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Review Article

High-performance Graphite-reinforced Sustainable Epoxy Composite

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Abstract

The industry constantly looks for lightweight, high-strength parts for airplanes and wind turbine blades. Despite the possibility of substituting polymers for metal components, there is a criticality implied by the poorer mechanical and thermal performance of polymers. This study examines the microstructure and mechanical properties of distinct industrial-grade filler (graphite) concentrations added to an epoxy matrix: 3 wt.%, 6 wt.%, 9 wt.%, 12 wt.%, and 15 wt.%. The mechanical performance improved with increasing filler concentration, with Graphite-9 wt.% showing the highest enhancement with a 118.48% improvement in mechanical performance The results indicate that an optimal graphite concentration of 9 wt.% enhances tensile, and flexural strength, whereas excessive graphite concentration (15wt.%) led to local embrittlement decreasing the mechanical properties. Scanning electron microscopy (SEM) analysis of the 15 wt.% composite reveals an uneven dispersion of graphite, contributing to the properties' reduction. The findings provide insight into the influence of graphite reinforcement on the mechanical performance of epoxy composites, aiding the optimization of composite formulations for aircraft and wind turbine blade applications.

Introduction

Epoxy-based composites are widely used in aerospace, automotive, and structural applications due to their excellent adhesion, chemical resistance, and durability. However, their mechanical properties can be further improved by reinforcement with fillers such as graphite, which offers high thermal and electrical conductivity and mechanical reinforcement [1-6]. Graphite's effectiveness as a reinforcement depends on its dispersion, interfacial bonding, and optimal weight percentage within the polymer matrix. Polymer-based composites are widely used in engineering applications due to their lightweight nature, excellent corrosion resistance, and high strength-to-weight ratio [5-8]. Epoxy resins are particularly favored among polymer matrices due to their outstanding adhesion, chemical resistance, and mechanical strength [7]. However, the inherent brittleness of epoxy limits its performance in applications requiring high toughness and durability. To overcome these limitations, reinforcing materials such as carbon fibers, nanoparticles, and graphite have been incorporated into epoxy matrices to enhance their mechanical properties [9-15]. Graphite, a crystalline form of carbon, has gained attention as a reinforcement material due to its high thermal conductivity, lubricating properties, and mechanical strength [16]. The addition of graphite to epoxy has been shown to improve the composite's mechanical properties, but its effectiveness depends on factors such as particle size, distribution, and weight percentage [15]. At optimal concentrations, graphite particles act as load-bearing reinforcements, improving hardness and tensile strength [4-6]. However, excessive graphite content can lead to particle agglomeration, reducing interfacial bonding and weakening the composite [10].

Various processing techniques have been used to fabricate epoxy-based composites, including solution mixing, hot pressing, and stir casting [17-21]. Cold stir casting is a relatively simple and cost-effective method that involves mixing the reinforcement into a liquid polymer matrix at ambient or

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slightly elevated temperatures, followed by curing [20-22]. This method ensures uniform distribution of reinforcements while minimizing thermal degradation of the polymer. However, the dispersion of particles remains a key challenge, particularly at higher filler loadings [20]. While several studies have investigated the effect of graphite on epoxy composites, there remains a need to optimize graphite concentration to achieve maximum mechanical strength. This study aims to contribute to the growing body of knowledge on epoxy-graphite composites by examining the effect of different graphite weight percentages on hardness, tensile strength, flexural strength, and density. The study employs cold stir casting for composite fabrication and evaluates the role of graphite dispersion in mechanical performance. Understanding these effects will help optimize composite formulations for applications in automotive, aerospace, and structural industries.

