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Research Article

Effectiveness of Nanosilica on Enhancing the Mechanical and Microstructure Properties of Kenaf/Carbon Fiber-Reinforced Epoxy-Based Nanocomposites

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With an ultrasonic frequency of 15 kHz and an 850 W power capacity, the effects of nanosilica particle inclusion on the tensile, flexural, and impact properties of woven fiber-reinforced kenaf/carbon fiber/epoxy hybrid composites were explored experimentally. The nanoparticles were dispersed uniformly in the epoxy using an ultrasonic probe. Test samples were made according to ASTM requirements for three distinct weight compositions of nanosilica particles (1, 1.5, and 2 wt%). The composites were made utilizing the compression moulding process with the following parameters: (i) weight ratio of nanosilica, (ii) length of kenaf fibers, and (iii) number of carbon fiber layers to achieve the objectives above. According to unmodified samples, with a nanosilica concentration of 1.5 wt%, tensile strength improved by 31%, flexural strength increased by 42.36%, and impact strength increased by 22.65%. It was established that the interaction of micro silica particles with epoxy and fiber, which improved interfacial tension, had a substantial impact on mechanical and water retention capabilities. The 1.5 wt% nanosilica inclusion absorbs less moisture than the 1 and 2 wt% silica composites. A scanning electron microscope was used to examine the fractured surface of the tested nanocomposites.

1. Introduction

Polymeric materials have grown to achieve better qualities, such as inserting high-strength fibers into brittle matrixes. Compared to traditional industrial materials such as metal and aluminium, fiber-reinforced polymer composites have greater specific modulus, durability, fatigue life, ease of manufacture, and cheap cost [1]. As a result, such composites have sparked widespread attention in a range of high industrial applications, particularly in the automotive, aircraft, sports, and infrastructure industries [2]. Fiber-reinforced composite laminates are also used in vehicle and vehicle cab doors, plane and plane cab covers, helicopter airframe epidermis, fish traps, tennis rackets, sneakers, and golf shafts. The review summarised various worldwide scientific research aimed at better understanding the mechanical characteristics of natural cellulose fibers and composite materials [3]. Several papers and reviews promote research on using thermoplastic elastomer matrices in regenerated cellulose fiber-based materials. Natural cellulosic fiber-reinforced composites are a well-documented alternative to synthetic fibers as a reinforcement in polymer composite materials [4]. Natural fibers are attractive reinforcements for polymer matrix composites because of their unlimited availability, much higher specific strength than conventional fibers, lower density, and easy disposal. Cellulosic fiber-based composites have been effectively used for less weight and low-cost applications in current periods [5]. Bast fiber bundles from long kenaf (Hibiscus cannabinus L., Malvaceae) are commonly used to manufacture cords, carpets, rugs, newspapers, and other items. Tree fibers like jute, flax, and hemp have low tensile strength, making them ideal for purposes that need to be strong and light [6]. Despite the increased interest in such composites, fiber choice is still influenced by relative cost instead of substance quality. Kenaf could have structural qualities equivalent to fiberglass while being lighter, renewable, and affordable. In one investigation, injection moulded kenaf fiber and thermoplastic composites with 40% kenaf fiber, and pp had similar tensile properties to glass fiber-reinforced pp (8.3 GPa vs. 9 GPa, correspondingly) [7]. Because of the frame interpolation design of the fibrils, woven hybrid composites are resistant to fracture propagation and have a high strain-to-failure ratio in tensions, compression, and impacts [8]. Epoxy resin has been the most widely utilized for thermosetting polymer composites due to its high rigidity, high stiffness, and good corrosion. At the same time, glass, carbon, and Kevlar fibers are widely employed as key reinforcing elements in fiber-reinforced composites [9].

