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Research article

Impact of silicon oxide nanopowder on the mechanical and electrical properties of carbon fiber/polyester composite materials

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Abstract: The porously branched P-type nano silicon oxide (SiO_2) utilized in this study, which has not been explored before in fiber composites, creates a balance between mechanical reinforcing and electrical insulating. Here, the carbon fiber weight fraction was varied from 20% to 60% with the addition of P-type SiO_2 (15–20 nm, 0.1–0.3 wt.%). The porous morphology of the fibers and their branched structure result in high adhesion to the polyester matrix. A vacuum cast was used to minimize air bubbles in the composite during the manufacturing phase. Tensile characteristics (ASTM D3039) and electrical conductivity of the composites were defined, and the characterization of the composite microstructure was performed. The addition of 0.3% nano-SiO_2 improved tensile strength by 87.4% at a carbon fiber weight fraction of 60%, and ductility was reduced. Specific resistance was reduced by 39% at a carbon fiber weight fraction of 20% with 0.3% SiO_2. Scanning electron microscopy (SEM) analysis revealed that with 0.1% SiO_2, the homogenization of the microstructures was enhanced, improving strength. Due to its porous structure and enhanced adhesion compared with conventional and hybrid silicon oxide systems, P-type SiO_2 demonstrates potential for industrial applications in aviation, vehicles, or biomedical materials.

Keywords: nano silicon oxide; carbon fiber; polyester; tensile strength; electrical conductivity

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1. Introduction

1.1. Research background

A composite is a multi-phase material in which two or more materials are mixed but not blended, resulting in a combined material with better functional and mechanical properties than its constituents [1]. From these materials, carbon fiber–reinforced plastic (CFRP) is promising due to its superior mechanical properties, such as a high strength/weight ratio, being used in advanced applications like aircraft, automobiles, and biomedical materials [2–4]. There has been a growing interest in the exploitation of natural fibers as reinforcement in polymer composite systems due to the current high demand for sustainability [5,6]. The properties of polymer composites have already been improved in several studies by using nanoparticles and modifying the fiber surface treatment. For instance, the effect of carbon nanotube (CNT) incorporation on the physical and mechanical properties of glass fiber polyester composites has been reported [7]. Furthermore, the mechanical properties of polyester/carbon fiber composites can also be improved through the addition of multi-walled carbon nanotubes employed for shipbuilding [8,9]. Other works have focused on the effects of environmental factors and stimulations, e.g., salt concentration, on the lifetime of these materials [10].

1.2. Research status

In the context of reinforcement, researchers have focused on the effect of nano-SiO_2 powder addition on the protective properties of polyester/carbon fiber composites [11]. In the case of epoxy composites, analogical studies showed that the addition of nano-SiO_2 improves the compatibility and dispersion of particles in the microstructure and positively influences mechanical properties [12,13]. Other works aimed to increase the composites' performance mainly by controlling the interfaces between fibers and the matrix. These attempts included chemical modification of the surface of carbon fibers [14], coating layers such as polyetheramine-polydopamine [15], or the application of infrared radiation to the composite during preparation [16]. Surface treatment through a two-step regimen using epichlorohydrin has a significant impact on enhancing the interfacial bonding and mechanical properties of carbon fiber-reinforced epoxy composites [17,18]. Additionally, the properties of polymer-based composites can be further improved using nanoparticle fillers and metal powders [19,20]. Furthermore, constructing three-dimensional (3D) aligned hybrid structures on fiber surfaces leads to a substantial improvement in thermal conductivity [21]. In the field of natural fiber composites, zinc oxide (ZnO) filler is utilized to maximize the compressive and impact strengths of jute-reinforced epoxy [22]. Regarding thermal stability, it is established that the thermal resistance of nanocomposites can be effectively enhanced through the incorporation of chitosan-graphene oxide (CGO), which improves their degradation temperature [23]. While polyurethane nanocomposites exhibit superior thermal and shape memory characteristics [24].

Four polymer composites (unfilled, eggshell-filled noncarbonized, carbonized, and hybrid) were formulated at 10 wt.% using manual layering. The results showed mechanical improvement in filled composites compared with the control unfilled composite, with the carbonized eggshell composite demonstrating the highest increase in tensile and flexural strength (43.9%), followed by the hybrid and non-carbonized composites. Scanning electron microscopy (SEM) analysis revealed that the reinforcement mechanism is associated with the filler's ability to deflect and inhibit crack propagation [25].

In another work, graphene oxide (GO) was directed onto fiber surfaces to improve the damping capability of CFRP composites. It was also verified that multilayer coatings represent an efficient approach to increasing the loss factor through slip between multilayers, where enhanced mutual friction effectively dissipates mechanical energy [26]. Studies have been conducted to increase the applicability of recycled carbon fiber (rCF) in needle-punched nonwoven composite materials (NW-CFRTP). Fine cross-section observations and mechanical testing revealed that this method achieves favorable fiber distribution, with a less than 30% volume ratio range, showing efficient fiber utilization, preserved fiber orientation, and minimal turbulent flow. The results, along with a multi-scale modeling scheme, provide a foundation for engineering applications of these materials in structural sectors such as automotive manufacturing [27]. Inspired by hierarchical reinforcement strategies observed in nature, a hierarchical glass fiber composite system was prepared using carbon nanotubes sprayed onto carbon fiber filaments. This hierarchical interpenetration resulted in substantial enhancements of 211% and 174% for $G_{Ic,ini}$ and $G_{Ic,prop}$, respectively, representing significant increases in interlayer fracture toughness through multi-scale conduction mechanisms and interlayer cross-linking [28].

1.3. Methods and objectives

This study aims to investigate the mechanical and electrical properties of fabricated P-type SiO_2 nanoparticle-reinforced carbon fiber/polyester composites produced using a vacuum casting method. This technique removes entrapped air bubbles from the samples, which are then cut using a computer numerical control (CNC) milling machine. This procedure involves preparing specimens with varying compositions. Three carbon fiber weight fractions (20, 40, and 60 wt.%) are examined alongside three nanoparticle concentrations (0.1, 0.2, and 0.3 wt.%) in the filled composites. To evaluate the influence of these additives, several characterization and testing methods were performed, including tensile testing, electrical conductivity measurements, and SEM to assess microstructure and nanoparticle distribution homogeneity in the composites. This study is significant, as it aims to improve the performance of advanced composite materials with broad industrial applications, such as in the aerospace and automotive industries, by investigating the effectiveness of nano-enhancement and its impact on functional and mechanical properties.

