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Improvement of Mechanical Properties of Graphene-Reinforced Carbon Fiber Composite Materials

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Abstract

In this study, graphene-reinforced epoxy matrix systems were developed to improve the mechanical performance of carbon fibre-reinforced composite materials. Graphene's superior mechanical, electrical, and thermal conductivity properties make it an effective reinforcement element for high-performance nanocomposite materials. Within the scope of the study, graphene nanosheets were homogeneously distributed into the epoxy resin using different hybrid methods such as ultrasonic, shear, and mechanical mixing. The resulting graphene-reinforced epoxy system was impregnated into carbon fibre fabrics to produce composite panels, which were subjected to tensile, compressive, and flexural tests. Experimental results revealed that homogeneous dispersion achieved through appropriate mixing methods led to significant improvements in the strength and stiffness properties of the composites. Additionally, a direct relationship was observed between graphene's interaction with the matrix, dispersion quality, and mechanical performance. This study is significant as it demonstrates the potential of combining nano-reinforcement and processing techniques to optimise mechanical properties in advanced composite material design.

Keywords: "Graphene nanoplatelets (GNPs), epoxy, carbon fiber reinforced polymer, composite, hybrid mixing, mechanical properties."

1. Introduction

In recent years, increasing requirements for lightweight and high mechanical strength in advanced engineering applications have significantly increased interest in carbon fiber reinforced polymer (CFRP) composite materials. They are widely used in a variety of applications such as aviation, automotive, wind energy, marine turbine blades and the sports sector [1-4]. In order to further enhance the mechanical properties of these materials, significant research is being conducted on the use of nano-reinforcements such as graphene. The potential of graphene to enhance the performance of composite materials is attributable to its distinctive properties, including a high specific surface area, superior mechanical strength, and excellent thermal and electrical conductivity [5-8]. In order to optimize the mechanical properties of polymer matrix composites, it is crucial that graphene is homogeneously dispersed and oriented within the matrix and that it forms a strong interfacial bond with the matrix. In this context, modifying the surface properties of graphene plays a critical role in improving both dispersion and interaction with the matrix. Hadden et al. [9] investigated the influence of graphene nanoplatelets (GNPs) on the mechanical behaviour of carbon fiber/epoxy hybrid composites using a combined experimental and multiscale modelling approach. Their results demonstrated that the dispersion quality and volume fraction of GNPs strongly affected the composite performance. Well-dispersed GNPs improved the matrix-dominated transverse mechanical properties by enhancing the stiffness of the epoxy matrix and promoting more efficient stress transfer at the fiber–matrix interface, whereas only minor changes were observed in the longitudinal properties dominated by the carbon fibers. The study highlighted homogeneous GNP dispersion as a key factor for effective reinforcement.

Besides graphene nanoplatelets, graphene oxide (GO) has also been investigated as an alternative graphene-based nanomaterial because of its oxygen-containing functional groups, which improve compatibility with epoxy matrices. Han et al. [10] fabricated carbon fiber/epoxy laminates using GO-modified epoxy resin and evaluated their interlaminar properties. The incorporation of 0.10 wt.% GO increased the interlaminar shear strength (ILSS) by approximately 8% and increased the glass

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transition temperature by about 5 °C. These improvements were attributed to enhanced fiber–matrix interfacial adhesion and the toughening effect of the GO-modified epoxy.

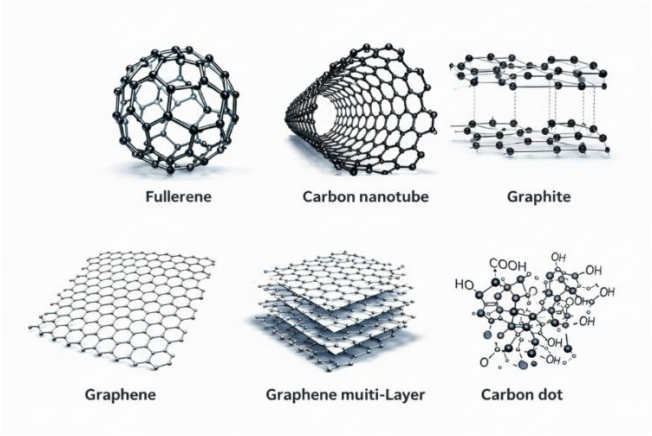


Fig. 1. Different structures of nano-carbon materials.