Hybrid composites are composites that contain more than two fibers in a single matrix. Hybridization can enhance the mechanical characteristics of organic fiber-reinforced polymeric materials by removing the flaws of separate composites [10]. Carbon fibers are composed of carbon molecules and lengthy, thin threads of substances with a size in the micrometres. The carbon atoms are linked together so that the crystalline surfaces are virtually parallel along the fiber's length [11]. Fiber is incredibly tougher than other fibers due to the parallel alignment of crystallites. Carbon fiber takes the lead in structural applications over other synthetic fibers because of its high fiber structure and physical and mechanical qualities in compressive and tensile modes. In current scientific and technological developments, carbon fiber is still regarded as one of the most important industrial materials [12]. Carbon fiber-based polymer composites were initially created in the 1960s as a commercial filler. They steadily extended their legs in many industries like the auto sector, civil infrastructure, advanced manufacturing, the aeronautical industry, aircraft, and so on [13]. Carbon fiber is presently the most attractive substance for the manufacture of sophisticated structural composite materials. Carbon fiber-reinforced polymeric composites have been employed for various construction purposes, including aircraft, wind-farm rotors, sporting goods, and transport, with low weight, specific stiffness, higher hardness, and remarkable fatigue life [14]. Fiberglass, ceramics, and beryllium are commercially accessible fibers employed for construction [15]. Under strain, the capacity to sustain loads is significantly greater than other building components (between 0 and 4%). As a result, carbon fiber is starting to replace these fibers, posing a serious threat to other synthetic fabrics [16]. Carbon fiber's organic origin makes it easier to make composites with biopolymers, resulting in high strength and stiffness, good resistance to corrosive, and lighter weight products at an affordable price. It is also used to make large-scale components with complicated designs [17].

Combining multiple types of micros or nano inside a similar polymer matrix is one technique to improve the mechanical performance of composite materials. These composites are known as nano-based composites, having one or more nanoscale dimensional particles. Polymeric materials altered with nanomaterials such as graphene, aluminium oxide, and nanosilica have attracted much attention for their mechanical and water retention properties [18]. Several studies have demonstrated that when nanocrystals are employed for reinforcing, the synthetic behavioural qualities increase more than the mechanical characteristics. Because of its remarkable electromagnetic, structural, and thermodynamic capabilities, nanosilicon oxide is another imperative element used for reinforcements [19], which has a solitary organism's width and a two-dimensional hexagonal design. It is widely employed in electrical and optical gadgets [20]. Due to its durability, it has become an excellent filler in epoxy restorative materials. The presence of an oxide position in nanosilica material that functions as a powerful adhesive throughout the matrices is the primary explanation. The technique of blending nanosilicon oxide nanopellets with the polymer matrices is known as ultrasonic irradiation.

As per the research findings, numerous researchers have been looking into the impact of various nanoscale particle concentrations on the mechanical characteristics of polymers. To the author's knowledge, no work has been identified in the available literature that reports the tensile, flexural, and impact characteristics of carbon- and kenaf-based hybrid composites incorporating silica nanoparticles. This research focuses on the mechanical and water retention capabilities of kenaf/carbon fiber-reinforced epoxy composites with varying weight concentrations of nanosilica particles (1, 1.5, and 2 wt%). Scanning electron microscopy (SEM) was used to examine the impact of nanosilica concentration on damage patterns in fabricated composites. Table 1 shows the mechanical properties of current reinforcements and matrix.

2. Investigational Resources

2.1. Materials. Kenaf and carbon fiber are used as foundation materials, nanosilica is used as a particle material, and epoxy is used as a matrix in manufacturing nanocomposite. GVR Fiber Industry in Madurai provided both reinforcements and matrix materials. The nanosilica particles were provided by Naga Chemicals Limited in Chennai, Tamil Nadu, India. The photographic picture of kenaf and carbon fiber mate is shown in Figure 1.

2.2. Fabrication of Composite Materials. The nanosilica and epoxy were mixed in the first phase utilizing a mechanical churned process for 15 minutes to blend matrix and filler. The ultrasonicator is then used to use ultrasonic vibrations to distribute the filler into the matrix. Several weight proportions of nanosilica filler loading were used to make a

Table 1: Mechanical properties of reinforcements and matrix.

Sl. no	Properties	Kenaf fiber	Carbon fiber	Epoxy resin
1	Cellulose (%)	66.4-67.25	—	—
2	Hemi cellulose (%)	9-9.43	—	—
3	Lignin (%)	2.3	—	—
4	Density (g/cm^3)	1.41	1.785	1.16
5	Tensile strength (MPa)	284-800	1717	8-19
6	Young's modulus (GPa)	63-78	127.7	0.58
7	Elongation (%)	2.5-3.1	1.5	1.6

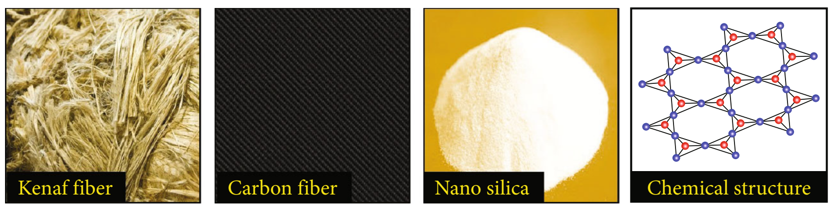


Figure 1: Photographic image of reinforcement and nanosilica and its chemical structure.

nanocomposite, such as 1, 1.5, and 2 wt%. The nano-sized silica and epoxy mixture was placed in a glass pipette, physically agitated, and kept in an elevated ultrasonic bath on pulse mode for 30 min.