2. Methodology

The mechanical properties of composite materials depend on the weight fractions of two or more of the materials that make up the composite material. Mathematical equations provide accurate data based on the weight or volume and density of each material. The weight of polyester represents the difference between the weight of the composite material minus the weight of the fibers, as expressed in Eq 1 [29]:

$$w_{mat.} = w_{comp.} - w_{fiber} \tag{1}$$

where $w_{mat.}$ is the weight of the polymer matrix material (polyester) in the composite sample, measured in g; $w_{comp.}$ is the total weight of the final composite sample, measured in g; and w_{fiber} is the weight of the reinforcing fibers (carbon fibers) used in the composite sample, measured in g. For a three-component composite, the weight of polyester is determined using Eq 2:

$$w_{mat.} = w_{comp.} - w_{fiber} - w_{nano} \tag{2}$$

where w_{nano} is the weight of the added SiO_2, measured in g. The volume of the fibers in the composite is determined according to Eq 3:

$$V_{fiber} = \frac{w_{fiber}}{\rho_{fiber}} \tag{3}$$

where ρ_{fiber} is the density of reinforcing fibers, measured in g/cm^3. The volume percentage of carbon fiber in polyester for the composite material is calculated as shown in Eq 4:

$$\frac{V_{fiber}}{W_{mat.}} = \left(\frac{W_f}{W_{mat.}}\right) \times \left(\frac{\rho_f}{W_{mat.}}\right) \tag{4}$$

where V_{fiber} is the volume of carbon fibers in the composite material (cm^3). The density of the composite material is calculated by Eq 5 :

$$\rho_{comp.} = \rho_{fiber}V_{fiber} + \rho_{mat.}V_{mat.} + \rho_{nano}V_{na} \tag{5}$$

where $\rho_{comp.}$ is the density of the composite material (g/cm^3), $\rho_{mat.}$ is the density of the matrix material (polyester) (g/cm^3), and ρ_{nano} is the density of the nanoparticles (SiO_2) (g/cm^3).

3. Materials and methods

3.1. Materials

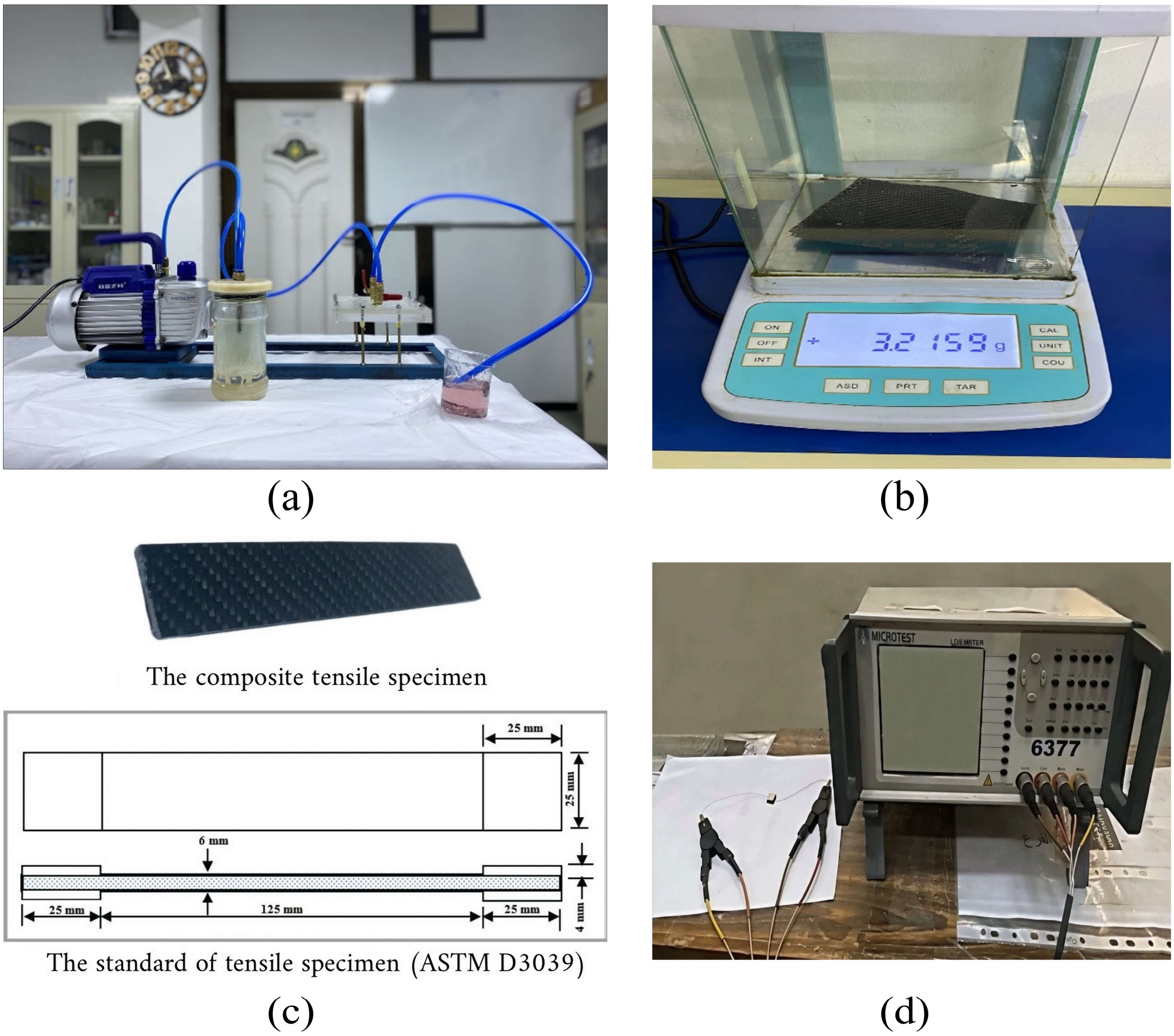
This study employed a composite material made of polyester reinforced with carbon fibers at different weight fractions (20, 40, and 60 wt.%), strengthened with varying percentages of SiO_2 (P-type) nanoparticles (0.1%, 0.2%, and 0.3%). These SiO_2 nanoparticles, ranging in size from 15 to 20 nm, possess high porosity (2–6 nm), resulting in a large surface area, and a branched structure that contributes to good adhesion with the other components of the composite. These nanoparticles exhibit high ultraviolet (UV) reflectivity, reaching up to 85%, as shown in Table 1. The study adopted low weight percentages of SiO_2 particles to prevent agglomeration and avoid producing brittle material, which is undesirable for many industrial applications.

