium hydroxide bath (5%, w/v) for two hours to remove hemicellulose and lignin, rinsed under running distilled water, and then air-dried, thereby enhancing their bonding capacity with the epoxy matrix. At the same stage, nano-sized silicon carbide powders were suspended in the epoxy resin and treated in an ultrasonic bath for 30 minutes, which broke up potential clusters and yielded a stable, homogeneous pre-mix. Following this pre-treatment, the dried lignocellulose fibers were added into the nano SiC-dispersed epoxy, and the blend was intensively agitated in a planetary mixer for a fixed period, resulting in a consistent phase architecture. The homogeneous liquid composite was then gravity-fed into a closed, heated mold, after which the mold was sealed and placed in an air-circulated oven at 80°C for 240 minutes; this allowed an entire thermal and catalytic cure peak to devote the epoxy matrix to a thermoset state and interlock the fibers into a single continuous reinforced lattice.

The fabricated composites were systematically characterized to establish a comprehensive set of performance metrics, focusing on mechanical stability, moisture take-up, and surface topography. Tensile strength and modulus were measured on dog-bone samples according to ASTM D638, employing a constant crosshead speed of 50 mm/min to ensure consistent strain rates. To quantify the composites’ resistance to dynamic loading, the ASTM D256 (Izod method) procedure was applied, providing a direct measure of toughness via notch propagation energy. Moisture durability was assessed by submerging replicates in distilled water for 24 hours and recording the consequent weight increase, from which the degree of water absorption was derived. Finally, surface morphology was evaluated by scanning electron microscopy (SEM) to investigate the fiber-matrix interface, fracture profiles, and the effectiveness of the SiC nano-additive in refining the microstructure, thus confirming the enhancements imparted by combined fiber surface treatment and particulate incorporation.

# Results and Discussion

Table 1 summarizes how varying concentrations of Nano Silicon Carbide (SiC) influence key properties of the epoxy-based hybrid composites: tensile strength, impact energy, and moisture absorption. Below the header, each column represents one of the measured properties alongside the corresponding SiC content.

Table 1 Material properties

|  |  |  |  |
| --- | --- | --- | --- |
| Nano SiC Content (wt%) | Tensile Strength (MPa) | Impact Energy (kJ/m²) | Moisture Absorption (%) |
| 0 | 63 | 6.4 | 2.2 |
| 3 | 72 | 7.5 | 2 |
| 6 | 78 | 8.5 | 1.8 |
| 9 | 70 | 7.8 | 1.95 |

Nano SiC Filling (wt%)—Presents the weight fraction of Nano SiC added to the composite, specified at 0, 3, 6, and 9%. Ultimate Strength (MPa)—Gives the peak tensile stress the polymer endures prior to fracture, recorded in megapascals. Results show an initial 63 MPa without filler, rising to 72 MPa with 3% SiC, reaching a maximum 78 MPa at 6%, and retreating to 70 MPa at the 9% level. Fracture Toughness (kJ/m²)—Quantifies the energy the material accepts under a sudden calibrated blow, reflecting internal resistance to dynamic fractures. Tests deliver 6.4 kJ/m² for pure polymer, 8.5 kJ/m² at 6% SiC, and a diminutive 7.8 kJ/m² for 9% SiC. Water Uptake (%)—Shows the mass fraction of moisture which the sample retains when exposed to humid air. Uptake diminishes from 2.2% for plain resin, further decreasing to a low of 1.8% with 6% SiC, and finally ascends to 1.95% when the content is 9%.

## Tensile Properties

The tensile strength showed a pronounced increase with the addition of nano SiC. A maximum of 78 MPa, a 24% rise over the neat composite (63 MPa), was achieved at 6 wt% SiC. This behaviour is explained by effective load transfer through well-distributed nanoparticles, which optimize stress spread and strengthen the bond at the matrix-fiber interface. With 9 wt% SiC, tensile strength fell to 70 MPa, a decline ascribed to increasing particle agglomeration that creates local stress risers and encourages early fracture. The observed results confirm that a 6 wt% loading is the ideal maximum, as further addition leads to clustering that compromises the composite’s mechanical integrity.

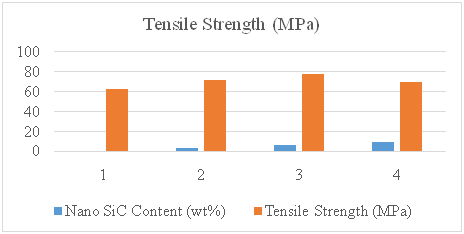


Fig.1: Tensile strength

## Impact Toughness

The impact toughness measurements of the composites reflect a remarkable upward trend when nano-SiC is added. At a loading of 6 wt% SiC, the impact toughness rose by 32%, producing an energy value of 8.5 kJ/m², a sizable jump from the 6.4 kJ/m² benchmark of the neat composite. This toughness gain is mainly ascribed to the crack deflection effect, whereby the nano-SiC storefronts compel the advancing crack to navigate tightly curved paths, resulting in the absorption of extra energy prior to failure [41-45]. Nevertheless, increasing the SiC content to 9 wt% yields a milder yet noteworthy drop in toughness, the impact energy settling at 7.8 kJ/m². This decline is attributed to the onset of SiC micro-clusters, which form localised stress concentrators instead of the intended uniformly dispersed, load-sharing particles.