The Taguchi L_9 design created nine hybrid composite plates using compression moulding with kenaf and carbon fibers. Hybrid fibers were mixed with nanosilica powder at 1, 1.5, and 2 wt% concentrations. They were treated with a 5% NaOH solution to provide natural fibers with hydrophobic properties. After four hours of treatment, the fibers were rinsed thoroughly to eliminate excess alkaline and dried for two days at room temperature. Finally, the fibers were heated for two hours in an oven before being sliced into three lengths and inserted into a $150 \times 150 \times 3$ mm mould with a blended nanoparticle mixture. The parameters and values employed in this study are listed in Table 2. The L_9 orthogonal array is shown in Table 3.

2.3. Testing. For tensile testing, the produced composite specimens were cut to ASTM D-638-03 replicas with dimensions of $150 \times 15 \times 3$ mm, ASTM D-790 (wide 10 mm, length 125 mm, and thickness 3 mm) for flexural testing, and ASTM D-256 (width 12.7 mm, length 64 mm, and thickness 3 mm) for impact testing. Figures 2(a) and 2(b) show the specimens of the tensile and impact. The following equations (1) and (2) are used to calculate the hybrid composites' tensile and flexural properties.

$$\text{Tensile Strength} = \frac{P}{b * t}, \tag{1}$$

where P is the tensile force in N, b is the specimen width in mm, and t is the thickness in mm.

$$\text{Flexural Strength} = \frac{3PL}{2bd^2}, \tag{2}$$

where P is the flexural force in N, b is the specimen width in mm, and d is the thickness in mm.

Table 2: Parameters and their levels for nanocomposite.

Sl. no	Parameters	Symbols	Levels		
			L1	L2	L3
1	Silicon powder (wt%)	A	1	1.5	2
2	Kenaf fiber length (mm)	B	10	15	20
3	Number of carbon fiber layers (no.)	C	1	2	3

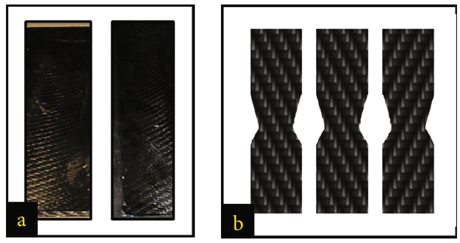
Table 3: Taguchi L_9 orthogonal array.

Trail no.	Nanosilicon powder (wt%) A	Kenaf fiber length (mm) B	Carbon fiber layers (no.) C
1	1	10	1
2	1	15	2
3	1	20	3
4	1.5	10	2
5	1.5	15	3
6	1.5	20	1
7	2	10	3
8	2	15	1
9	2	20	2

2.4. Fractographic Study. SEM was used to investigate cracked composite materials at a microscopic level. Before SEM clarity, the samples were laved, dried, and chemically covered with 10 nm gold to improve the electrical properties of the composite materials.

3. Result and Discussion

3.1. Effect of Kenaf Fiber Length. The influence of fiber length on the mechanical properties (tensile, flexural, and impact) of kenaf/carbon fiber-based nanocomposites is shown in Figure 3. Mechanical parameters improved with fiber length, with a maximum tensile strength of 426.31 MPa, flexural



(a) (b)

Figure 2: Photographic image of (a) tensile specimen and (b) impact specimen.