The importance of graphene dispersion techniques has been further demonstrated by Donda et al. [11], who investigated different mixing methods for preparing GNP-modified epoxy resins prior to manufacturing carbon fiber laminates. Ultrasonication significantly reduced nanoparticle agglomeration and improved the homogeneity of the epoxy nanocomposites, resulting in approximately 14% higher ultimate tensile strength and 46% greater elongation at break than conventionally mixed epoxy. However, although ultrasonication enhanced the mechanical performance of the epoxy nanocomposites, the corresponding carbon fiber laminates did not exhibit a similar improvement in tensile strength. The authors attributed this behaviour to the increased viscosity of the GNP-modified resin, which limited resin impregnation into the carbon fiber fabrics and promoted stress concentration. Rather than modifying the epoxy matrix, Srivastava et al. [12] strengthened the fiber–matrix interface by coating graphene nanoplatelets directly onto carbon fibers following desizing and surface oxidation treatments. Carbon fiber/epoxy laminates fabricated by vacuum-assisted resin transfer molding (VARTM) exhibited significantly improved flexural strength owing to enhanced interfacial bonding and more efficient load transfer. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) confirmed improved interfacial adhesion and revealed a modified fracture mechanism that delayed interfacial debonding. Hybrid carbon nanofillers have also been explored to exploit the complementary advantages of different nanomaterials. Yuksel et al. [13] investigated epoxy nanocomposites and carbon fiber-reinforced laminates containing hybrid graphene nanoplatelets (GNPs) and multi-walled carbon nanotubes (MWCNTs). Among the investigated formulations, a MWCNT:GNP ratio of 1:3 with a total nanofiller content of 0.3 wt.% produced the highest tensile strength. Moreover, hybrid nanofillers improved the tensile strength and tensile strain of CFRP laminates, while increasing the glass transition temperature from 87.25 °C to 114.67 °C, demonstrating their positive contribution to the thermo-mechanical performance of the composites. Namdev et al. [14] evaluated the influence of GNP loading on the mechanical and physical properties of carbon fiber/epoxy hybrid composites fabricated by the hand lay-up technique. Laminates containing 0.3, 0.5, and 0.7 wt.% GNP were subjected to tensile, flexural, interlaminar shear, impact, hardness, density, water absorption, and morphological analyses. The composite containing 0.5 wt.% GNP exhibited the best overall mechanical performance, with approximately 11% higher tensile strength and 18% higher flexural strength than the neat laminate. FE-SEM observations confirmed a more uniform nanoparticle distribution and lower void content at this GNP concentration, whereas higher GNP loading caused nanoparticle agglomeration and reduced the mechanical performance. In a subsequent study, Namdev et al. [15] further examined the influence of GNP concentration on the thermo-mechanical behaviour of carbon fiber/epoxy composites fabricated by hand lay-up followed by compression molding. The laminate containing 0.5 wt.% GNP again exhibited the optimum performance, showing the highest tensile strength, flexural strength, interlaminar shear strength, Vickers hardness, thermal conductivity, and heat deflection temperature. Conversely, the maximum impact strength was obtained at 0.25 wt.% GNP. Microstructural analyses performed using FE-SEM, EDX, XRD, and FTIR confirmed that improved nanoparticle dispersion and stronger fiber–matrix interactions were responsible for the enhanced composite performance. Shen et al. [16] further examined the influence of GNP concentration on the mechanical properties of epoxy and epoxy/carbon fiber composites fabricated by solvent-type prepreg processing followed by hot press molding. The neat epoxy nanocomposite containing 0.25 wt.% GNP exhibited the optimum performance, showing the highest ultimate tensile strength (66.00 MPa, a 20% increase) and flexural strength (115.46 MPa, a 9% increase) compared to the unfilled epoxy, while the flexural modulus continued to increase monotonically up to 1.5 wt.% GNP loading (a 19% increase). Conversely, both tensile and flexural strengths declined progressively beyond 0.5 wt.% GNP due to nanofiller agglomeration and void formation. For the carbon fiber-reinforced laminates, the same 0.25 wt.% GNP content increased the tension–tension fatigue life by 1.2 to 37.1 times relative to the neat laminate across all applied stress levels. Microstructural analyses performed using SEM confirmed that corrugation and crosslinking of GNPs within the matrix crevices restrained crack growth and improved fiber–matrix adhesion, whereas nonuniform dispersion and void formation at higher GNP contents were responsible for the degraded performance. Wang et al. [17] further examined the synergetic effect of GNP and multiwalled carbon nanotube (CNT) hybrids on the mechanical properties of epoxy and epoxy/carbon fiber composites fabricated using the same solvent-based prepreg and hot press process. At

a fixed hybrid loading of 1 wt.% in the epoxy nanocomposite, varying the CNT:GNP mixing ratio produced the optimum ultimate tensile strength and flexural properties, exceeding those of the neat epoxy and of composites containing either filler alone. For the carbon fiber-reinforced laminates, CNT/GNP hybrids added at 0.5, 1.0, and 1.5 wt.% likewise increased the ultimate tensile strength, flexural properties, and interlaminar shear strength (ILSS) relative to the neat laminates at all loading levels. The authors attributed this synergetic reinforcement to the CNTs entangling with and bridging the GNP interlayer gaps, which restrained crack initiation in the resin and further suppressed crack propagation within the composite laminates. Topkaya et al. [18] investigated the effect of graphene nanoparticle (GNP) reinforcement on the mechanical properties of glass fiber-reinforced polymer (GFRP), carbon fiber-reinforced polymer (CFRP), and aramid fiber-reinforced polymer (AFRP) composites fabricated using the hot-pressing method. GNP was incorporated into the composites at loadings of 0.1, 0.2, and 0.3 wt.% to produce hybrid laminates. The results showed that the addition of 0.2 wt.% GNP significantly improved the tensile strength and elastic modulus of GFRP and CFRP composites, whereas it slightly reduced the tensile strength of AFRP composites despite increasing their elastic modulus. SEM observations revealed complete fiber separation in GFRP and CFRP composites and their GNP-reinforced counterparts, while AFRP-based composites exhibited fiber deformation without complete fiber separation. Moreover, EDS analysis confirmed an increase in carbon content after GNP incorporation, indicating the successful integration of graphene nanoparticles into the composite structure. Prasanthi et al. [19] investigated the mechanical properties of carbon fiber-reinforced epoxy composites modified with carbon-based nanofillers, including multi-walled carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs), through experimental and numerical analyses. The incorporation of CNTs and GNPs significantly enhanced the tensile strength, flexural strength, impact resistance, thermal conductivity, and elastic modulus of the composites compared with neat CFRP laminates. The hybrid reinforcement of CNTs and GNPs exhibited a greater improvement in mechanical performance than the use of CNTs alone, demonstrating a synergistic reinforcement effect. Furthermore, scanning electron microscopy (SEM) was employed to characterize the fracture surfaces, while numerical simulations were performed to evaluate the tensile behavior and elastic constants, including transverse modulus and major and minor Poisson's ratios. The experimental and numerical results showed good agreement, confirming the effectiveness of carbon-based nanofiller reinforcement for improving the mechanical performance of CFRP composites. Gupta et al. [20] investigated the effects of graphene nanoplatelet (GNP) incorporation on the electrical, mechanical, and viscoelastic properties of carbon fiber-reinforced epoxy (CF/epoxy) composites. GNPs were incorporated into the epoxy matrix at concentrations of 0.1, 0.2, 0.3, and 0.4 wt.%. The results demonstrated that the surface electrical conductivity increased approximately eightfold, reaching 2.32 S/m at 0.4 wt.% GNP. The mechanical properties were significantly enhanced with increasing GNP content up to 0.3 wt.%, where the composites exhibited a maximum tensile strength of 1008 MPa, flexural strength of 952 MPa, and impact strength of 13 J/cm². However, further increasing the GNP content to 0.4 wt.% resulted in a deterioration of the mechanical performance due to fiber–matrix debonding. Dynamic mechanical analysis (DMA) further revealed improvements in the storage modulus and loss modulus at 0.1 wt.% GNP loading, whereas higher GNP concentrations adversely affected the composite behavior because of the non-uniform dispersion and increased agglomeration of GNPs.

Although previous studies have demonstrated that graphene nanoplatelets can effectively improve the mechanical performance of carbon fiber/epoxy composites, the reported results vary considerably depending on the graphene dispersion technique, processing route, and manufacturing method. In particular, a systematic comparison of different graphene mixing techniques under identical processing conditions remains limited in the literature. Therefore, the present study aims to investigate the influence of different hybrid mixing techniques, including ultrasonic, shear, and mechanical mixing, on the dispersion of graphene within an epoxy matrix and the resulting mechanical performance of carbon fiber-reinforced composite laminates. Graphene-modified epoxy systems were combined with carbon fiber fabrics to fabricate composite laminates, and tensile, compression, and flexural tests were conducted to evaluate the effects of graphene addition and mixing methods. The findings provide further insight into the relationship between graphene dispersion quality, fiber–matrix interaction, and the mechanical performance of carbon fiber/epoxy composites.