Table 1. SiO_2 properties.

Characteristic	Value
Purity	+99.5%
Average particle size (APS)	15–20 nm porous particles
Color	White
Porous size	2–6 nm
Appearance	Solid
Melting temperature	1610 °C
Initial boiling temperature	2230 °C
Flammability	Solid, gas
Relative density	2.4 g/cm^3

3.2. Methods

An acrylic mold integrated with a vacuum system was designed and fabricated to conduct the casting process under airless conditions, thus preventing air bubble formation in the composite material and ensuring high-quality samples, as shown in Figure 1a. The weights of the composite material components were measured using a high-precision scale, as shown in Figure 1b. To achieve optimal homogeneity of SiO_2 mixed with the polyester matrix, mixing was performed for 5–15 min using alternating cycles of 5–10 s of mixing followed by 2–5 s rest periods. A power supply of 100 W was used to prevent overheating. Ultrasonic mixing was carried out using a UP200Ht device. A series of tensile samples was prepared according to the ASTM D3039 standard [30], as illustrated in Figure 1c, using various carbon fiber weight fractions and different SiO_2 weight ratios. Tensile testing was performed on five samples of each type at a test speed of 13.3 mm/s (approximately 800 mm/min) at room temperature. To prepare the conductivity samples, composite samples were cut into 1 × 1 cm pieces with a thickness of 4 mm. The samples were coated with silver paste. Copper wires were then attached to the samples using a small amount of solder at the wire ends, which were connected to probes linked to a resistance measuring device, as shown in Figure 1d.



(a)

(b)

The composite tensile specimen

The standard of tensile specimen (ASTM D3039)

(c)

(d)

Figure 1. (a) Vacuum casting mold of composite samples; (b) high-precision weighing scale; (c) tensile test specimens; and (d) LCR meter device from Microtest.

4. Results and discussion

The experimental results of the tensile tests conducted on composite materials, incorporating various weight fractions of carbon fibers enhanced with different amounts of SiO_2, are discussed. The discussion is divided into three parts: the first part explains the effect of varying the weight fraction of carbon fibers; the second explores the impact of different weight ratios of SiO_2 nanopowder; and the third focuses on the microstructure of the samples as observed by SEM. The findings analyze the influence of SiO_2 addition at various weight ratios, as well as the effect of carbon fiber weight fraction on mechanical and electrical properties.

4.1. Influence of the weight fraction

Figure 2 illustrates the stress–strain relationship, which appears linear, indicating brittle behavior of the material. Compared with polyester alone, increasing the fiber weight ratio enhances the tensile strength of the carbon fiber/polyester composite. For composites reinforced with 0.1 wt.% SiO_2, experimental results reveal that at a carbon fiber weight fraction of 20%, the ultimate tensile stress increased by 34.3%. At a weight fraction of 40%, there was a 73.9% increase, while at a weight fraction of 60%, the tensile stress rose by 84.4%.

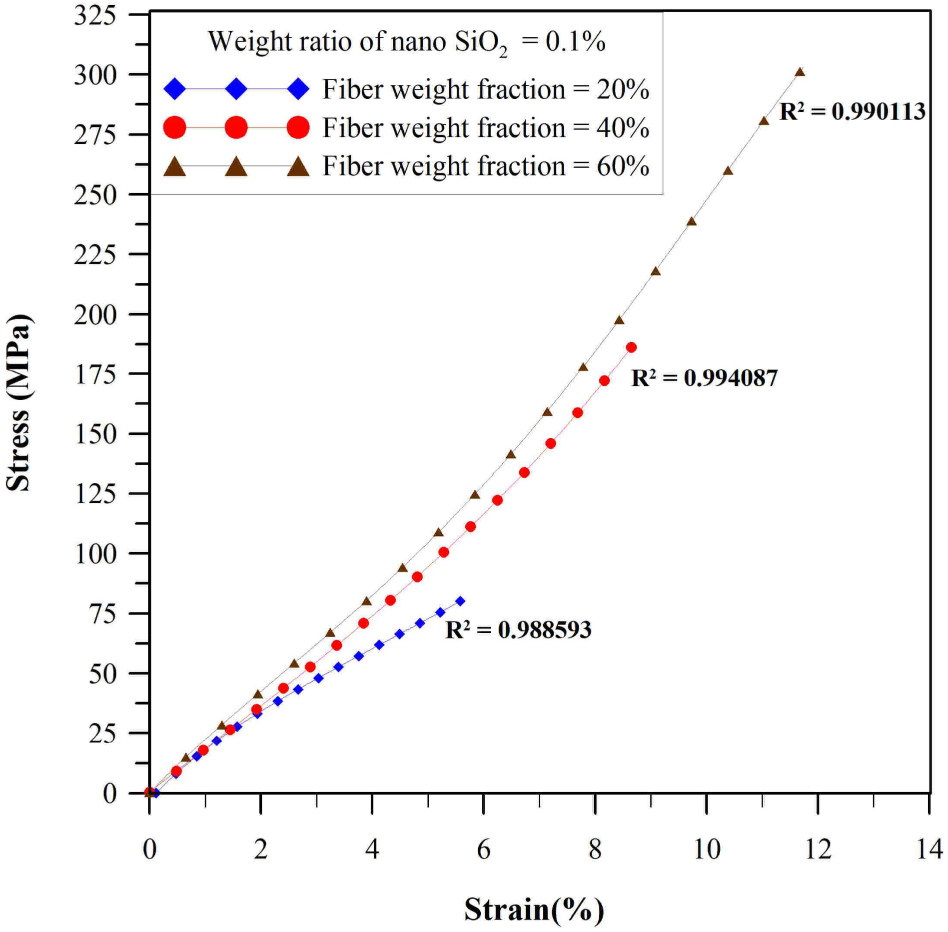


Figure 2. Tensile strength of carbon/polyester composite fibers at carbon fiber weight fractions of 20%, 40%, and 60% with 0.1% nano-SiO_2 P-type.

The tensile strength of a carbon fiber/polyester composite sample at various weight fractions (20%, 40%, and 60%), enhanced by adding 0.2% SiO_2, is illustrated in Figure 3. Experimental results show that the tensile strength of the composite material improved with the increase in the weight fraction of carbon fiber. A 20% weight fraction exhibited the lowest tensile strength but the highest ductility. While samples with 60% weight fraction achieved maximum tensile strength, elongation was reduced. Adding SiO_2 at percentages of 0.1%, 0.2%, and 0.3% led to an enhancement of the material's durability and tensile strength. This improvement is a result of the nanoparticles' ability to fill microscopic voids within the composite structure, resulting in a more uniform distribution of mechanical stresses and hindering crack propagation, thus enhancing the material's mechanical performance. Experimental results at a carbon fiber weight fraction of 20% show that adding 0.1% SiO_2 increases tensile strength by 36.1%. At a weight fraction of 40%, the increase in tensile strength was 75.9%, while at a weight fraction of 60%, the tensile strength increased by 82.4%. The coefficient of determination (R^2) serves as a statistical measure to determine the degree of conformity between the model and experimental data. A value of 1 represents the highest degree of conformity and is calculated using the ordinary least squares (OLS) method.

