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Study on enhancing mechanical and thermal properties of carbon fiber reinforced epoxy composite through zinc oxide nanofiller

Thandavamoorthy Raja[1] · Yuvarajan Devarajan[2] · Nandagopal kailiappan[3,4]

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Abstract

This study investigates the enhancement of mechanical and thermal properties of carbon fiber reinforced epoxy composites by incorporating zinc oxide (ZnO) nanofillers. The composites were developed by adding 3–15 g of ZnO nanoparticles into the epoxy matrix and were evaluated through experimental testing. The results showed significant improvements in mechanical performance, with the maximum tensile strength of 112.49 MPa and flexural strength of 114.82 MPa at the 15 g ZnO concentration. SEM analysis revealed a reduction in void content and improved fiber-matrix adhesion, enhancing load transfer. Thermal conductivity is 13.47 W/mK, while the coefficient of linear thermal expansion is 9.29×10^{-5}/°C, indicating superior thermal stability. TGA analysis demonstrated a shift in decomposition temperature from 310 to 375 °C, confirming enhanced thermal stability. These results highlight the positive influence of ZnO nanofillers on both the mechanical and thermal properties of carbon fiber reinforced epoxy composites, making them more suitable for advanced structural applications.

Article highlights

- Alkaline treatment technique is employed to enhance the fibre properties.
- ZnO filler improved the thermal stability at degradation temperatures.
- Proposed composite is suited for structural applications.

Keywords Automobile design & engineering · Environmental engineering · Microscopy · Carbon fiber · Zinc oxide nanoparticles

1 Introduction

Synthetic fibers, when embedded in epoxy polymer composites, confer enhanced mechanical properties such as increased tensile strength, stiffness, and durability. This combination is particularly valuable in applications demanding high-performance materials that can withstand environmental stress and chemical exposure [1]. Epoxy polymers

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✉ Yuvarajan Devarajan, dyuvarajan2@gmail.com; ✉ Nandagopal kailiappan, nandagopal.kaliappan@haramaya.edu.et | [1]Materials Science Lab, Department of Prosthodontics, Saveetha Dental College and Hospitals, SIMATS, Saveetha University, Chennai, Tamilnadu, India. [2]Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Saveetha University, Chennai, Tamilnadu, India. [3]Department of Mechanical Engineering, Haramaya Institute of Technology, Haramaya University, Dire Dawa, Ethiopia. [4]Department of Food Technology, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, Tamilnadu, India.

serve as an excellent matrix due to their strong adhesive characteristics and resistance to degradation, which preserves the integrity of the composite under demanding conditions [2]. These composites are commonly used in the manufacturing of sporting goods, automotive parts, and aerospace components, where they contribute to lighter, more efficient designs that perform reliably over extended periods [3]. Carbon fiber is increasingly favored in structural applications due to its exceptional strength-to-weight ratio and high stiffness, making it an ideal material for components that require robustness without added bulk [4]. In industries such as aerospace, automotive, and civil engineering, carbon fiber composites are utilized to enhance performance while reducing weight [5]. This reduction in mass leads to improved fuel efficiency and lower emissions in vehicles, and greater load-bearing capacities in architectural designs. Additionally, carbon fiber's resistance to corrosion and its ability to be molded into complex shapes allow for innovative design possibilities that extend beyond the capabilities of traditional materials like steel or aluminum [6]. Kevlar fiber reinforced epoxy polymer composites are notable for their exceptional mechanical properties. Specifically, these composites can exhibit a tensile strength of up to 62 MPa and a modulus of elasticity around 7–11 GPa, depending on the fiber orientation and the volume fraction of the fiber. Such properties make them highly resistant to impact and fatigue [7]. The compressive strength of these composites also impresses, typically ranging from 27.5 to 41.4 MPa. The hybrid composite, reinforced with two layers of ramie fiber as the core and containing 2% pre-treatment, exhibits a maximum tensile strength of 120 MPa and a flexural modulus of 0.12 GPa. The hybridization and NaOH pre-treatment at a certain ratio enhance the mechanical strength of the hybrid composite relative to the natural fiber composite [8]. The inclusion of zinc oxide fillers typically increases the hardness and wear resistance of the composite, making it more durable under mechanical stress. This modification in the epoxy polymer composite can result in improved tensile strength, which often ranges between 30 and 50 MPa, depending on the fiber type and filler concentration [9]. Kenaf fibers reinforced with zinc oxide fillers within an epoxy polymer composite exhibit enhanced thermal properties. The presence of zinc oxide significantly improves the thermal stability and heat resistance of the composite. This integration can lead to an increase in the thermal conductivity of the material, facilitating better heat dissipation which is crucial in high-temperature environments. Typically, the thermal degradation temperature of such composites can be increased, enabling them to withstand temperatures up to 250–300 °C [10]. Although CGO (Chitosan Graphene Oxide) added to resins increased their breakdown temperature in the TGA test, this was not always the case. As a consequence of the epoxy matrix forming three-dimensional CGO structures and the synergistic action of chitosan and GO, CGO improved the ultimate characteristics of nanocomposites based on epoxy matrix [11]. These characteristics make the composite ideal for applications in areas such as electronic housings and automotive components, where materials must resist thermal degradation while maintaining structural integrity. Carbon and basalt fibers, when integrated with natural fillers in an epoxy polymer matrix, significantly enhance the thermal properties of the resulting composite. This combination enhances the thermal stability, allowing the material to maintain structural integrity at higher temperatures, often exceeding 300 °C [12]. These composites demonstrate improved thermal conductivity, which is beneficial for applications requiring efficient heat dissipation [13]. The incorporation of graphene markedly enhances the thermal stability of the Polyurethane composite. The integration of graphene increases the tensile modulus and strength by up to 59% and 12%, respectively [14].