2. Fabrication of Graphene-Reinforced Carbon Fibre/Epoxy Composites

2.1. Materials

In this study, graphene nanoplatelets (GNP's) with a purity of 99.9%, an approximate thickness of 5 nm, a specific surface area of 135 m^2/g, and a particle diameter of 7 µm were used. Nanografi Chemicals Türkiye supplied the GNPs. As the composite matrix material, epoxy resin coded AKANA-A 11546 from CET Composite and Epoxy Technology (Türkiye) was utilized. This resin has a density of 1.1–1.2 g/cm³ and a viscosity range of 1200–1400 MPa·s. The curing agent AKANA-B 1346 was mixed with the epoxy at a weight ratio of 100:34. The hardener has a density of 0.94–0.95 g/cm³ and a viscosity of 10–20 MPa·s at 25 °C. In the preparation of the mixture, 99% pure acetone was used as a solvent, and Triton-X 100 was chosen as a surfactant to reduce surface tension and improve dispersion. Epoxy systems were modified with GNP at concentrations of 0.25%, 0.5%, and 1% to prepare samples with different reinforcement levels. The prepared graphene-reinforced epoxy mixtures were impregnated onto the surface of carbon fibre fabrics. During the impregnation process, the mixture was spread manually with a brush onto the fabric layers, taking care to ensure even distribution between each layer. A multi-layered arrangement was applied to achieve the desired thickness of the composite structure, after which the samples were placed in a mould and subjected to curing under a

specific pressure. This ensured that the graphene-reinforced resin penetrated the fibre structure, resulting in a homogeneous composite structure.

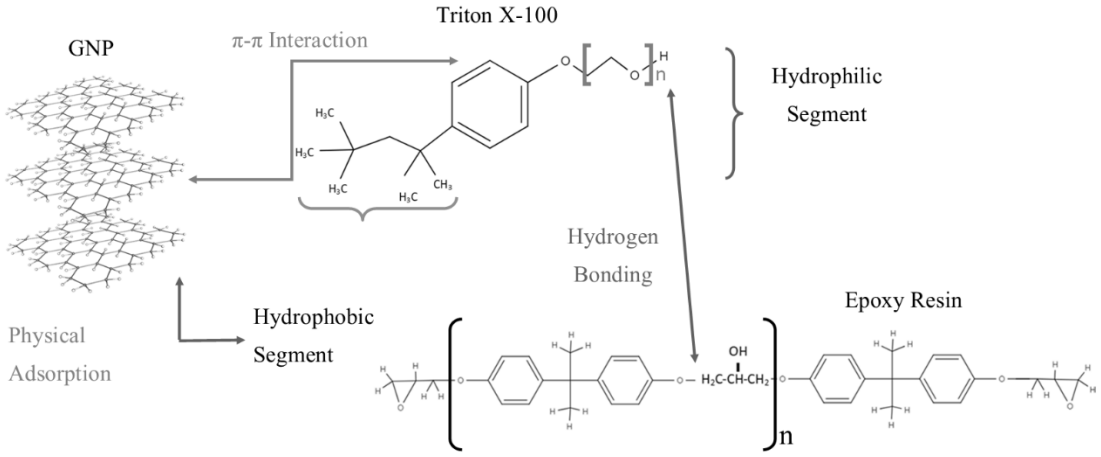


Fig. 2. Schematic of the effect of Triton X-100 molecule in GNP/epoxy nanocomposites [2]

In order to improve the dispersion of graphene nanoplatelets (GNPs) within the epoxy matrix, a non-ionic surfactant, Triton X-100, was incorporated into the formulation. This surfactant functions by reducing surface tension between the GNPs and the surrounding resin, promoting better wettability and distribution of graphene sheets. The molecular interaction mechanism of Triton X-100 in the nanocomposite system is illustrated in Fig. 2, where the surfactant is shown to encapsulate GNP surfaces, thereby preventing agglomeration and enhancing interfacial bonding with the matrix.

2.2. Hybrid-Mixing-Based Fabrication of Epoxy

In this study, the mixture containing 0.25% graphene was first dispersed in acetone at a ratio of 1:50. The dispersion process was carried out for 30 minutes using ultrasonic mixing at a power of 40 W. This sonication protocol was applied to effectively exfoliate the graphene layers and disperse them homogeneously in the solution. This minimised the agglomeration of graphene particles. To control temperature increases during the process, the sonication vessel was placed in a container filled with ice, thereby preventing thermal degradation that could occur during high-energy processes.Following the initial sonication stage, epoxy resin (with a hardener at a weight ratio of 100:34) and Triton-X-100 surfactant (at a ratio of 1:15) were added to the mixture, and sonication was applied for an additional 30 minutes under the same conditions. This step is critical for ensuring that the functional graphene is homogeneously distributed in the resin matrix and that the nanocomposite structure can acquire the desired properties.After sonication, the mixture was stirred with a shear mixer at 5,000 rpm for 30 minutes. It was then heated at 85 °C and 900 rpm using a magnetic stirrer. The purpose of this step is to accelerate the evaporation of acetone from the solution while maintaining the dispersion of graphene. The weight of the mixture was measured at regular intervals until the acetone was completely evaporated, confirming that the solvent was completely removed.After the solvent removal process was completed, 34 units of hardener by weight were added to the mixture, and mechanical stirring was performed for 5 minutes to ensure good chemical mixing of the components. The resulting mixture was then degassed in a vacuum oven for 10 minutes to remove trapped air bubbles and prevent void formation in the final composite. The mixture was then poured into moulds and degassed a second time under vacuum for 5 minutes. In the final stage, the samples were cured in an oven at 120°C for 2 hours to harden them.The same production process was repeated for samples containing 0.5% and 1% graphene. Fig. 3 shows a schematic representation of the preparation process for GNP-reinforced epoxy resin.