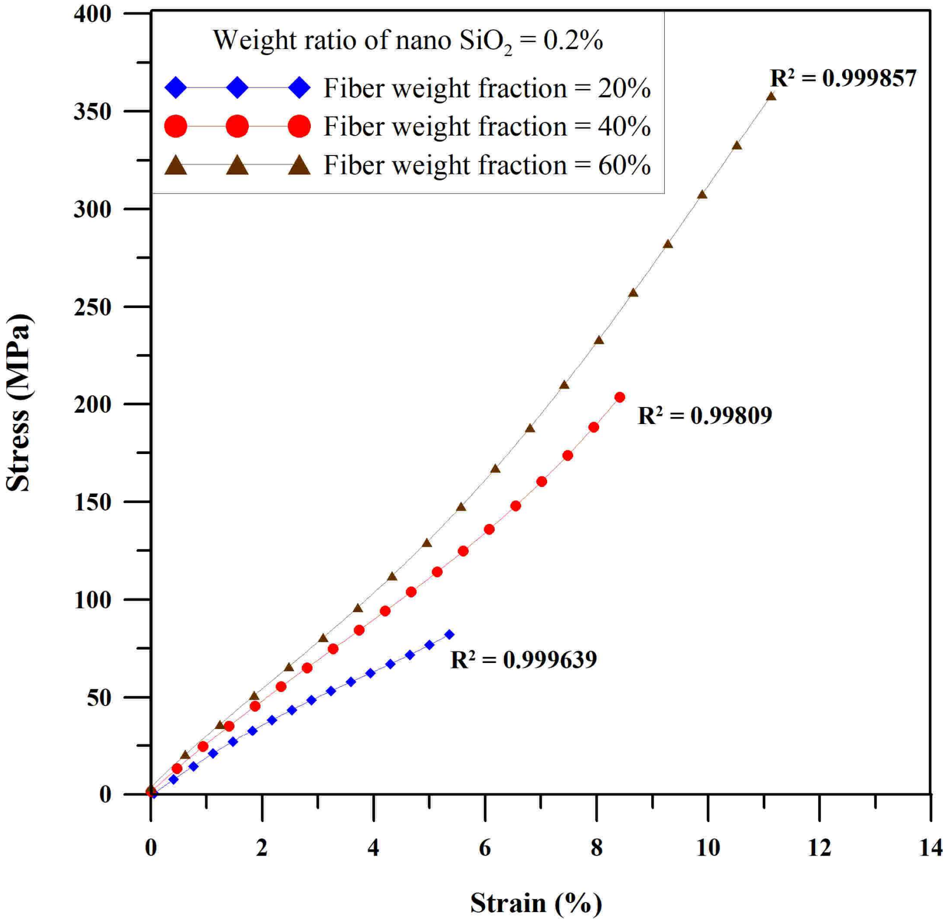


Figure 3. Tensile strength of carbon/polyester composite fibers at carbon fiber weight fractions of 20%, 40%, and 60% with 0.2% nano-SiO_2 P-type.

Figure 4 shows the experimental results for tensile stress of composite fibers with different carbon weight fractions (20%, 40%, and 60%) with 0.3% SiO_2. The results show that tensile stress increases with increasing SiO_2 particle weight percentage. Increasing the carbon fiber weight fraction also has an effect, but both lead to a decrease in elongation, indicating increased material brittleness. Nanoparticles play a significant role in filling the interfacial spaces in the microstructure, thus enhancing the composite material's strength. It was observed that the tensile strength at a SiO_2 weight percentage of 0.3% increased by 40.6%, 79.3%, and 87.4% as a result of increasing the carbon fiber weight fraction by 20%, 40%, and 60%, respectively.

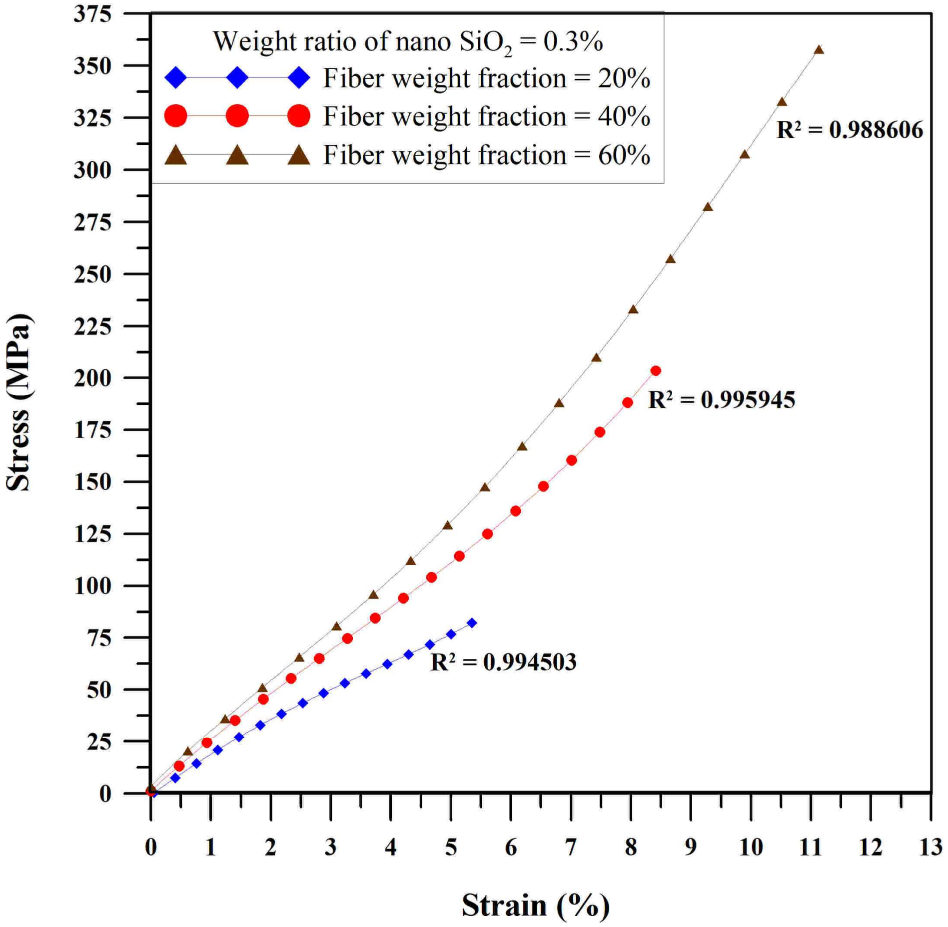


Figure 4. Tensile strength of carbon/polyester composite fibers at carbon fiber weight fractions of 20%, 40%, and 60% with 0.3% nano-SiO_2 P-type.