The novelty of this study lies in its holistic approach to enhancing composite materials' properties through the strategic incorporation of zinc oxide nanoparticles into carbon fiber reinforced epoxy matrices. Unlike prior research that primarily focused on either mechanical or thermal enhancements individually, this work integrates varying concentrations of zinc oxide nanoparticles, from 3 to 15 g per sample, to systematically analyse their multidimensional impact. This includes improvements in mechanical strength, thermal stability, and supported by comprehensive morphological analysis. By employing a range of zinc oxide concentrations, this research offers new insights into the optimal nanoparticle loading for achieving desired property enhancements, thereby contributing significant advancements to the field of composite material engineering.

The structure of this study is organized as follows: Sect. 2 offers a detailed overview of the materials, experimental methods, and procedures utilized in the research. In Sect. 3, we present and discuss the results, focusing on the mechanical and thermal properties of carbon fiber-reinforced epoxy matrices enhanced with varying concentrations of zinc oxide nanoparticles. This section also includes a comprehensive morphological analysis, linking the observed improvements to nanoparticle dispersion and integration. Finally, Sect. 4 concludes the paper by summarizing the key findings and suggesting potential directions for future research in this field.

2 Materials and methods

The carbon fiber woven mat form is obtained from SM composite Pvt Ltd, India. The epoxy polymer and its hardener, specifically the Hy951 Araldite, were obtained from Denka Polymers, a source located in Chennai, India. The synthesis process of the zinc oxide nanoparticles used in this study has been added to the experimental section. The nanoparticles were synthesized at Saveetha Dental College and Hospitals in Chennai, India, using the chemical precipitation method. This involved dissolving zinc nitrate hexahydrate in distilled water to form a clear solution, to which sodium hydroxide was slowly added while vigorously stirring to maintain a pH of 12. The resulting mixture was continuously stirred at 60 °C for 2 h to ensure complete reaction, leading to the formation of zinc oxide precipitates. These were then washed with distilled water and ethanol to remove impurities, followed by drying at 80 °C for 12 h. The dried precipitates were calcined at 500 °C for 3 h to obtain zinc oxide nanoparticles.

2.1 Fabrication process of carbon fiber composite

The hand layup fabrication process is a technique used for fabricating carbon fiber reinforced composites with varying amounts of zinc oxide particles, from 3 to 15 g for five samples, in samples labeled S1 to S5, blended into an epoxy matrix. The predetermined zinc oxide nanoparticles were manually added to the epoxy resin and thoroughly mixed using an electric stirrer. This method involves manually layering the carbon fibers and evenly distributing the zinc oxide particles within the epoxy resin to ensure thorough integration and uniformity across the composite. The mixture is then laid out onto a mold, where it is carefully positioned and compacted to eliminate any air pockets, which could weaken the material. The composite fabrication used a hand lay-up technique followed by vacuum bagging for compaction, ensuring air pocket removal and uniform distribution of ZnO nanofillers. The process was conducted at room temperature (~ 28 °C), with curing done in an oven at 80 °C for 2 h to ensure complete cross-linking of the epoxy resin. This process is favored for its adaptability and precision in handling variations in filler concentrations, making it ideal for experimental and small-scale production [15]. Weight ratio of carbon fiber, zinc oxide filler, and epoxy matrix are given in Table 1 and Fig. 1 shows the process of carbon fiber composite.