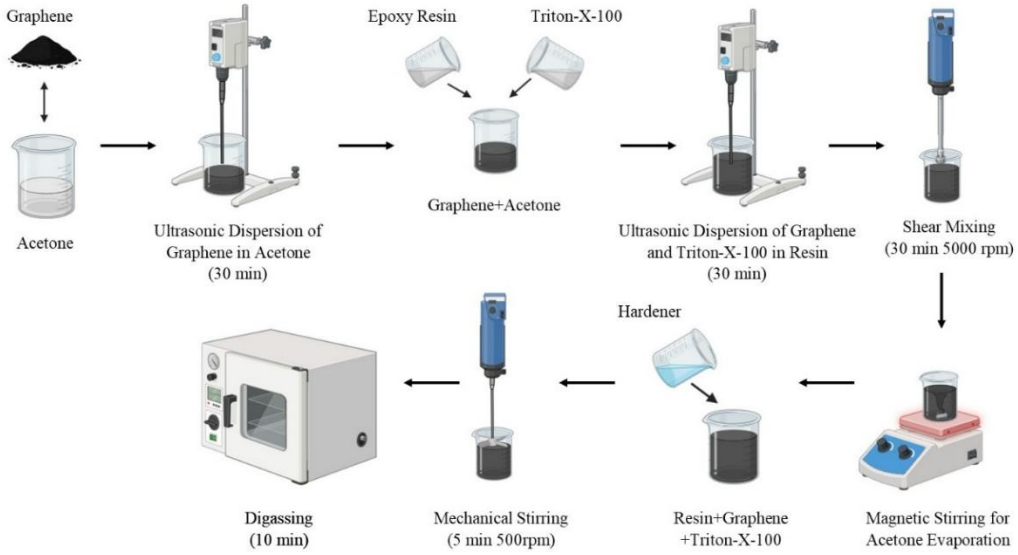


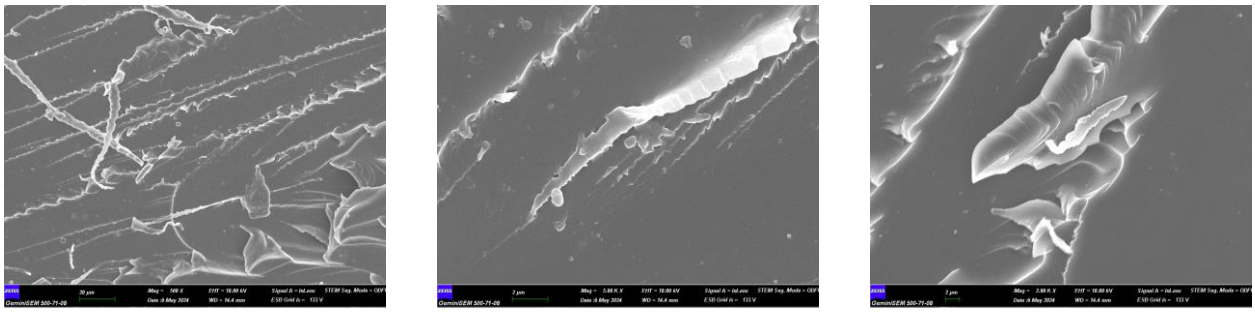
Fig. 3. Fabrication method of epoxy resin reinforced graphene nanoplatelet.

The preparation of GNP-reinforced epoxy resin involved a multi-stage hybrid mixing protocol, combining ultrasonic dispersion, shear mixing, magnetic stirring, and mechanical mixing. This combination ensured efficient exfoliation of graphene nanoplatelets, homogeneous distribution, and solvent removal. A schematic representation of the step-by-step fabrication process of the GNP/epoxy nanocomposite system is presented in Fig. 3, illustrating each critical step from initial dispersion in acetone to final degassing and curing stages. Following the preparation of the graphene-reinforced epoxy system, the resin was manually applied to layers of carbon fiber fabric to produce composite laminates. The impregnated fabric layers were then subjected to pressing and thermal curing to ensure consolidation and matrix infiltration. Fig. 4 illustrates the overall fabrication process of the GNP-reinforced carbon fiber/epoxy composite, including resin application, mold setup, vacuum-assisted degassing, and oven curing. This schematic highlights the integration of nanomodified resin into a fiber-reinforced composite structure to obtain a homogeneous and mechanically robust material.

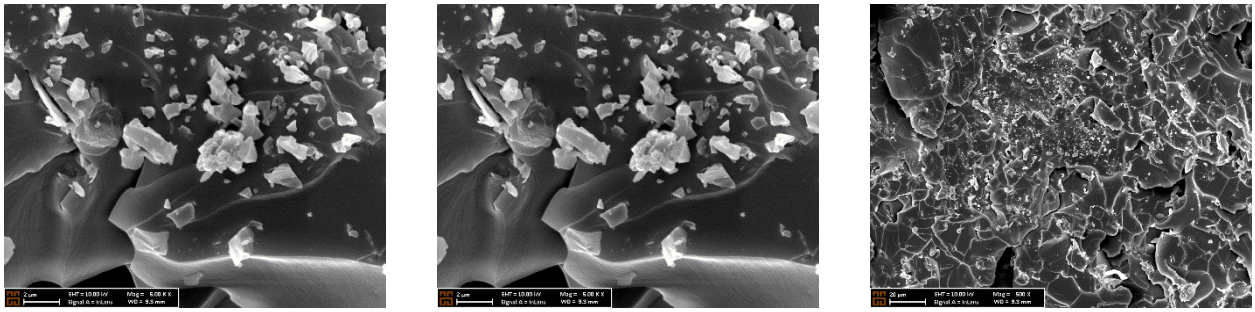
Fig. 4. Fabrication of carbon fiber/epoxy composite reinforced GNP.

3. Results

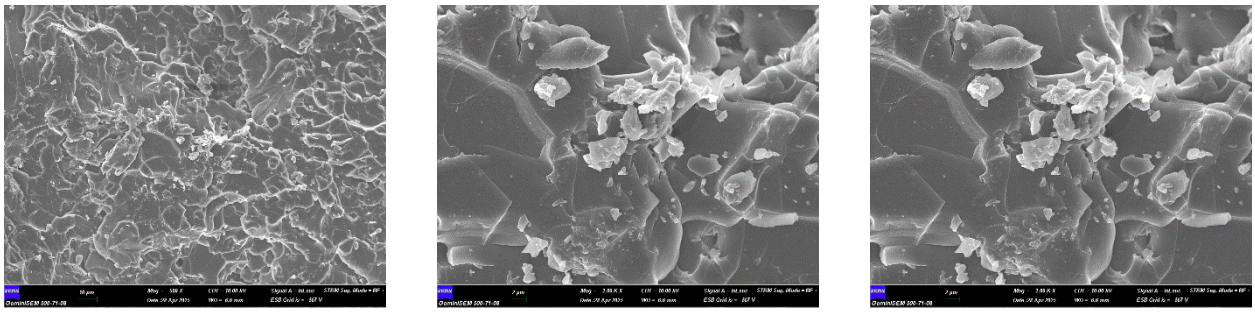
In this study, graphene nanoplatelet (GNP)-reinforced carbon fiber/epoxy composite materials were fabricated using a hybrid mixing strategy involving ultrasonic, shear, magnetic, and mechanical dispersion techniques. GNPs were incorporated into the epoxy resin at different weight fractions (0.25%, 0.5%, and 1%) to investigate the effect of reinforcement concentration on the mechanical performance. The nanomodified epoxy systems were subsequently used to impregnate carbon fiber fabrics, resulting in multilayered composite laminates. Mechanical characterization including tensile, compression, and flexural tests was conducted to evaluate the influence of graphene addition and mixing methodology on composite strength and stiffness.