4.2. Effect of the weight of SiO_2

The addition of SiO_2 particles contributed to enhancing the durability of the composite material by reducing the interfacial spaces in the microstructure. The improvement achieved by adding nanoparticles depends primarily on the properties of these particles, such as their size, shape, distribution, surface area, and their effect on performance [31]. It has been shown that adding SiO_2 particles to epoxy results in an improvement in mechanical properties [32]. Figure 5 shows a comparison of experimental results at a carbon fiber weight fraction of 20% with the addition of SiO_2 particles at weight percentages of 0.1%, 0.2%, and 0.3%, leading to increases in tensile strength of 23.3%, 36.7%, and 40.6%, respectively. The results also show a decrease in the ductility of the composite material with an increase in the proportion of SiO_2 particles, making the material more brittle.

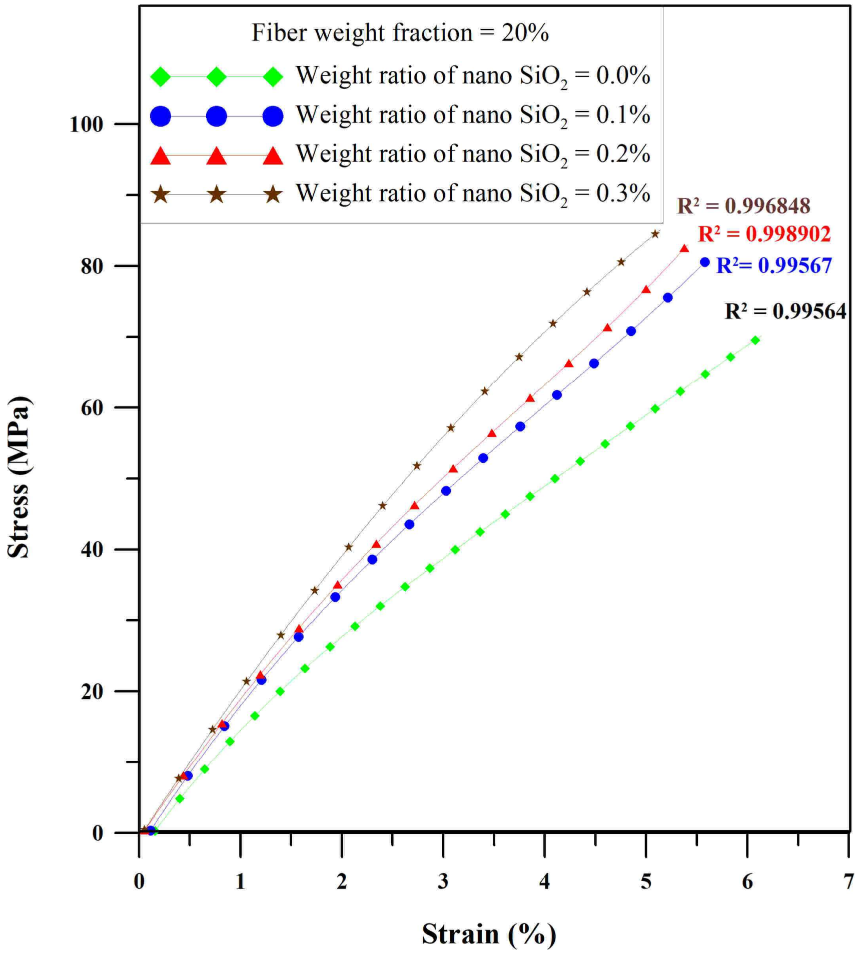


Figure 5. Tensile strength of composites at carbon fiber weight fraction of 20% with 0%, 0.1%, 0.2%, and 0.3% of nano-SiO_2 P-type.

Figure 6 demonstrates the effect of increasing the weight percentage of SiO_2 particles at a carbon fiber weight fraction of 40%. The results show that increasing the SiO_2 content contributes to increasing the ultimate tensile stress of the composite material, along with increasing the Young's modulus, thus improving the composite's strength. However, it leads to a decrease in elongation. This improvement in strength makes composite materials suitable for many industrial applications, such as structures requiring high strength with low strain. The experimental results show that increasing the SiO_2 particle content by 0.3%, 0.2%, and 0.1% resulted in increases in tensile stress of 67.6%, 54.8%, and 79.3%, respectively.