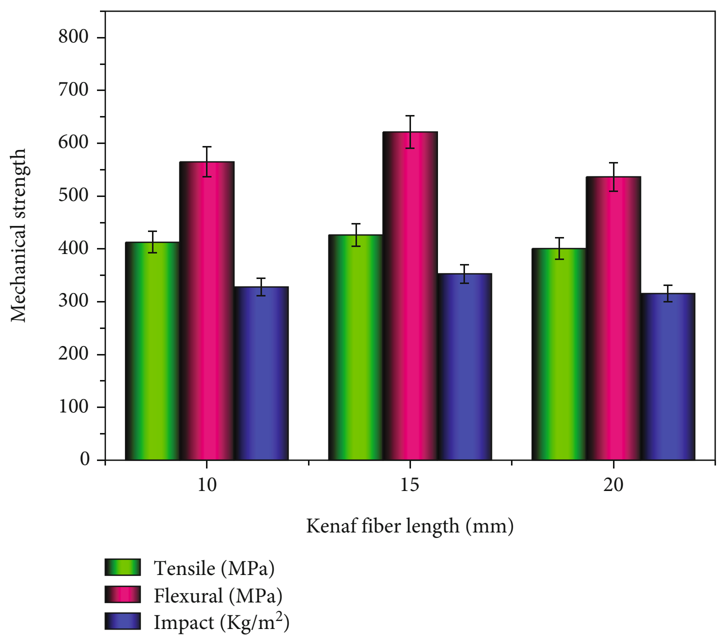


Figure 3: Mechanical properties of nanocomposites based on kenaf fiber length: (a) tensile strength; (b) flexural strength; (c) impact strength.

strength of 621.28 MPa, and impact strength of 352.87 kg/m^2 at 15 mm. The chemical process at the on through is likely too powerful to carry the load, increasing the composites' mechanical characteristics [21].

The mechanical strength of the fibers decreases as the thread length rises. This might be due to a lack of bonding between the resin and the fiber during composite manufacturing, which generated a tiny gap. Arib et al. [1] have also noticed it. Impact failure in composites is caused by matrix fracture, matrix, and fiber debon [21] ding, and fiber pull out. Even though fiber pull-out is a common failure mode in fiber-reinforced composites, delamination between the fiber and the matrix occurs anytime the applied load is exceeded. As a result, the interfacial bond strength of the composite was weakened. A fiber strength fracture happens when the stress levels surpass the fiber strength. The fractured threads may be pulled out of the resin, causing energy loss. The presence of voids in the composites and the fact that the fibers are not perfectly aligned may have contributed to the poor testing results. SEM indicates it.

3.2. Effect of Silicon Powder Addition. Figure 4 indicates the effectiveness of nanosilica filler additions in terms of tensile, flexural, and impact properties. The weight of 1.5% silica additions outperformed 1 and 2% in terms of mechanical strength (426.31 MPa tensile strength, 621.28 MPa flexural strength, and 352.87 kg/m^2 impact strength). The increased mechanical characteristics of silica in resin at a concentration of 1.5 wt% may be due to better stress distribution and transmission [22]. Increasing the quantity and size of holes in the polymer matrix, more filled silica affected the decohesion bonding between the fiber and the matrix.

Consequently, the epoxy, kenaf, carbon, and silica formulations produce good adhesive bonding among surfaces contracted at a concentration of 1.5 wt% [23]. Adding more than the specified weight % silica, on the other hand, resulted in a negative result, indicating a loss of mechanical strength. Furthermore, it has been demonstrated to have low fiber and matrix border adherence, resulting in aggregation due to weak adhesion and poorer composite strength properties. SEM images indicate the above findings. Figures 5(a)–5(c) demonstrate the percentage contributions