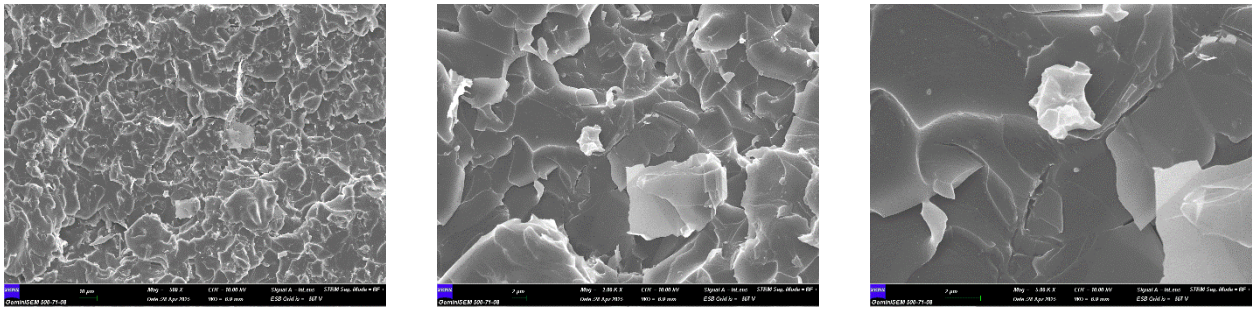
(a) Neat epoxy;



(b)%0.25 Graphene



(c)%0.5 Graphene



(d)%1 Graphene

Fig. 5. SEM images of the fracture surfaces of pure epoxy and graphene-reinforced epoxy composite specimens with different graphene contents: (a) neat epoxy, (b) 0.25 wt.% graphene, (c) 0.5 wt.% graphene, and (d) 1 wt.% graphene.

Additionally, SEM analyses were performed to examine the dispersion quality and interfacial morphology of the composites. The following section presents the experimental results along with discussions on the observed trends and performance enhancements.

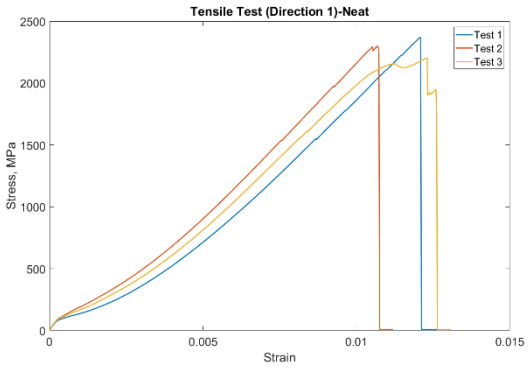
With the addition of graphene (Fig. 5 b–d), pronounced changes are observed in the fracture surface morphology. In the specimens containing 0.25 wt.% graphene, the graphene sheets are homogeneously dispersed within the resin matrix, and the fracture surface exhibits a rougher and more irregular morphology. This increased surface roughness supports the crack-hindering effect of graphene reinforcement, such as crack deflection and crack pinning mechanisms.

In samples containing 0.5% G (Fig. 5.1c), it was observed that the graphene layers were effectively bonded to the matrix and that charge transfer occurred more homogeneously. In these samples, nucleated microstructure regions and multidirectional crack orientations indicate an increase in energy absorption capacity. In contrast, in the system containing 1 wt.% graphene (Fig. 5.1d), partial agglomeration of graphene sheets is detected, leading to the formation of voids within the matrix in certain regions. These agglomerates induce local stress concentrations, thereby partially increasing the brittle behavior of the material.

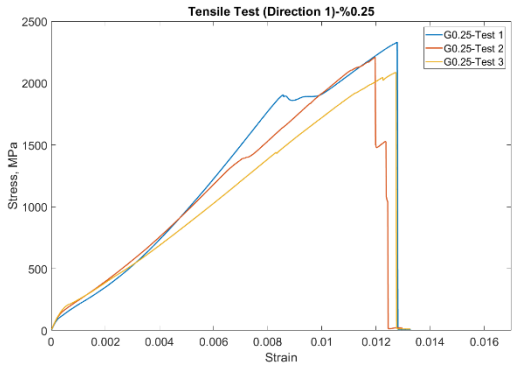
Fig. 6 presents the stress–strain curves obtained from tensile tests of the composite specimens manufactured along the fiber direction. All specimens exhibit an initial linear elastic region at the onset of deformation, representing the elastic modulus of the material. Beyond the elastic region, a more pronounced yield-like transition region is observed, particularly in the graphene-reinforced specimens. In the neat epoxy composites (Fig. 6a), the stress–strain curve exhibits a sharp fracture behavior. This response originates from the brittle nature of the epoxy matrix and is characterized by a sudden load drop at the moment of failure.

For the 0.25 wt.% graphene-reinforced composites (Fig. 6b), a noticeable increase in the maximum stress value is observed. This improvement can be attributed to the ability of graphene sheets to facilitate load transfer within the epoxy matrix and to hinder crack propagation. Moreover, the expansion of the nonlinear region of the curve indicates an enhancement in the ductility (toughness) of the material.

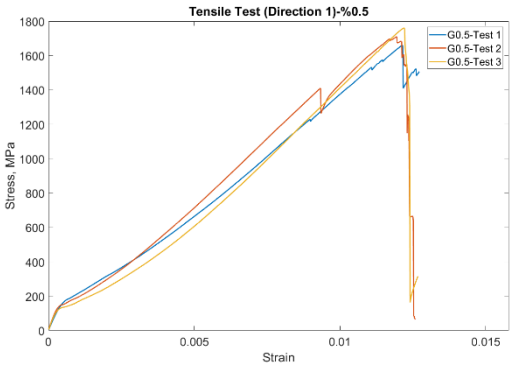
In the composites containing 0.5 wt.% graphene (Fig. 6c), the elastic modulus and the pre-yield deformation capacity reach their highest levels. This graphene content is considered the optimum region where the fiber–matrix interface is most effectively strengthened. This observation is also consistent with the homogeneous dispersion detected in the SEM analyses.