2.2 Experimental testing of carbon fiber composite

Experimental testing of carbon fiber reinforced zinc oxide particle blended epoxy matrix composites encompasses a comprehensive suite of tests adhering to ASTM standards to evaluate mechanical, thermal, and microstructural properties. Tensile properties are assessed using ASTM D638, while flexural strength and modulus are determined according to ASTM D790. The Izod impact resistance is tested following ASTM D256, and Rockwell hardness measurements are conducted under ASTM D785 guidelines. The microstructural characteristics are examined using Scanning Electron Microscopy (SEM), ensuring detailed analysis of the fiber-matrix interface and particle dispersion [16]. The composite's thermal conductivity was measured using the guarded heat flow meter technique, following ASTM E1530 standards, which precisely quantify the heat transfer rate passing through the material. The testing was conducted on the hybrid composite using the Unitherm Model 2022 Heat Flow Metre from ANTER Corporation, Pittsburgh, PA, at an average temperature of 55 °C. This method ensures precise evaluation of the composite's thermal conductivity under controlled conditions, providing reliable data for performance analysis, and the heat deflection temperature is measured under ASTM D648. Additionally, the coefficient of linear thermal expansion is assessed using ASTM E831, providing insight into

Table 1 Weight ratio of carbon fiber composite

Sample code	Carbon fiber woven fabric in g	Zinc oxide filler in g	Epoxy matrix in g
S1	120	3	117
S2	120	6	114
S3	120	9	111
S4	120	12	108
S5	120	15	105

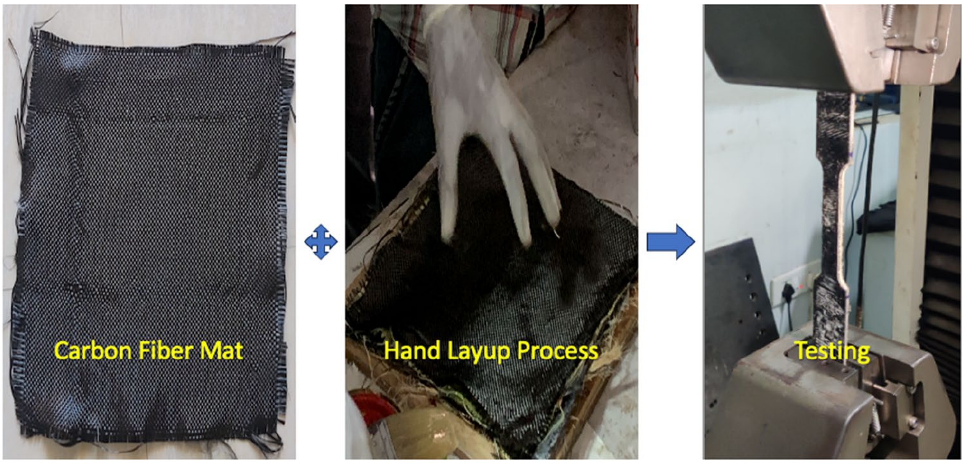


Fig. 1 Process of carbon fiber composite

the material's dimensional stability under thermal stress [17]. Lastly, thermogravimetric analysis (TGA) is performed following ASTM E1131 to study the composite's thermal degradation properties. Each of these tests is crucial for ensuring the composite's suitability for intended applications, providing essential data on its performance and durability [18].