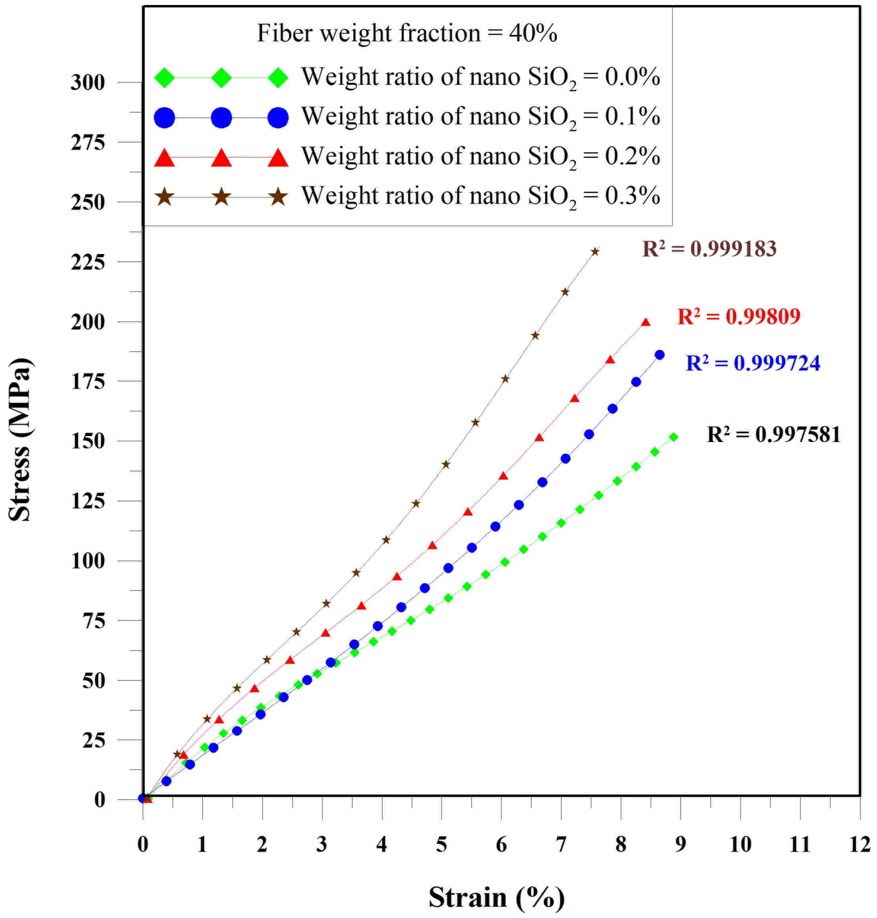


Figure 6. Tensile strength of composites at carbon fiber weight fraction of 40% with 0%, 0.1%, 0.2%, and 0.3% of nano-SiO_2 P-type.

Figure 7 shows the experimental results for the tensile stress of carbon fibers with a 60% weight fraction reinforced with SiO_2 at 0%, 0.1%, 0.2%, and 0.3%. The addition of SiO_2 improved the ultimate tensile strength and stiffness of the composite material, but it simultaneously reduced its elongation. Specifically, increasing the weight percentage of SiO_2 led to an 82.8% increase in ultimate stress compared to composite samples without nanoparticles. When SiO_2 was added at a ratio of 0.2%, the ultimate stress increased by 82.4%. An even greater increase of 87.4% was observed when SiO_2 was added at a ratio of 0.3%.

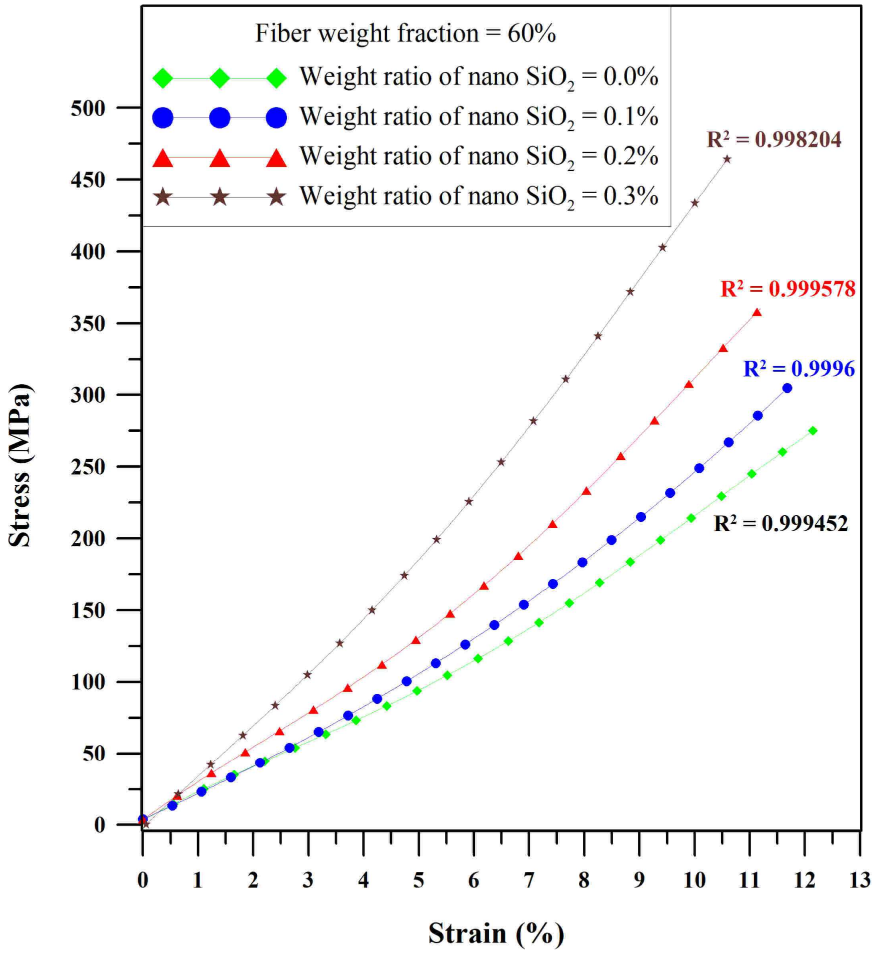


Figure 7. Tensile strength of composites at carbon fiber weight fraction of 60% with 0%, 0.1%, 0.2%, and 0.3% of nano-SiO_2 P-type.

4.3. Impact of SiO_2 and fiber weight fraction on electrical conductivity

The addition of carbon fibers alters the pathways for electrical leakage and electron transfer between surfaces. When the weight fraction of carbon fibers is increased, the electrical resistance of the composite sample at a thickness of 4 mm also rises. Experimental results indicate that incorporating SiO_2 reduces electrical conductivity. The reduction in electrical conductivity observed with a higher weight fraction of fibers is similar to the effect of increasing the SiO_2 weight ratio. However, increasing the weight fraction of carbon fibers contributes to an increase in the overall electrical conductivity compared with the polyester sample. The experimental results shown in Figure 8, at a carbon fiber weight fraction of 20%, indicate that increasing the SiO_2 weight ratio by 0.1%, 0.2%, and 0.3% resulted in decreases in electrical conductivity of 21.1%, 39%, and 20.5%, respectively. At a carbon fiber weight fraction of 40%, the decrease in electrical conductivity was 9%, 45%, and 13%, respectively. Finally, at a carbon fiber weight fraction of 60%, electrical conductivity decreased by 17%, 35%, and 16%, respectively.

Figure 8 also shows the experimental results for electrical conductivity at a 0.1% SiO_2 particle concentration and different weight fractions of carbon fibers. Increasing the weight fraction of carbon fibers from 20% to 40% led to a 25% decrease in electrical conductivity, while increasing the weight fraction from 40% to 60% led to a decrease of 20%. At a SiO_2 particle weight ratio of 0.2%, increasing the carbon fiber weight fraction from 20% to 40% decreased electrical conductivity by 23%, while increasing the weight fraction from 40% to 60% caused a decrease of 13%. At a SiO_2 particle concentration of 0.3%, increasing the carbon fiber weight fraction from 20% to 40% caused a reduction in electrical conductivity of 15%, and increasing from 40% to 60% led to a decrease of 6%. Experimental results show that increasing the weight ratio of SiO_2 particles and carbon fibers improves mechanical properties while reducing electrical conductivity. This makes the composite suitable for applications requiring electrical insulation combined with high mechanical performance.