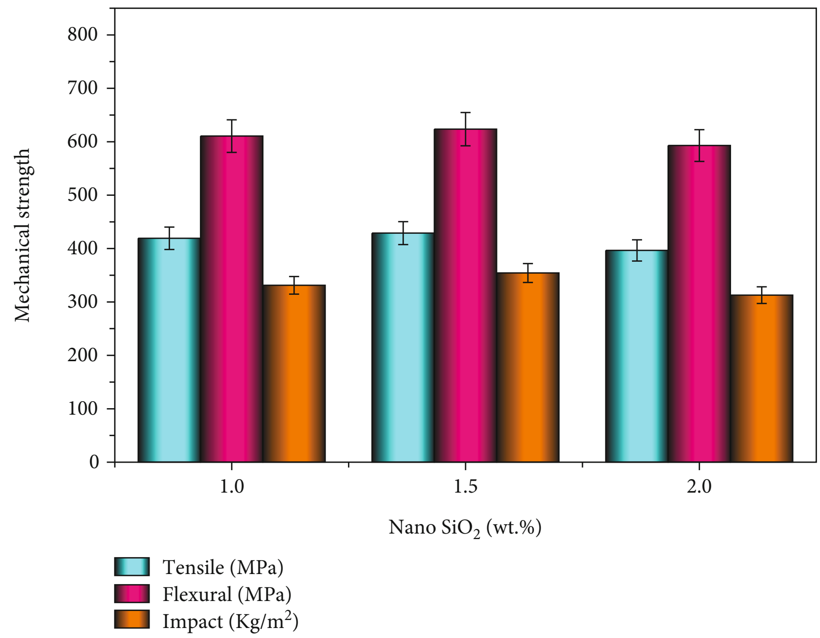


FIGURE 4: Mechanical properties of nanocomposites based on the weight ratio of nanosilica.

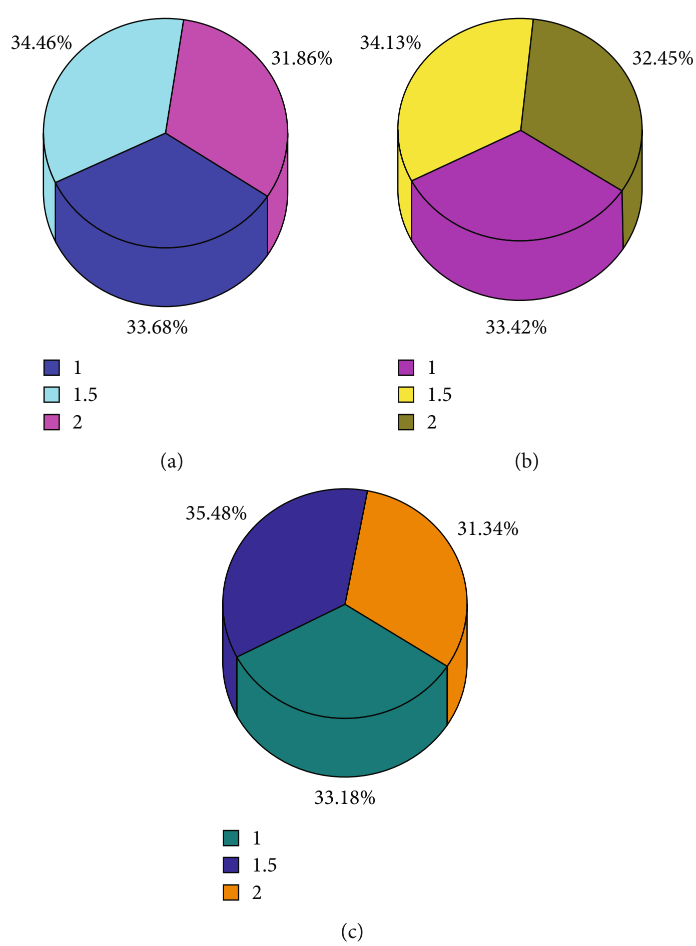


FIGURE 5: Nanosilica contributions of mechanical properties: (a) tensile; (b) flexural; (c) impact properties.

of nanosilica to the mechanical properties. The maximum strength was achieved when 1.5 wt% silica nanoparticles were loaded into the composite. This discovery demonstrated that adding nanoparticles to composites enhanced composite properties by increasing surface area, enhancing energy retention capacities, and reducing space inside the hybrid composite. This indicates that adding 1.5% filler to the SiO_2 filler improves the epoxy's aptitude to spread and dispense tension to the required amount. Furthermore, the homogenous scattering of SiO_2 particles in the matrix, which results in improved fillers, matrix interactions, and fiber contact area, most likely created this situation. As a result, stress transfer became easier, and the specimen could resist more load, resulting in composite samples with higher strength.