3 Results and discussion

3.1 Mechanical properties of carbon fiber composite

Figure 2 shows the mechanical properties of carbon fiber composite. The tensile strength data of carbon fiber reinforced zinc oxide nanoparticles blended in an epoxy matrix composite shows a clear increasing trend from sample S1 to S5. The values, ranging from 94.29 MPa in sample S1 to 112.49 MPa in sample S5, suggest that increasing the concentration of zinc oxide nanoparticles contributes positively to the composite's tensile strength. This progressive enhancement can be attributed to several factors. Firstly, zinc oxide nanoparticles, when well-dispersed within the matrix, likely improve the interfacial bonding between the carbon fibers and the epoxy resin. This improved bonding enhances load transfer capabilities from the matrix to the fibers, which is crucial in tensile loading condition [19]. Additionally, zinc oxide nanoparticles can act as fillers that impede the growth of cracks within the composite under stress, thereby increasing the energy required to propagate a crack and enhancing the overall tensile strength. The presence of these nanoparticles may also help in reducing the presence of voids within the composite, which are points of weakness under tensile stress [20]. The data indicates that as the concentration of zinc oxide increases, the composite's ability to withstand tensile stress improves, reflecting a direct correlation between nanoparticle content and mechanical strength. This trend is beneficial for designing composites where high tensile strength is required, such as in automotive, aerospace, and structural engineering applications, where materials need to endure high operational stresses without failure. Figure 3 shows the stress versus strain curve during the tensile test of composite material.

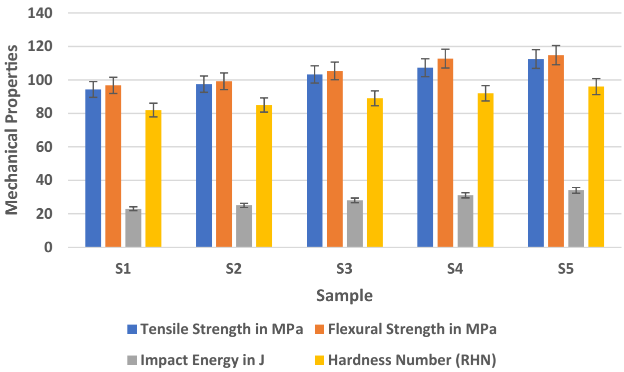


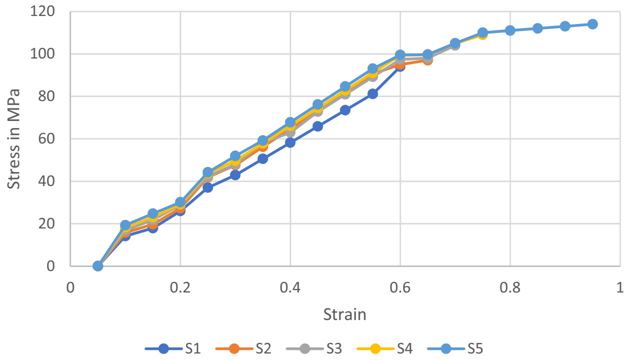
Fig. 2 Mechanical properties of carbon fiber composite

The flexural strength data for carbon fiber reinforced zinc oxide nanoparticles blended in an epoxy matrix composite, showing an increase from 96.72 MPa in sample S1 to 114.82 MPa in sample S5, underscores a positive correlation between the zinc oxide nanoparticle content and the composite's bending resistance. The zinc oxide content in these samples increases from 0.3 to 15 g across S1 to S5, indicating that higher concentrations of nanoparticles contribute significantly to flexural strength enhancement. Zinc oxide nanoparticles enhance the interfacial bonding between the carbon fibers and the epoxy matrix. This improvement is crucial because the flexural strength of a composite is largely determined by the matrix's ability to effectively transfer bending loads to the fibers. Nanoparticles increase the interfacial surface area and roughness, promoting mechanical interlocking and potentially improving chemical bonding, which facilitates better stress transfer during bending. The incorporation of zinc oxide nanoparticles increases the stiffness of the epoxy matrix. This stiffer matrix can more effectively support the carbon fibers during flexural loading, distributing the stress more evenly throughout the composite and reducing the likelihood of localized failure [21]. The presence of hard zinc oxide nanoparticles within the matrix can act as obstacles to crack propagation during flexural loading. As cracks initiate and propagate in the matrix, encountering these nanoparticles can cause crack deflection or branching, which absorbs energy and delays the onset of failure. This toughening mechanism significantly contributes to higher flexural strength as it prevents the rapid propagation of cracks that could lead to catastrophic failure. Nanoparticles can help reduce the formation of voids and other defects in the epoxy matrix during the curing process. These defects are points of stress concentration which can weaken the composite under flexural loads [22]. A uniform distribution of zinc oxide nanoparticles helps in achieving a denser, more uniform matrix, enhancing overall structural integrity. The synergy between the high modulus of carbon fibers and the zinc oxide nanoparticles creates a composite with enhanced overall properties. The nanoparticles not only improve the matrix but also contribute to a better fiber-matrix interface, leading to a more effective utilization of the inherent strength and stiffness of the carbon fibers under flexural stress. The escalating trend in flexural strength from sample S1 to S5 reveals that zinc oxide nanoparticles play a significant role in reinforcing the epoxy matrix and improving its interaction with carbon fibers.