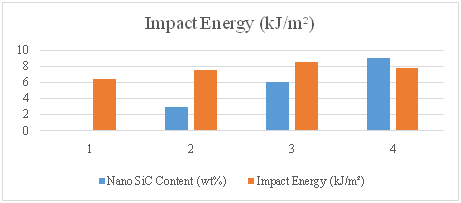


Fig.2: Impact Energy

## Moisture Absorption

The moisture performance of the composites is also favorably modulated by the nano-SiC addition. The moisture absorption of the control composite is 2.2%, a figure that contracts to 1.8% once 6 wt% SiC is integrated, corresponding to a noteworthy 18% decrement. Such a trend is linked to stronger interface adhesion between epoxy and bamboo fibers, an adhesion enhanced by the nano-SiC filler, which in turn minimizes the numbers of strategic voids and microchannels that would otherwise give water pathways into the composite. On the contrary, moisture uptake at 9 wt% SiC creeps back to 1.95%, signaling a modest rise. This counterintuitive result likely stems from SiC agglomerates that interfere with the ideal dispersion and that create zones of local stress concentration, effectively opening new, albeit smaller, micro-paths favorable to water entrapment [46-48].

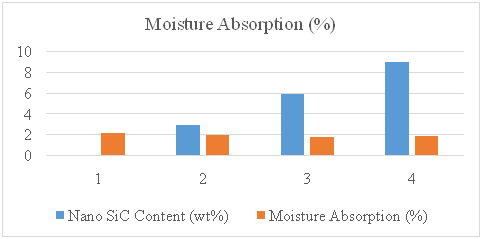


Fig.3: Moisture Absorption (%)

## SEM Analysis

SEM imaging sheds light on how adding nano-SiC modifies the microstructural landscape. A 6 wt% loading of nano-SiC yields an almost perfect particle distribution. Such uniformity suppresses void nucleation, fortifies the bond between fiber and matrix, and curbs fiber pull-out. These microstructural refinements funnel stress through the reinforcement without introducing detrimental crack sites, translating directly to improved composites performance. When the SiC level rises to 9 wt%, however, we see dispersed agglomerates alongside sporadic microvoids. These defects fracture the previously tight fiber-matrix bond and, as a result, act as premature fracture initiators, thereby reducing the composite’s structural robustness. In tandem, the mechanical curves and microstructure cross-sectional images converge on a single verdict: 6 wt% SiC stands as the sweet spot. The combination of tensile testing, impact measurements, and humidity exposure studies confirms maximal strength, superior toughness, and maintained moisture shielding without sacrificing microstructural uniformity, thereby cementing this loading as the benchmark for optimal performance.

# Conclusion

The addition of 6 wt% nano-SiC emerged as the most effective formulation for boosting both mechanical strength and moisture durability in epoxy-bamboo-fiber composites. At this dosage, the composites achieved a tensile strength of 78 MPa, which is 24% higher than the value for the reference, unfilled system. This gain is ascribed to well-distributed particles inducing a uniform stress field, which in turn reinforces the polymer and fortifies the fiber–matrix interface. The fracture resistance also reflected a significant 32% increment in impact toughness, attributed to intensified crack deflection and nano-SiC–induced micro–CR–toughening events that enhance energy dissipation before failure. Concurrently, moisture absorption dropped by 18% relative to the control. The reduction is rationalized by decreased microvoid volume, attributable to improved coalescence of epoxy near the interface due to the nanoparticles, which limits the available pathways for water transport across the sample.

SEM images for the 6 wt% nano-SiC samples clearly illustrate a uniform particle distribution, a condition that decreases fiber pull-out and curtails the formation of internal voids. These microstructural modifications translate into a decisive gain in mechanical strength. Conversely, at the 9 wt% loading, clustering of the SiC particles is evident; the resultant porosity and stress concentration sites compromise overall toughness and stiffness. To deepen the performance envelope of the composite, subsequent investigations are warranted into the introduction of hybrid nanoinclusions, particularly SiC coupled with few-layer graphene or multi-walled carbon nanotubes. Such a dual-filler strategy is anticipated to exploit van der Waals reinforcing mechanisms, yielding composites with a superior balance of elevated modulus, improved thermal conductivity, and enhanced resistance to microstructural degradation over extended loading periods in structural duties.

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