3.3. Effect of Carbon Fiber Layers. Figure 6 exhibits the effectiveness of tensile, flexural, and impact properties of woven carbon layers. The three layers showed higher mechanical strength when compared to single- and double-layer carbon fiber. Because the principal load-carrying component of silica and kenaf-based hybrid epoxy composites is woven carbon fiber. The quantity of carbon % in the nanocomposite grows as the number of carbon fiber layers increases. The fiber-matrix contact area was improved. As a result, breaking the link between the interwoven bundles of fibers inside the composites requires greater energy [24]. A single-layer carbon fiber epoxy composite can withstand a minimal load. As the weight proportion of carbon fiber in composites increases, the capacity to absorb additional load improves. As the quantity of carbon fiber inside the laminated hybrid composite rises, the strain leads to failure, and the flexibility to deform increases [25]. The poor performance in single-layer composite construction is attributed to insufficient load transfer due to the unequal distribution of fibers across the matrix. As a result, a matrix-rich area emerged in the composite, with poor fiber-to-fiber coupling [26]. The fiber reinforcement was easily removed from the matrix when loaded in this arrangement. It reveals that the carbon composite's single-layer reinforcing effect is insufficient to bear the mechanical load [27]. The mechanical characteristics of the composite improve as the fiber content is increased from one to three layers. This is largely due to the creation of strong connections between the fibers and the matrix, which occurs due to the fiber's capacity to fill up holes in the composite by admitting more short filaments and ensuring proper load distribution [28]. Figure 7 shows the carbon fiber contributions of mechanical properties such as tensile, flexural, and impact strength.

3.4. Microstructural Analysis. A Zeiss SUPRA 55-VP scanning electron microscope (SEM) was used to perform microscopic analyses of broken composite specimens at Sathyabama University, Chennai. To improve the composites' electrical conductivity, the examples were washed, dried, and surface covered by 10 nm of gold past to the SEM clarification. The micrographs were taken at 10, 20, 100, and 200 μm magnification [29]. Figures 8(a)–8(d) illustrate the fractured surfaces of the kenaf/carbon fiber-reinforced nanocomposite following flexural, tensile, and impact tests [30]. The consistent blending of nanosilica on the epoxy matrix is shown in Figure 8(a). Figure 8(b) shows an SEM image of the cross-sections of the kenaf fiber-reinforced epoxy composite after mechanical (tensile) failure [31]. Due to decreased interfacial adhesion, the fibers are removed from the polymer interface, as seen in Figure 8(b). The fiber's exterior is rough, indicating that the fibers and epoxy frameworks have little contact [32].

Figure 8(b) shows a kenaf fiber sliding from the matrix (for a 10 mm fiber length). Increasing the fiber length to 15 mm may also help compatibility [33]. Surface breakage is reduced when fiber length increases from 10 to 20 mm (Figure 8(c)). Consequently, the epoxy, kenaf, and carbon fiber formulations produce good adhesion binding among surface adhesions at a concentration of 1.5% nanosilica. Adding 2 weight % nanosilica, on the other hand, resulted in a negative result, suggesting a drop in mechanical strength [34]. Furthermore, larger loadings of 2 wt% have been observed to have poor boundary adherence of fiber and matrix, resulting in aggregation due to poor adhesion and worse composite strength attributes in kenaf/carbon and epoxy. Figure 8(d) of the SEM picture demonstrates this [35].

4. Water Retention Characteristics

Figure 9 illustrates the proportion of weight growth for kenaf, kenaf/carbon crossbred specimens, and kenaf/carbon/nanosilica hybridized specimens submerged in deionized water at room temperature as a consequence of the square root of time [36]. For chopped kenaf and epoxy-based specimens submerged at room temperature for 640 hours, the greatest percentage of weight growth is around 17%. For carbon fiber hybridized specimens (kenaf/carbon) submerged at room temperature for 640 hours, the greatest percentage of weight growth is around 8% [37]. Finally, for nanosilica hybridized specimens (kenaf/carbon/nanosilica) submerged at room temperature for 640 hours, the greatest percentage of weight growth is around 5%. The result of the carbon fiber and nanosilica hybridization shows a significant decrease [38]. Although carbon fibers are impervious to water retention, kenaf fibers and epoxy resin are both vulnerable. Water absorbs along with the fiber-resin interaction and flows through all the nanocomposites, causing hydrolyzing destruction of any covalent bond between fiber and resin and polymer expansion [39]. In light of this, it can be concluded that, compared to the pure kenaf-based samples, the number of contacts between the kenaf/carbon fibers and the resin is substantially enhanced. Moisture has less resistance in the kenaf sample and may flow in more directions, increasing hygroscopic as seen in Figure 9. The mechanical and water-absorbing capabilities of jute/glass fiber-reinforced epoxy composite materials were investigated, and the results showed that hybrid composites improved water retention and mechanical qualities [40]. The maximum strength was achieved when 1.5 wt% silica nanoparticles were loaded into the composite. This discovery demonstrated that adding nanoparticles to composites