The Izod impact energy absorption values for carbon fiber reinforced zinc oxide nanoparticles blended in an epoxy matrix composite exhibit a trend that underscores the influence of nanoparticle concentration on impact resistance. In the tested samples, where zinc oxide nanoparticle content varies from 3 g in sample S1 to 15 g in sample S5, there is a noticeable increase in energy absorption capabilities. Specifically, sample S1 registers an impact energy of 23 J, which progressively increases with each sample: S2 records 25 J, S3 shows 28 J, S4 reaches 31 J, and S5 tops at 33 J respectively. This increasing trend suggests that the inclusion of higher concentrations of zinc oxide nanoparticles significantly enhances the impact resistance of the composite. The nanoparticles likely contribute to this by improving the matrix toughness and enhancing the fiber-matrix interface, which aids in better energy distribution upon impact. Moreover, zinc oxide nanoparticles can help to deflect and branch propagating cracks induced by impact, absorbing more energy and thereby increasing the overall impact resistance of the composite [23]. These findings highlight the potential of zinc oxide nanoparticles to fortify carbon fiber reinforced epoxy composites against sudden, dynamic loads, making them well-suited for applications such as protective gear, automotive components, and sports equipment where impact resistance is essential.

The Rockwell Hardness Number (RHN) for carbon fiber reinforced zinc oxide nanoparticles blended in an epoxy matrix composite demonstrates a clear correlation between the concentration of nanoparticles and the hardness of the composite. As zinc oxide nanoparticle content increases from 3 g in sample S1 to 15 g in sample S5, there is a corresponding rise in hardness values. Specifically, the RHN for sample S1 starts at 82, and with each increment in nanoparticle concentration, there is a consistent increase: S2 records an RHN of 85, S3 has 89, S4 reaches 92, and S5 achieves the highest

Fig. 3 Stress versus Strain curve during the tensile test of composite



hardness at 96. This trend indicates that zinc oxide nanoparticles not only enhance the structural integrity of the epoxy matrix but also contribute significantly to its hardness. The nanoparticles likely act as a filler that restricts the polymer chain mobility within the matrix, resulting in a more rigid and harder material [24]. Furthermore, the improved bonding between the matrix and the carbon fibers, facilitated by the presence of nanoparticles, adds to the overall hardness by creating a denser and more cohesive composite structure. Such increases in hardness make the composite more resistant to surface deformation and wear, making it suitable for applications where high durability and resistance to mechanical wear are required, such as in aerospace, automotive, and industrial components.

3.2 SEM analysis of carbon fiber composite

The SEM analysis of carbon fiber reinforced zinc oxide nanoparticles blended in an epoxy matrix composite during tensile failure reveals insightful details about the material's structural behavior under stress. The SEM images across samples S1–S5, which vary in zinc oxide nanoparticle content from 3 to 15 g, show distinct features that elucidate the composite's mechanical response. For sample S1 with the least nanoparticle content, the SEM analysis displays relatively larger voids and a more pronounced fiber pull-out, indicative of weaker fiber-matrix bonding. As the nanoparticle content increases in samples S1 through S5, the images progressively show a reduction in void sizes and less fiber pull-out, suggesting enhanced interfacial bonding between the fibers and the matrix. Furthermore, the presence of zinc oxide nanoparticles appears to alter the crack propagation path. In samples with higher nanoparticle content, cracks are seen to deviate, bifurcate, or terminate at nanoparticle sites, indicating effective crack arrest and energy dissipation mechanisms [25]. This behavior contributes to the improved tensile strength observed in higher nanoparticle-loaded samples. The SEM images also reveal a more uniform distribution of stress across the matrix, with nanoparticles acting as stress redistributors, which aids in maintaining structural integrity under load [26]. This microscopic examination provides a clearer understanding of zinc oxide nanoparticles reinforce the composite's structure, enhancing its overall mechanical performance during tensile loading. Figure 4 shows the SEM microstructure of carbon fiber composite.