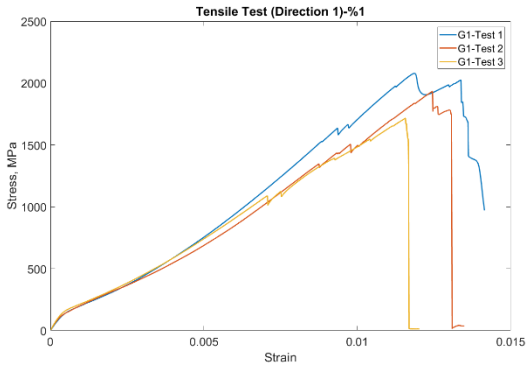
(a) Neat epoxy composite



(b) %0.25-Graphene



(c) %0.5- Graphene



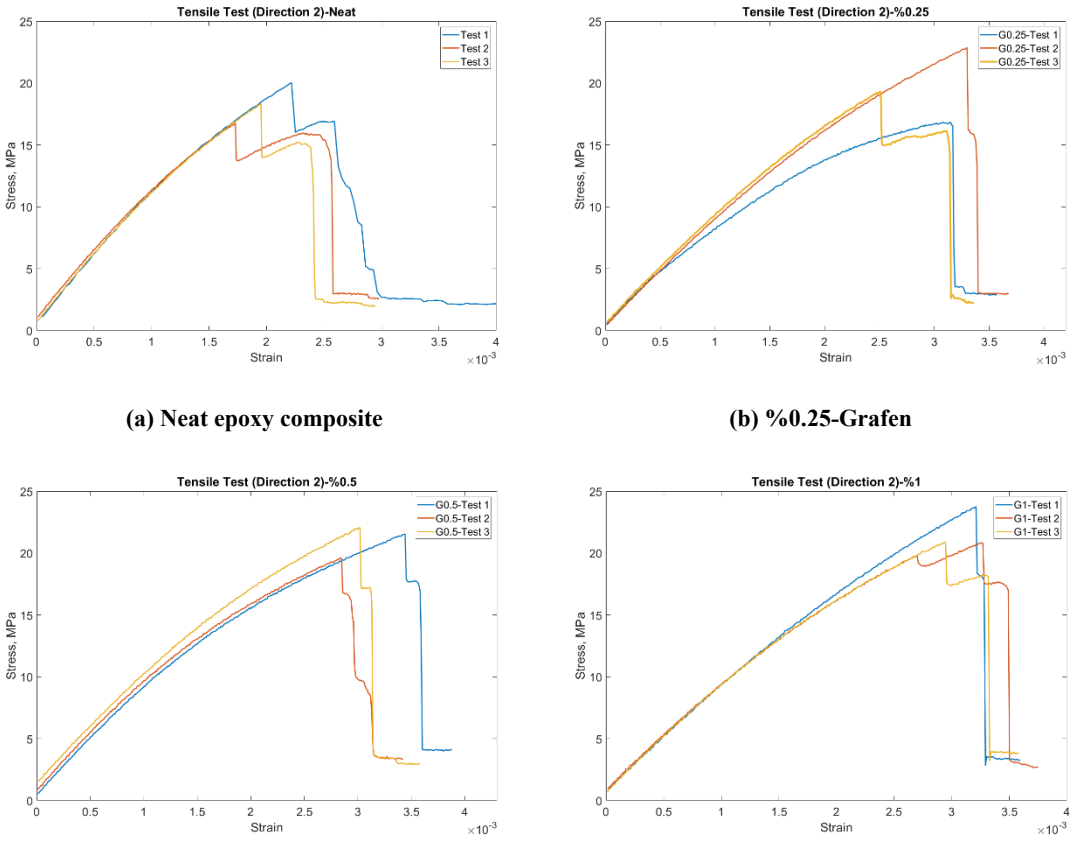
(d) %1- Graphene

Fig. 6. Stress–strain curves obtained from tensile tests conducted along the fiber direction (1-direction): (a) neat epoxy composite; (b) 0.25 wt.% graphene-reinforced composite; (c) 0.5 wt.% graphene-reinforced composite and (d) 1 wt.% graphene-reinforced composite.

In the composites containing 1 wt.% graphene (Fig. 6.d), a tendency toward brittle behavior is again observed in the stress–strain curves, accompanied by a reduction in both the maximum stress value and the strain capacity. This behavior can be explained by the formation of agglomerated graphene particles at higher graphene contents, which lead to local stress concentrations. The overall trend indicates that beyond a certain graphene content, the homogeneous dispersion is lost, leading to a weakening of the matrix integrity. Therefore, the mechanical enhancement effect of graphene reinforcement is effective only at low concentrations where an adequate and uniform dispersion is achieved.

Tensile tests performed in the direction perpendicular to the fiber orientation are of great importance in revealing the influence of the matrix phase and the fiber–matrix interface on the mechanical behavior of the composite material. In these tests, the load is applied transverse to the fibers, and the load-carrying capacity of the material is largely governed by the epoxy matrix and the quality of the interfacial bonding. Fig. 7 presents the stress–strain curves obtained from tensile tests performed perpendicular to the fiber direction. All specimens exhibit an initial linear elastic region, followed by nonlinear deformation and sudden fracture behavior. Compared to the tests conducted parallel to the fiber direction, the maximum stress levels are noticeably lower. This indicates that, in this loading direction where the load-carrying contribution of the fibers is limited, the mechanical response is predominantly matrix-controlled.

In the neat epoxy composites (Fig. 7a), the stress–strain curves display a sudden and brittle fracture behavior with a limited deformation capacity. The very limited plastic deformation prior to fracture is associated with the inherently brittle nature of the epoxy matrix. For the composites reinforced with 0.25 wt.% graphene (Fig. 7b), a slight increase in the maximum tensile stress compared to neat epoxy is observed, along with a more stable deformation process. It is considered that the low graphene content partially delays crack propagation within the matrix and improves interfacial bonding. In the specimens containing 0.5 wt.% graphene (Fig. 7c), the maximum stress levels are similar to those of the 0.25 wt.% graphene-reinforced composites. However, fluctuations observed in some curves prior to fracture are noteworthy. This behavior is attributed to local stress concentrations within the matrix and the non-uniform dispersion of graphene sheets.