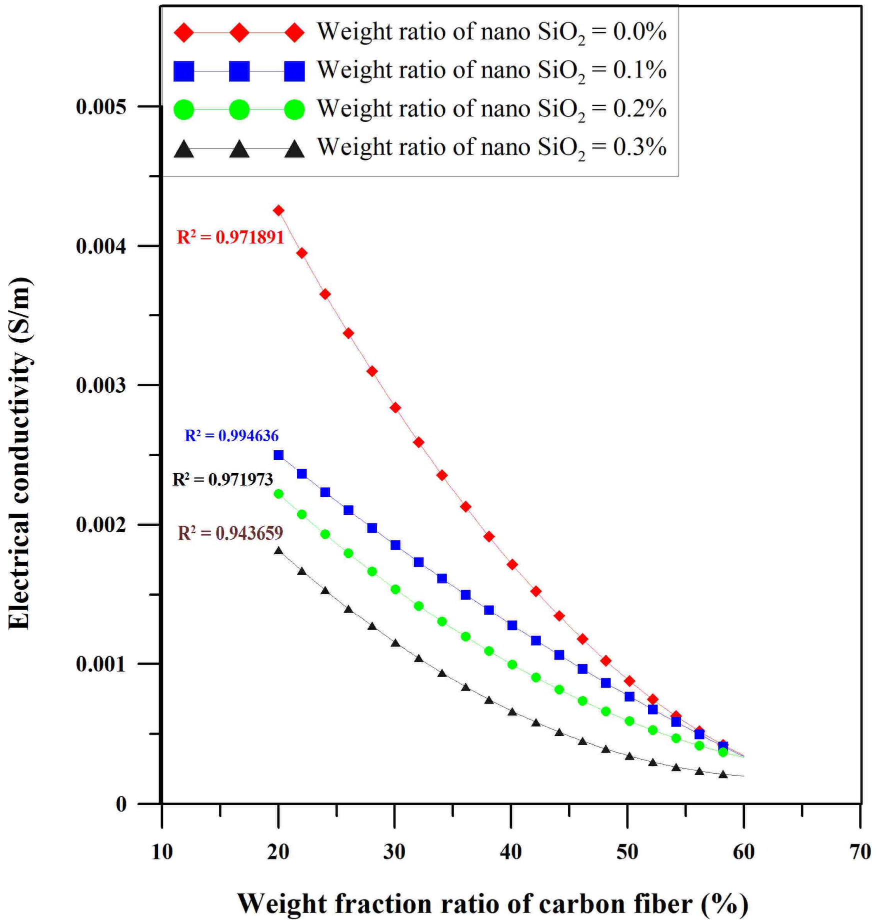


Figure 8. Electrical conductivity of 0.1%, 0.2%, and 0.3% SiO_2 weight ratio at different carbon fiber weight fractions.

4.4. SEM image analysis

Figure 9a–c present SEM images obtained using the FEI (Field Electron and Ion Company) Inspect F50 for samples reinforced with 0.1% SiO_2 at carbon fiber weight fractions of 20%, 40%, and 60%, respectively. SEM analysis was performed at 8000× magnification with 10 μm resolution within the 50–500 nm range at an accelerating voltage of 30 kV, which provides greater sample penetration. SEM images show that the SiO_2 particles are homogeneously dispersed within the composite's microstructure. The uniform distribution of nanoparticles effectively improves the strength of the composite material.