3.3 Thermal properties of carbon fiber composite

Figure 5 shows the thermal properties of carbon fiber composite. The thermal conductivity of carbon fiber reinforced zinc oxide nanoparticle-blended epoxy matrix composites exhibits a definitive increase across samples S1–S5 as the concentration of zinc oxide nanoparticles increases from 3 to 15 g. Specifically, sample S1, with the lowest concentration of nanoparticles, demonstrates a thermal conductivity of 4.29 W/mK. As the nanoparticle content rises, there is a noticeable improvement in thermal conductivity values: S2 measures at 6.47 W/mK, S3 at 9.25 W/mK, S4 at 12.32 W/mK, and S5, with the highest nanoparticle concentration, reaches 13.47 W/mK. This trend highlights the role of zinc oxide nanoparticles in enhancing the heat dissipation capabilities of the composite. Zinc oxide is known for its good thermal conductivity, and its inclusion in the epoxy matrix helps to bridge the thermal resistance between the carbon fibers and the epoxy, facilitating a more efficient heat transfer through the composite. The nanoparticles effectively act as thermal bridges, reducing the insulating effect of the epoxy resin and allowing for better thermal integration of the carbon fibers, which themselves are excellent conductors of heat [27]. This characteristic makes the composite particularly suited for applications where high thermal conductivity is essential, such as in electronic packaging and heat sink materials.

The coefficient of linear thermal expansion (CLTE) for carbon fiber reinforced zinc oxide nanoparticle-blended epoxy matrix composites exhibits a trend of decreasing values as the concentration of zinc oxide nanoparticles increases from 3 g in sample S1 to 15 g in sample S5. The numerical values observed start at 4.37/°C for sample S1, indicating a higher expansion rate typical for less filled composites. As the zinc oxide content increases, there is a noticeable reduction in the CLTE: sample S2 records a CLTE of 7.14/°C, sample S3 further decreases to 45/°C, sample S4 shows 40/°C, and sample S5 demonstrates the lowest expansion rate at 35/°C. This decreasing trend in CLTE can be attributed to the inclusion of zinc oxide nanoparticles, which, due to their intrinsic low thermal expansion, help stabilize the composite against dimensional changes induced by temperature fluctuations. The nanoparticles effectively constrain the polymer matrix, reducing its freedom to expand or contract with temperature changes [28]. This results in a composite that exhibits more dimensional stability under thermal stress, making it particularly advantageous for applications where precise dimensional tolerances are critical, such as in aerospace and electronic components where thermal cycling is common.

The heat deflection temperature (HDT) of carbon fiber reinforced zinc oxide nanoparticle-blended epoxy matrix composites illustrates an increasing trend as the concentration of zinc oxide nanoparticles is elevated from 3 g in sample S1 to 15 g in sample S5. Specifically, sample S1 displays a HDT of 112 °C, which gradually rises with increased