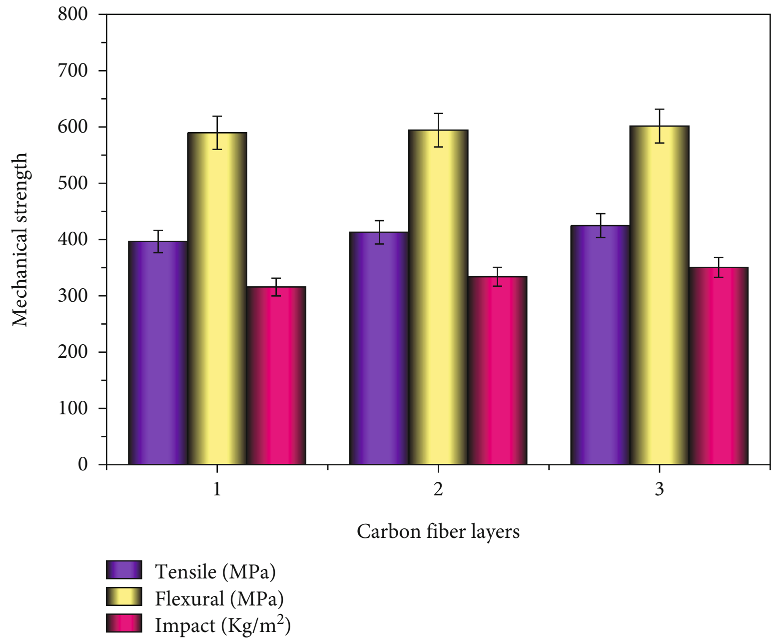


FIGURE 6: Mechanical properties of nanocomposites based on number of layers of carbon fiber.

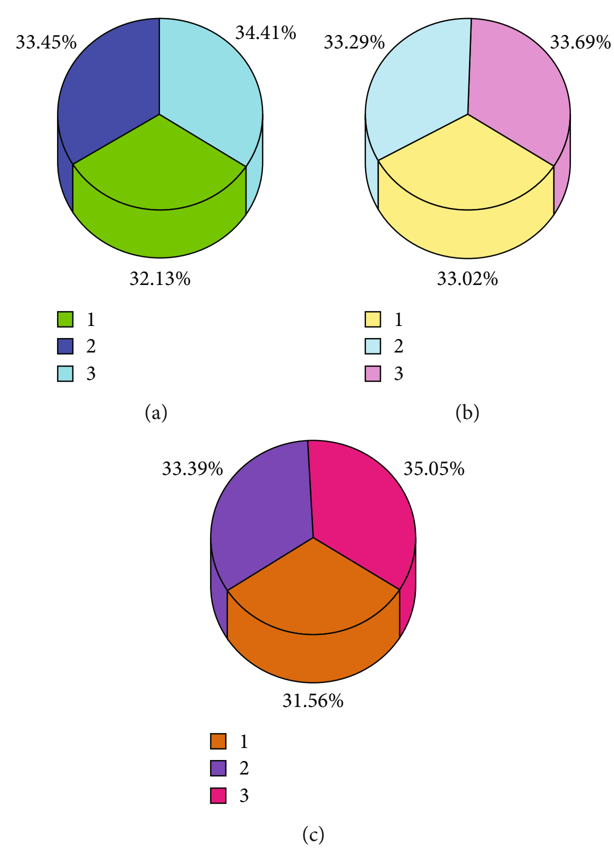


FIGURE 7: Carbon fiber contributions of mechanical properties: (a) tensile; (b) flexural; (c) impact properties.

enhanced composite properties by increasing surface area, enhancing energy retention capacities, and reducing space inside the hybrid composite. This indicates that adding 1.5% filler to the SiO_2 filler improves the epoxy's aptitude to spread and dispense tension to the required amount. Furthermore, the homogenous scattering of SiO_2 particles in the matrix, which results in improved fillers, matrix interactions, and fiber contact area, most likely created this situation. As a

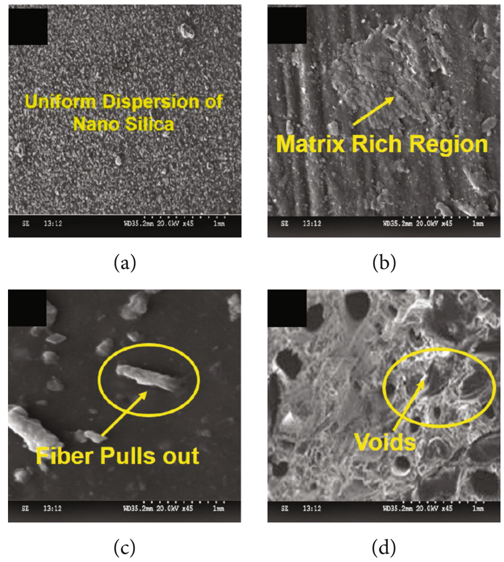


FIGURE 8: Microstructural analysis of kenaf/carbon/nanosilica-based nanocomposites.