Experimental procedures

Manufacturing process

The materials used are waterborne transparent epoxy resin (LY556), hardener (HY-951), sodium hydroxide (NaOH) solution, and acetone as a dispersing agent were procured from Herenba Instruments and Engineers (Chennai - 600053, Tamil Nadu, India). The reinforcing material: graphite powder (average particle size of 50 µm) was sourced from the Department of Industrial Chemistry, Nnamdi Azikiwe University, Awka, Nigeria. The resin-to-hardener ratio was maintained at 2:1 by weight, and the graphite was added in varying weight percentages: 0 wt%, 3 wt.%, 6wt.%, 9wt.%, 12wt.% and 15wt.%. Silicon-based mold release agents were applied to ensure easy demolding of the cured samples. Cold stir casting was employed for composite fabrication [8]. The graphite powder was dried in an oven at 80°C for 2 hours to remove moisture and prevent porosity in the final composite. The dried powder was then ultrasonicated in ethanol for 30 minutes to enhance dispersion before mixing with epoxy resin. The epoxy resin and graphite suspension were mechanically stirred at 500 rpm for 10 minutes using a high-shear stirrer to ensure the uniform dispersion of graphite particles. The curing agent was gradually added to the mixture while stirring continued for another 5 minutes to prevent premature gelation. To eliminate air bubbles, the mixture was subjected to vacuum degassing for 5 minutes before casting. Pre-cleaned silicone molds were coated with a release agent to facilitate demolding. The prepared epoxy-graphite mixture was carefully poured into the molds and allowed to settle. The filled molds were kept at room temperature for 24 hours to allow initial curing. Post-curing was conducted at 80 °C for 2 hours to achieve complete polymerization and enhance the mechanical properties of the composites [9].

Testing process

After curing, the composite specimens were machined according to ASTM standards for mechanical testing. Hardness was measured using a Vickers Hardness tester, following ASTM D2240. A load of 500g was applied to a pyramid-shaped industrial indenter, and the size of the indentation on the surface of the material was measured three times. Five readings were taken at different points on each sample, and the average value was recorded to ensure accuracy. The Instron-Series 3369 Universal Testing Machine was used for tensile and flexural tests as per ASTM standards. ASTM D3039 and ASTM D7264 standard procedure was used for determining the tensile and flexural strength properties, respectively, of the composites. Dog-bone-shaped specimens were prepared, and tensile tests were conducted at a crosshead speed of 2 mm/min. The peak stress at failure was recorded as the tensile strength. Flexural strength was determined using a three-point bending test as per ASTM D7264. Specimens were loaded at a span-to-depth ratio of 16:1, and the maximum stress before failure was recorded [13]. The density of the composites was measured using the Archimedes' principle, with water as the immersion medium. The theoretical density was calculated based on the rule of mixtures, and experimental values were compared to assess void content and material integrity [1]. To investigate the dispersion of graphite particles and fracture behavior, scanning electron microscopy (SEM) (with model number TESCAN VEGAN III.) was conducted. Fractured tensile samples were gold-coated and examined under SEM at various magnifications. The micrographs provided insights into particle distribution, interfacial bonding, and potential failure mechanisms [22].

Results and discussion

Microstructural analysis of the fabricated composites

The micrograph analysis of the epoxy composite reinforced with 15 wt.% graphite (Figure 1) reveals a rough and porous fracture surface, indicative of weak interfacial bonding between the epoxy matrix and the graphite reinforcement. The presence of voids and particle agglomeration suggests that higher graphite content may have hindered proper dispersion, leading to stress concentrations and premature failure under mechanical loading (Wang, et al. 2021). The EDS also shows a high percentage of carbon, suggesting a significant contribution from the epoxy resin matrix, which is carbon-based. The relatively high sulfur content could be due to impurities in the graphite filler or the presence of additives used in the epoxy curing process. The presence of oxygen is associated with epoxy functional groups and possible oxidation on the graphite surface. The presence of oxygen, nitrogen, and sulfur suggests possible chemical interactions or impurities in the composite. The additional elements might result from processing or environmental exposure.

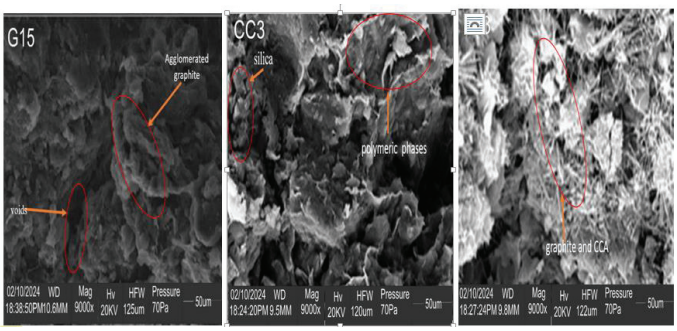

Figure 1: Scanning electron microscope of graphite (3%), (9%), and (15%) of epoxy reinforced composite.