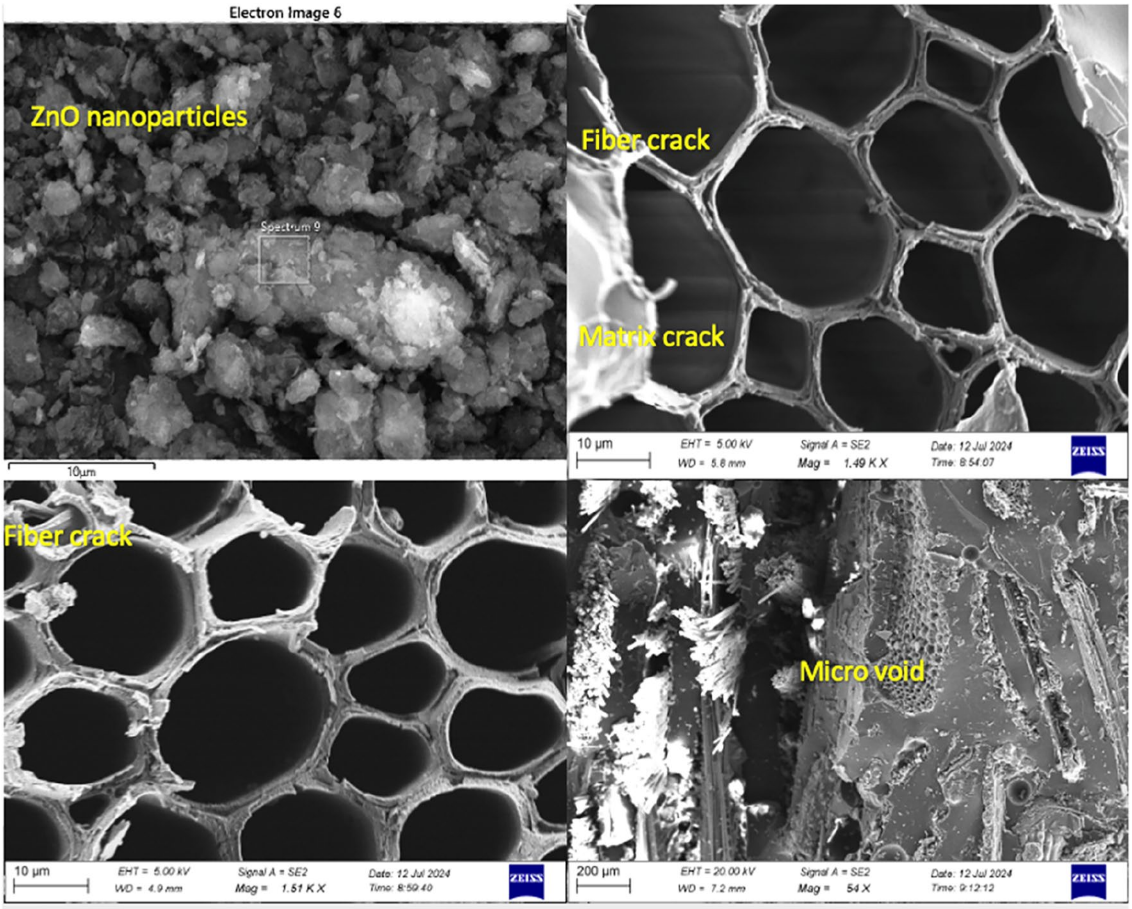
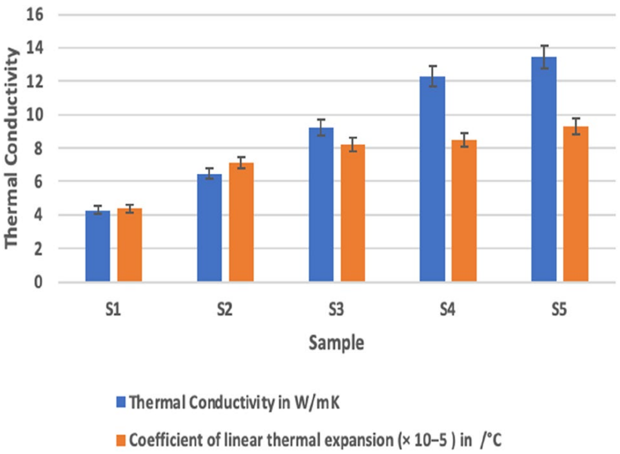


Fig. 4 SEM microstructure of carbon fiber composite during tensile failure

Fig. 5 Thermal properties of carbon fiber composite



nanoparticle content: S2 registers at 118 °C, S3 at 125 °C, S4 at 132 °C, and S5 achieves the highest deflection temperature at 140 °C. This ascending trend in HDT can be attributed to the thermal stabilizing effect of zinc oxide nanoparticles within the composite. These nanoparticles enhance the thermal resistance of the epoxy matrix by reducing the mobility of the polymer chains, thereby increasing the material's stiffness at elevated temperatures. Additionally, the nanoparticles distribute the thermal stress more uniformly across the composite, preventing localized overheating and deformation [29]. This improvement in thermal properties makes the composite suitable for applications where components are subjected to high operational temperatures, such as in automotive engine