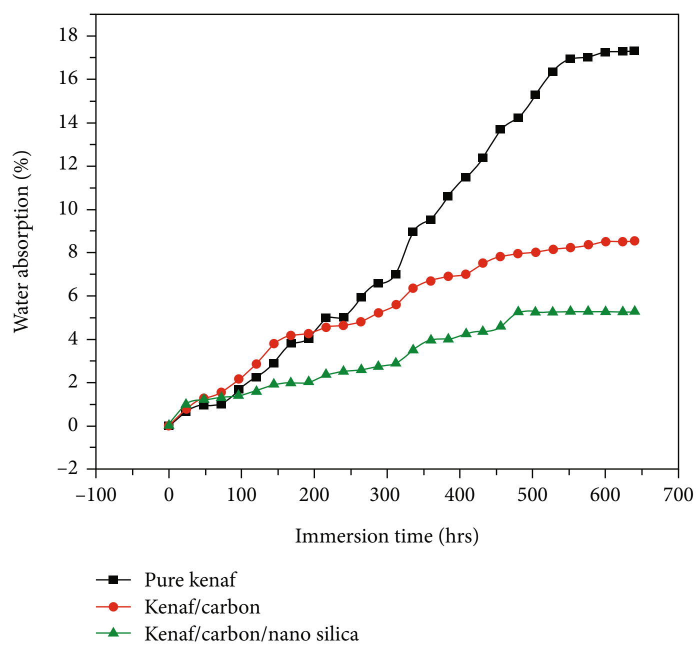


FIGURE 9: Water retention behaviour of kenaf/carbon/nanosilica/epoxy-based hybrid composites.

result, stress transfer became easier, and the specimen could resist more load, resulting in composite samples with higher strength.

The results shown in Figure 9 demonstrate that combining carbon and nanoparticles substantially lowers the quantity of water retention. It is also worth noting that the kenaf/carbon/nanosilica sample absorbed moisture at a lower rate than kenaf alone. The carbon fiber and nanosilica were combined so that the water retention in these hybrid composites was reduced. The periphery was strengthened with carbon fiber and nanofillers, while the centre was reinforced with kenaf fiber, which appears to provide the best waterproofing.

5. Conclusion

The kenaf/carbon and nanosilica-based epoxy natural nanocomposites were successfully fabricated through the compression moulding method, and the mechanical properties like flexural, tensile, and impact properties were found. The following conclusion was reached:

(i) Compared to 10 mm and 20 mm, the 15 mm fiber length shows the highest mechanical properties (426.31 MPa of tensile, 621.28 MPa of flexural, and 358.87 kg/m^2 of impact). Because 15 mm of kenaf fiber is distributed evenly throughout the epoxy matrix, it reduces the formation of voids in the composite materials

(ii) The mechanical properties of kenaf/carbon and nanosilica-based epoxy composites were increased when the number of layers of carbon fiber was increased. It shows the highest tensile strength of 424.73 MPa, 601.58 MPa of flexural, and 350.49 kg/m^2 of impact strength

(iii) Compared to 1 wt% and 2 wt%, the 1.5 wt% of nanosilica revealed improved mechanical strength. This is because the effects of voids are balanced by the incidence of controlled filler additions (428.96 MPa of tensile, 623.54 MPa of flexural, and 354.12 kg/m^2 of impact)

(iv) According to unmodified samples, with a nanosilica concentration of 1.5 wt%, tensile strength improved by 31%, flexural strength increased by 42.36%, and impact strength increased by 22.65%

(v) Compared to pure kenaf (17%), kenaf/carbon combinations (8%) and kenaf/carbon/nanosilica combinations (5%) absorbed minimum moisture. The morphological analysis of kenaf/carbon/nanosilica-based composites reveals that poor adhesion is the main reason for the lower mechanical properties

Data Availability

The data used to support the findings of this study are included within the article. Should further data or information be required, these are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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