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At lower reinforcement levels (3 wt.% and 9 wt.%), improved dispersion of graphite within the epoxy matrix is expected, promoting better stress transfer and load distribution [13]. However, excessive graphite content (15 wt.%) may introduce defects such as clustering and matrix discontinuities, ultimately reducing mechanical performance. Similar observations have been reported in previous studies on polymer-graphite composites [22] (Figure 2).

Properties analysis of the fabricated composites

Hardness of epoxy-graphite composites: The hardness values of epoxy reinforced with 3 wt.%, 6 wt.%, 9 wt.% 12 wt.% and 15wt.% of graphite is presented in Figure 3. The results indicate that hardness initially increases with graphite content, reaching a peak at 12 wt.%, before declining at higher reinforcement levels. This trend suggests that at lower concentrations, graphite acts as a reinforcing filler, enhancing the resistance of the epoxy matrix to localized plastic deformation. However, beyond an optimal concentration (above 12 wt.%), excessive graphite may lead to weak interfacial adhesion and increased porosity, reducing the overall hardness of the composite [13]. Similar findings have been observed in graphene and carbon-based polymer composites, where optimal filler dispersion plays a crucial role in hardness improvement [16].

Tensile strength of epoxy-graphite composites: Figure 4 presents the tensile strength values for epoxy composites with varying graphite content. The results show that the composite reinforced with 9wt.% graphite exhibits the highest tensile strength, while the strength decreases significantly as graphite content increases to 9wt.% and 15wt.%. The improved tensile strength at 9wt.% graphite loading can be attributed to efficient stress transfer between the epoxy matrix and graphite particles, leading to enhanced load-bearing capacity. However, at 9wt.% and 15wt.%, particle agglomeration, and poor interfacial adhesion introduce stress concentration sites, leading to premature failure [9]. The decrease in tensile strength at higher graphite concentrations aligns with previous studies on carbonaceous fillers in epoxy, where excessive filler content led to reduced mechanical performance due to poor dispersion [14].

Flexural strength of epoxy-graphite composites: The variation in flexural strength with increasing graphite content is shown in Figure 5. Similar to the trend observed in tensile strength, the composite with 9wt.% graphite exhibits the highest flexural strength, while further increases in graphite content lead to a decline. Flexural strength is highly dependent on the interfacial bonding between the matrix and the reinforcement. At 9wt.% graphite, the well-dispersed filler enhances the composite's ability to resist bending stresses. However, at higher graphite content, weak interfacial adhesion and increased void formation act as failure initiation points, reducing the flexural load-bearing capacity of the composite [1]. This behavior has also been reported in hybrid polymer composites, where excessive filler content compromises flexural properties [14].

Density of epoxy-graphite composites: Figure 6 presents the density values of epoxy-graphite composites. The results indicate a steady increase in density with increasing graphite content. This increase is expected, as graphite has a higher density compared to the epoxy matrix [16]. While higher density suggests a greater filler loading within the matrix, it does not necessarily correlate with improved mechanical performance.

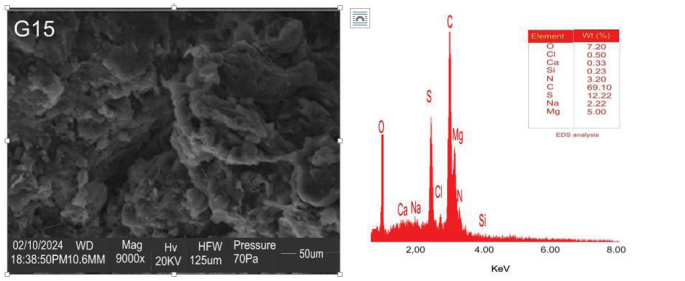

Figure 2: SEM/EDS of epoxy reinforced with graphite composite.