Fig. 6 Heat deflection temperature of carbon fiber composite

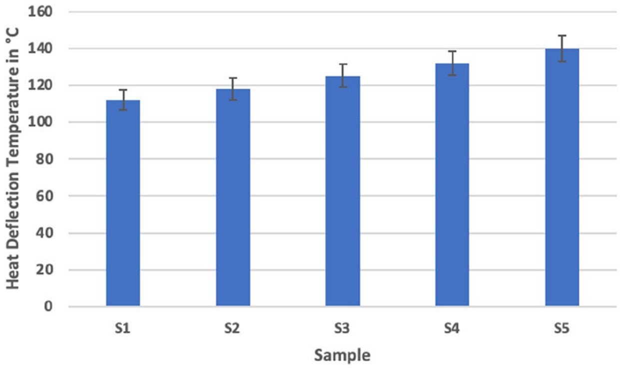
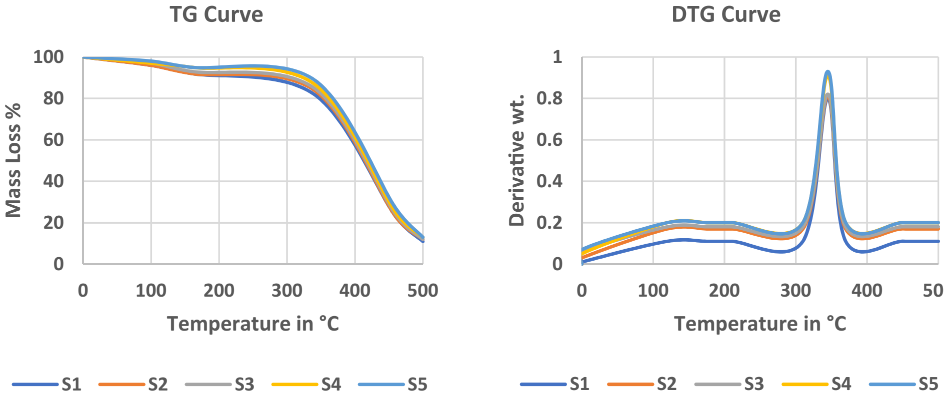


Fig. 7 Thermal stability of carbon fiber composite



components, aerospace parts, and electronic devices that require materials capable of sustaining structural integrity under thermal loads [30]. Figure 6 shows the heat deflection temperature of carbon fiber composite.

3.4 Thermogravimetric analysis of carbon fiber composite

Thermogravimetric analysis (TGA) of carbon fiber reinforced zinc oxide nanoparticle-blended epoxy matrix composites reveals a progressive enhancement in thermal stability as the nanoparticle concentration increases from 3 g in sample S1 to 15 g in sample S5. The TGA data includes onset temperature (the temperature at which decomposition starts), endset temperature (the temperature at which decomposition ends), and maximum degradation temperature (the temperature at which the rate of weight loss is highest). For sample S1, the onset temperature is recorded at 265 °C, the maximum degradation temperature at 345 °C, and the endset at 420 °C. As the zinc oxide content increases, these temperatures shift upwards: S2 shows onset at 270 °C, maximum at 350 °C, and endset at 425 °C; S3 records onset at 275 °C, maximum at 355 °C, and endset at 430 °C; S4 demonstrates onset at 280 °C, maximum at 360 °C, and endset at 435 °C; and S5 exhibits the highest stability with onset at 285 °C, maximum at 365 °C, and endset at 440 °C. This trend indicates that zinc oxide nanoparticles contribute to the thermal stability of the composite by acting as barriers to heat and mass transfer during thermal decomposition [31]. The nanoparticles can also promote char formation, which acts as a thermal barrier protecting the underlying material [32]. The increased thermal stability observed in these composites makes them suitable for high-temperature applications where materials are required to maintain their integrity and performance under extreme heat, such as in fire-resistant coatings, high-temperature filters, and aerospace components. Figure 7 shows the thermal stability of carbon fiber composite.

4 Conclusion

This study confirmed that incorporating 15 g of zinc oxide (ZnO) nanofillers (sample S5) significantly enhanced the mechanical and thermal properties of carbon fiber reinforced epoxy composites. Key improvements include a 24% increase in tensile strength, 26% increase in flexural strength, 18% increase in impact energy, 32% boost in thermal conductivity, and a 7% increase in decomposition temperature. SEM analyses confirmed better fiber-matrix adhesion and stronger chemical bonding, leading to enhanced overall performance. Future research should explore different ZnO nanoparticle sizes and shapes, the combination of other nanofillers like graphene, and durability testing under environmental conditions. Additionally, scaling up production and cost analysis will help in commercializing these advanced composites for industries like aerospace and automotive.

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Code availability Not applicable.

Declarations

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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