(a) Neat epoxy composite **(b) %0.25-Grafen**

(c) %0.5-Grafen **(d) %1-Grafen**

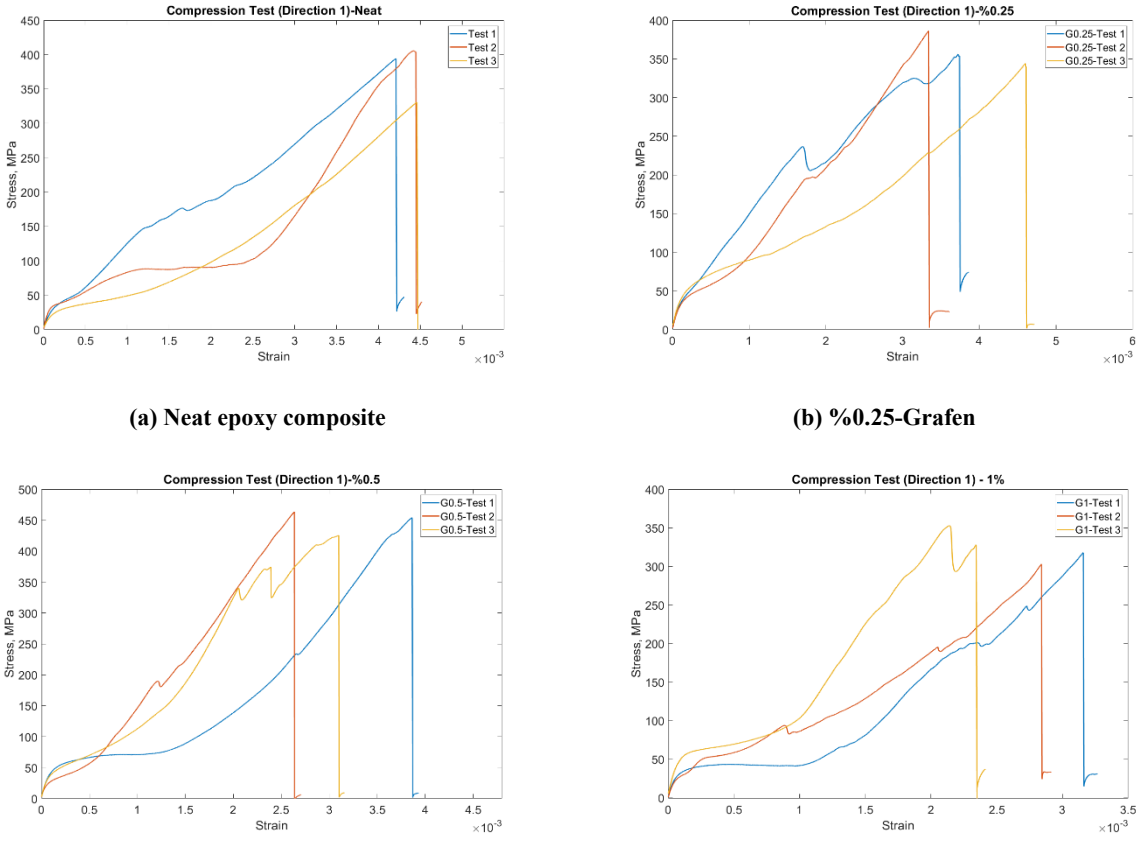
Fig. 7. Stress–strain curves obtained from tensile tests conducted perpendicular to the fiber direction (2-direction): (a) neat epoxy composite; (b) 0.25 wt.% graphene-reinforced composite; (c) 0.5 wt.% graphene-reinforced composite and (d) 1 wt.% graphene-reinforced composite.

For the composites containing 1 wt.% graphene (Fig. 7d.), the stress–strain curves exhibit a more irregular character, and fracture occurs abruptly. At higher graphene contents, the formation of agglomerated regions is considered to introduce discontinuities at the fiber–matrix interface, thereby adversely affecting the load-carrying capacity of the material.

Fig. 8. presents the stress–strain curves obtained from compression tests performed along the fiber direction. For all specimens, an initial linear elastic region is observed at the onset of loading, followed by nonlinear deformation and sudden load drops. The fluctuations seen in the curves are associated with micro-buckling of the fibers and localized crushing of the matrix under compressive loading. In the neat epoxy composite (Fig. 8a), the increase in compressive stress occurs in a relatively stable

manner, and failure takes place with a sudden load drop. This behavior indicates that the fibers are sufficiently supported by the matrix; however, once the critical load level is exceeded, structural stability is rapidly lost.

In the specimens reinforced with 0.25 wt.% graphene (Fig. 8b), an increase in the maximum compressive stress is observed, and the deformation process progresses in a more gradual manner. This behavior suggests that the low graphene content enhances matrix stiffness, delays fiber buckling, and improves the load-carrying capacity. Moreover, the increased interaction at the fiber–matrix interface reflects the influence of localized stress distributions within the matrix on the compressive response. For the composites containing 0.5 wt.% graphene (Fig. 8c), the highest compressive stress values are achieved. However, pronounced fluctuations are evident in the stress–strain curves, indicating intermittent micro-instabilities during deformation. In contrast, the specimens containing 1 wt.% graphene (Fig. 8d) exhibit a reduction in maximum compressive stress along with a more irregular deformation behavior prior to failure. At higher graphene contents, the formation of agglomerated regions is considered to introduce discontinuities within the matrix, adversely affecting fiber stability under compressive loading.



(a) Neat epoxy composite **(b) %0.25-Grafen**

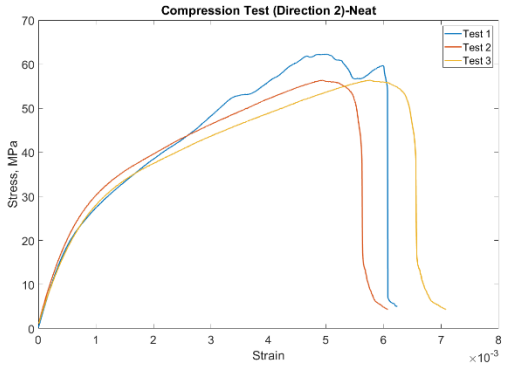
(c) %0.5-Grafen **(d) %1-Grafen**

Fig. 8. Stress–strain curves obtained from compression tests conducted along the fiber direction (1-direction): (a) neat epoxy composite; (b) 0.25 wt.% graphene-reinforced composite; (c) 0.5 wt.% graphene-reinforced composite and (d) 1 wt.% graphene-reinforced composite.