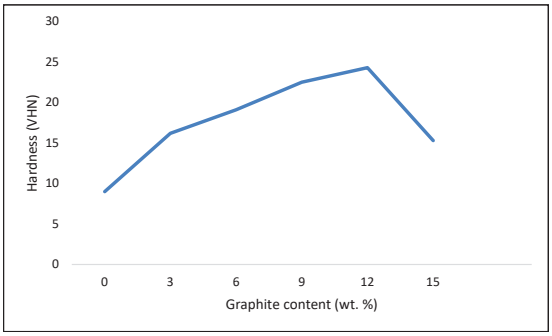

Figure 3: Hardness of Epoxy-Graphite Composites against the weight percentages.

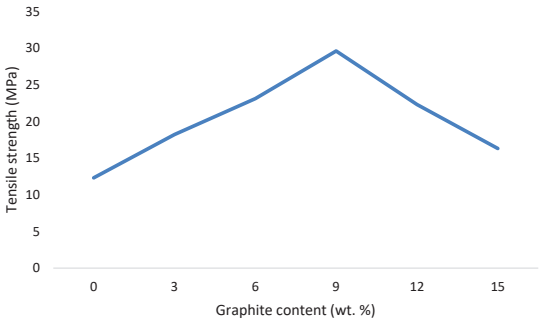

Figure 4: Flexural strength of epoxy-graphite composites against weight percentages.

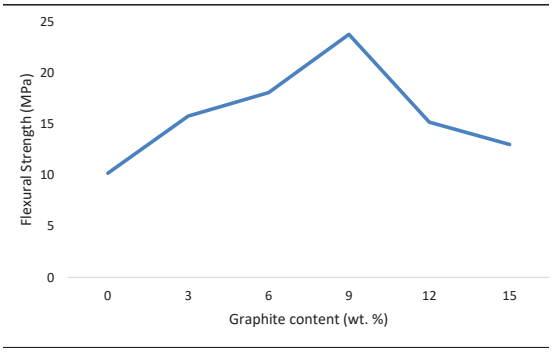

Figure 5: Flexural of epoxy-graphite composites against weight percentages.

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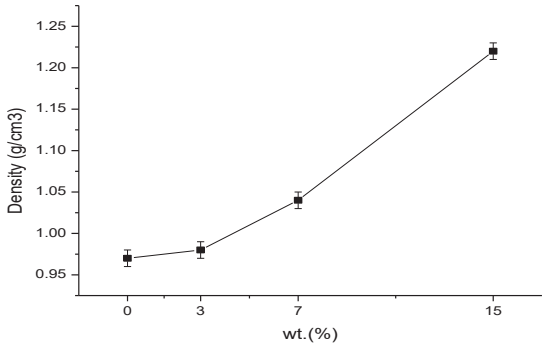

Figure 6: Density of epoxy reinforced with graphite composites against weight percentage.

As seen in the hardness, tensile strength, and flexural strength results, excessive graphite content negatively impacts the composite's mechanical integrity due to issues such as particle agglomeration and void formation [19].

Generally, the mechanical performance of epoxy-graphite composites is highly dependent on the dispersion and interfacial bonding of the reinforcement within the matrix. The results indicate that an optimal graphite content (around 3wt.%) leads to enhanced hardness, tensile strength, and flexural strength due to improved stress transfer and load-bearing capacity. However, beyond this threshold, mechanical properties deteriorate due to poor dispersion, weak interfacial adhesion, and void formation [13]. These findings align with previous studies on carbon-based polymer composites, emphasizing the importance of optimizing filler concentration to achieve a balance between mechanical performance and processability [22]. Future studies could focus on surface modification of graphite particles or hybrid reinforcement strategies to overcome the limitations associated with higher filler content.

Conclusion

This study investigated the mechanical properties and microstructural characteristics of epoxy-graphite composites with varying graphite content (3 wt.%, 7 wt.%, and 15 wt.%). The results demonstrate that graphite reinforcement significantly influences the hardness, tensile strength, flexural strength, and density of the composite, with the optimal performance observed at 7 wt.% graphite loading. The findings suggest that while graphite reinforcement enhances the mechanical properties of epoxy composites, there is an optimal filler concentration beyond which the benefits diminish due to poor dispersion and weak interfacial adhesion. Based on the results, 7 wt.% of graphite is the most effective composition for improving the performance of epoxy-graphite composites. These insights are valuable for developing advanced polymer composites for structural and industrial applications, where lightweight materials with enhanced mechanical properties are required.

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