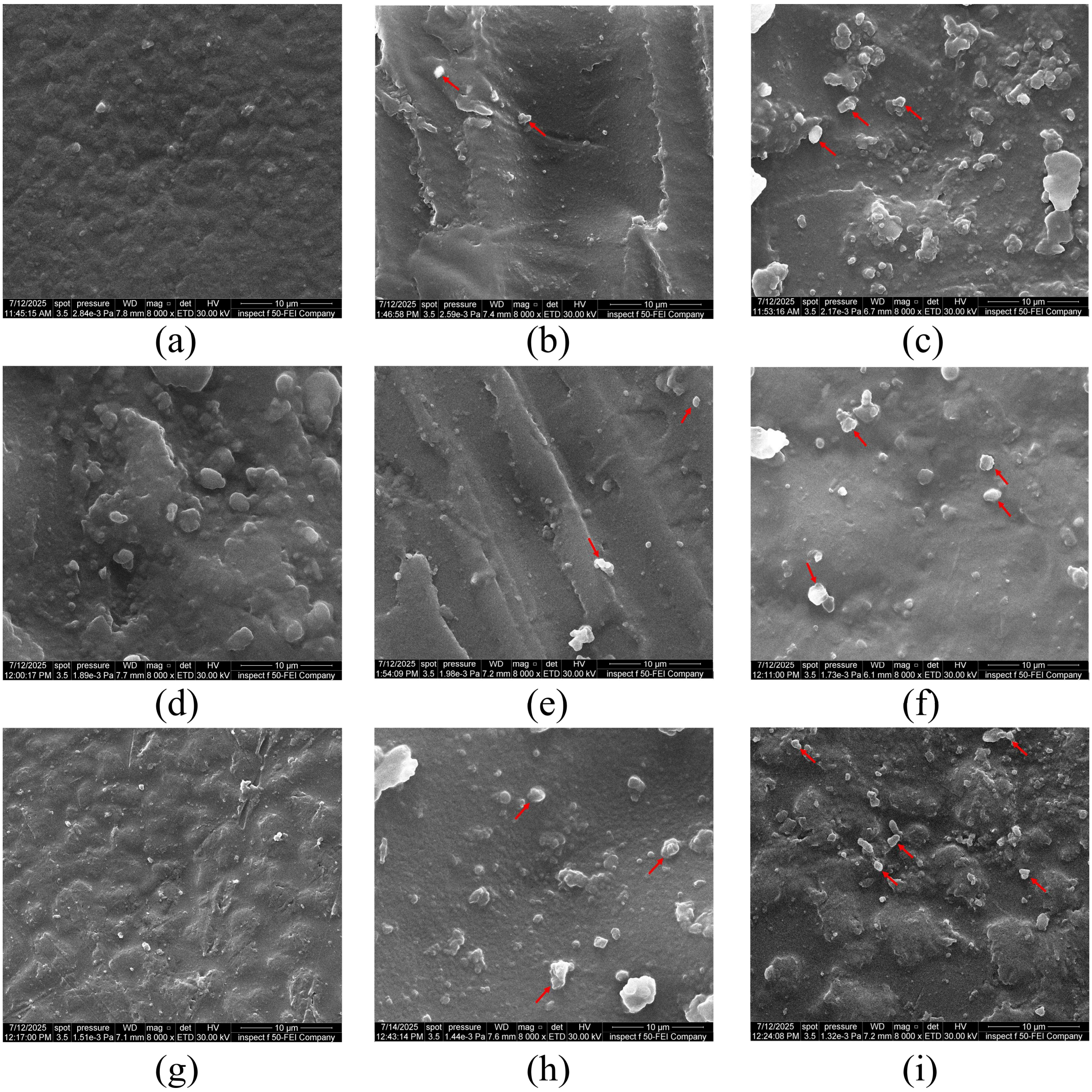


Figure 9. SEM images of samples containing SiO_2 particles at different weight ratios (0.1%, 0.2%, and 0.3%) with different carbon fiber weight fractions (20%, 40%, and 60%). 0.1% SiO_2 at carbon fiber weight fractions of (a) 20%, (b) 40%, and (c) 60%; 0.2% SiO_2 at carbon fiber weight fractions of (d) 20%, (e) 40%, and (f) 60%; 0.3% SiO_2 at carbon fiber weight fractions of (g) 20%, (h) 40%, and (i) 60%.

Figure 9d–f shows SEM images at 8000× magnification of samples reinforced with 0.2% SiO_2 particles and carbon fiber weight fractions of 20%, 40%, and 60%. Microstructural observations detected limited nanoparticle aggregation. Based on the porosity and branched structure of the particles, this aggregation can be justified and may improve adhesion. Higher agglomeration was observed in composites with a carbon fiber weight fraction of 40% compared with those containing 0.3% SiO_2 particles. However, the mechanical performance of the composites continued to improve.

Figures 9g–i correspond to SEM micrographs of composites containing 0.3% SiO_2 particles with varying carbon fiber weight fractions (20%, 40%, and 60%, respectively). Here, the particle agglomeration rate was higher than that of composites with 0.2% SiO_2, despite homogeneous particle distribution remaining evident from microscopic analysis. The increase in aggregation is attributed to morphological features such as porous and branched structures, which provide a high surface area and strong surface adhesion. This implies that increasing mixing time and frequency may reduce agglomeration. However, the data presented here show a continuous increase in the mechanical properties of the composite along with a decrease in electrical conductivity, confirming the effectiveness of this particle addition in forming a nanostructure that enhances mechanical properties.

4.5. Effect of SiO_2 nanoparticle morphology on mechanical and electrical properties

This research provides an in-depth understanding of the dual role of porosity and branching in P-type SiO_2 particles, which contributes to effective contact with fiber surfaces, uniform dispersion within the matrix, and modification of electrical conductivity pathways within the composite. Moreover, particle morphology enhances adhesion and bonding between components and fills interfacial microstructural gaps, thereby improving load-carrying capability and promoting more homogeneous stress distribution throughout the composite. These insulating particles also act as effective barriers to conduction pathways.

Similar behavior was observed at a 0.2% SiO_2 concentration, where electrical conductivity decreased, reaching a reduction of approximately 45% when the carbon fiber weight fraction was fixed at 40%. In these composites, a percolation threshold was identified, reflecting a sharp reduction in conduction with marginal additions of nanoparticles, confirming their effectiveness in modifying the electrical behavior of the composite material. Enhancement of strength and insulation properties depends on achieving a uniform and homogeneous distribution of SiO_2 particles within the microstructure. Nanoparticles contribute to the cohesion of the microstructure by filling interstitial gaps and disrupting electrical pathways, thereby achieving electrical insulation. Furthermore, the microstructural properties of the matrix determine the final composite properties through improved interfacial compatibility, resulting in enhanced overall performance.

The morphological properties of P-type SiO_2, such as porosity and branching, promote cohesion and homogeneity, resulting in improved mechanical performance and electrical insulation. Experimental results showed the greatest improvement in mechanical properties at a carbon fiber weight fraction of 60% and a SiO_2 weight ratio of 0.3%, where tensile strength increased by 87.9%. Electrical conductivity decreased by 45% at a SiO_2 weight ratio of 0.2% and a carbon fiber weight fraction of 40%, thereby improving electrical insulation. The improvement in mechanical performance is primarily attributed to the ability of nanoparticles to fill microstructural gaps and enhance cohesion and adhesion between the composite components. Conversely, the decrease in electrical conductivity is due to the insulating properties of SiO_2 particles, enhanced by their distinctive morphology (such as porosity and branching), which effectively prevents current flow and increases conduction path length within the microstructure.

5. Conclusions

The experimental results of this study lead to the following conclusions:

- A carbon fiber weight fraction of 60% combined with 0.3% SiO_2 shows the best mechanical performance. For this combination, tensile stress increased by 87.4%.

- A carbon fiber weight fraction of 20% decreases electrical conductivity by 21.1%, 39%, and 20.5% for SiO_2 additions of 0.1%, 0.2%, and 0.3%, respectively. The maximum reduction in electrical conductivity (45%) occurred at a carbon fiber weight fraction of 40% with 0.2% SiO_2.
- SEM observations indicate that optimal nanoparticle distribution is achieved at 0.1% SiO_2, resulting in a homogeneous nanoparticle distribution that enhances mechanical properties. The characteristic porosity and branching structure of the P-type particles improve interfacial adhesion and cohesion. Increasing SiO_2 content up to 0.3% increased particle agglomeration due to surface properties; however, mechanical properties continued to improve, indicating that agglomerated particles represent only a minor fraction of the composite.
- Carbon fiber composites have extensive advanced engineering applications. The incorporation of nanoparticles enhances mechanical strength and resistance, enabling use in transportation structures (automobiles, ships, and aircraft) as well as coatings and adhesive technologies. These findings open the door to further research on thermal conductivity and thermal stability at high temperatures for more efficient electronic components and renewable energy systems.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Conceptualized the study, performed all experiments, analyzed the data, and wrote the manuscript: Nooralhuda Kareem Khalaf; provided guidance on the overall research, supervised the results, and edited the manuscript: Raed Naeem Hwayyin; provided guidance on the electrical experiments and general research advice, and reviewed the manuscript for clarity and accuracy: Ahlam Luaibi Shuraiji. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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