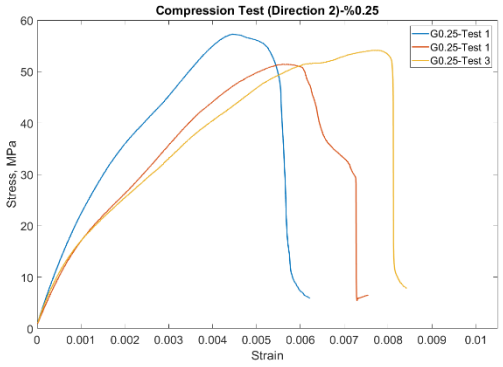
Fig. 9 presents the stress–strain curves obtained from compression tests performed perpendicular to the fiber direction. This testing configuration represents a loading condition in which the compressive behavior of the composite material is predominantly matrix-dominated, while the load-carrying contribution of the fibers remains limited. In the neat epoxy composite, (Fig. 9a) the compressive stress initially increases with a relatively smooth slope, followed by a sudden loss of load-carrying capacity after reaching the maximum stress. This behavior indicates rapid propagation of matrix cracks and effective fiber–matrix interfacial debonding under transverse compressive loading. For the specimens containing 0.25 wt.% graphene, (Fig. 9b) a limited increase in the maximum compressive stress is observed compared to the neat epoxy composite. The increased slope of the elastic region suggests that graphene partially stiffens the matrix, delays damage initiation, and provides a more stable deformation process under compression. However, the abrupt drop in load-carrying capacity after failure indicates that the fracture mechanism remains predominantly brittle in nature.

In the composites reinforced with 0.5 wt.% graphene, (Fig. 9c) the maximum compressive stress and strain capacity exhibit a more balanced distribution compared to the other graphene contents. This behavior is attributed to a more homogeneous dispersion of graphene within the matrix, which contributes to delaying crack propagation and enhancing deformation resistance under compressive loading. In the composites reinforced with 0.5 wt.% graphene, (Fig. 9d) the maximum compressive stress and strain capacity exhibit a more balanced distribution compared to the other graphene contents. This behavior is attributed to a

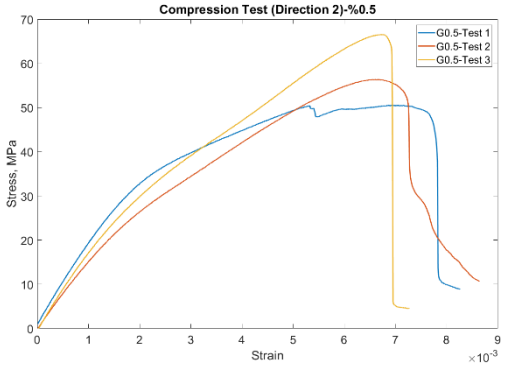
more homogeneous dispersion of graphene within the matrix, which contributes to delaying crack propagation and enhancing deformation resistance under compressive loading. In contrast, the specimens containing 1 wt.% graphene (Fig. 9d) show an increase in maximum compressive stress in some cases; however, significant scatter among the stress–strain curves is observed. This behavior can be associated with the increased tendency for graphene agglomeration at higher contents, leading to local stress concentrations. As a result, localized damage is initiated at earlier stages under compressive loads, adversely affecting the overall mechanical stability of the composite.



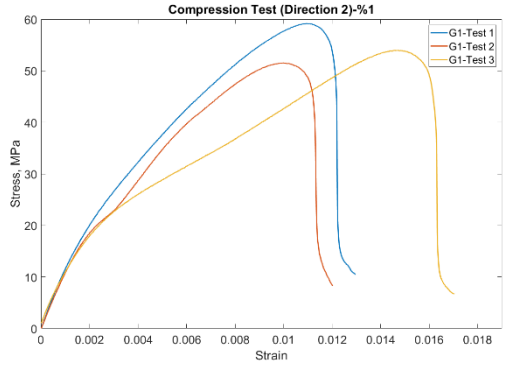
(a) Neat epoxy composite



(b) %0.25-Grafen



(c) %0.5-Grafen



(d) %1-Grafen

Fig. 9. Stress–strain curves obtained from compression tests conducted perpendicular to the fiber direction: (a) neat epoxy composite; (b) 0.25 wt.% graphene-reinforced composite; (c) 0.5 wt.% graphene-reinforced composite and (d) 1 wt.% graphene-reinforced composite.

4. Conclusion

In this thesis, the tensile, compressive, and flexural behaviors of graphene-reinforced carbon fiber/epoxy composites were experimentally investigated both along the fiber direction (Direction 1) and perpendicular to the fiber direction (Direction 2). The obtained results indicate that the incorporation of graphene exerts a nonlinear and direction-dependent influence on the mechanical performance of the composites.

In the tensile tests conducted along the fiber direction, the neat epoxy matrix composites exhibited the highest average tensile strength. While a limited change in tensile strength was observed with the addition of 0.25 wt.% graphene, a pronounced reduction occurred at graphene contents of 0.5 wt.% and 1 wt.%. This behavior can be attributed to the increased tendency for graphene sheet agglomeration at higher contents, leading to disruption of the epoxy matrix continuity. Since the load-bearing mechanism in the fiber direction is predominantly governed by the carbon fibers, the contribution of graphene reinforcement in this direction is considered to be limited.

In contrast, the effect of graphene reinforcement became more pronounced in the tensile tests performed perpendicular to the fiber direction. In particular, increases in the average maximum tensile stress were observed at graphene contents of 0.5 wt.% and 1 wt.%. This improvement can be explained by the ability of graphene to restrict microcrack propagation within the epoxy matrix and to enhance stress transfer at the fiber–matrix interface. However, a general decreasing trend in elastic modulus values was observed with increasing graphene content. This behavior is associated with the increased matrix brittleness and the difficulty in achieving homogeneous graphene dispersion at higher loadings.

In the compression tests conducted along the fiber direction, the composites reinforced with 0.5 wt.% graphene exhibited the highest average compressive strength. While the neat epoxy and 0.25 wt.% graphene-reinforced specimens showed lower compressive strengths, a significant reduction was observed at a graphene content of 1 wt.%. This response under compressive loading can be attributed to interfacial weakening and the earlier activation of local buckling mechanisms at higher graphene contents.

For compression tests performed perpendicular to the fiber direction, the influence of graphene addition on compressive strength was found to be more limited. Although no pronounced differences were observed among the average maximum compressive stress values, graphene reinforcement was found to affect the deformation behavior. The reduction in elastic modulus with increasing graphene content indicates the adverse effects of graphene agglomeration under matrix-dominated loading conditions.

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