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Investigation of mechanical properties of nano-graphene reinforced polymer composites

Nano-grafen takviyeli polimer kompozitlerin mekanik özelliklerinin incelenmesi

Onur Kazım ATEŞ[1], Filiz KARABUDAK*[1], Hamid ZAMANLOU[2]

[1]*Gümüşhane Üniversitesi, Mühendislik ve Doğa Bilimleri Fakültesi, Makine Mühendisliği Bölümü, 29100, Gümüşhane*

[2]*Atatürk Üniversitesi, Mühendislik Fakültesi, Makine Mühendisliği Bölümü, 25000, Erzurum*

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Abstract

The demand for lightweight and durable materials in industries such as automotive, aerospace, and chemical engineering has driven research into advanced composite materials. This study investigates the interaction between nano-graphene and polymer matrices, focusing on how varying concentrations of nano-graphene can optimize mechanical properties and potentially revolutionize the design of structural components. Polymer composite materials were produced using glass fiber fabric and an epoxy resin system employing the hand lay-up method. Nano-graphene was incorporated into the matrix at weight percentages of 0.2%, 0.4%, 0.6%, 0.8%, and 1%.Notably, the addition of 1% nano-graphene resulted in a significant tensile strength increase, achieving a maximum value of 186.73 MPa, compared to the control group at 53.71 MPa. This enhancement is attributed to the improved stress transfer mechanisms facilitated by the nano-graphene's high surface area and exceptional mechanical properties. However, an unexpected decrease in bending strength was observed, with the glass fiber control group composites exhibiting the highest bending strength of 404.75 MPa. This trend suggests that while nano-graphene enhances tensile properties, it may introduce interfacial weaknesses or disrupt fiber alignment in bending scenarios. These findings reveal the complex nature of nano-graphene reinforcement, emphasizing the need for tailored formulations to balance tensile and bending performance. Further investigation into the interfacial bonding and distribution of nano-graphene within the polymer matrix is warranted to develop optimized composite materials for structural applications.

Keywords: Bending, Nano-graphene, Polymer Composite, Tensile

Öz

Otomotiv, havacılık ve kimya mühendisliği gibi sektörlerde hafif ve dayanıklı malzemelere olan talep, araştırmaları ileri kompozit malzemelere yönlendirmiştir. Bu çalışma, nano-grafen ve polimer matrisler arasındaki etkileşimi araştırarak, değişen nano-grafen konsantrasyonlarının mekanik özellikleri nasıl optimize edebileceğine ve yapısal bileşenlerin tasarımında potansiyel olarak devrim yaratabileceğine odaklanıyor. Polimer kompozit malzemeler, cam elyaf kumaş ve epoksi reçine sistemi ile elle yatırma yöntemi kullanılarak üretildi. Nano-grafen matrise %0,2, %0,4, %0,6, %0,8 ve %1 ağırlık yüzdelerinde dahil edildi. Özellikle %1 nano-grafen ilavesi, 53,71 MPa'lık kontrol grubuyla karşılaştırıldığında maksimum 186,73 MPa değerine ulaşarak önemli bir çekme mukavemeti artışıyla sonuçlandı. Bu gelişme, nano-grafenin yüksek yüzey alanı ve olağanüstü mekanik özelliklerinin kolaylaştırdığı gelişmiş stres transfer mekanizmalarına bağlanıyor. Ancak cam elyaf kontrol grubu kompozitlerinin en yüksek bükülme mukavemetini 404,75 MPa ile sergilemesiyle bükülme mukavemetinde beklenmedik bir azalma gözlendi. Bu eğilim, nano-grafenin gerilme özelliklerini artırırken, arayüzey zayıflıkları oluşturabileceğini veya bükme senaryolarında fiber hizalamasını bozabileceğini öne sürüyor. Bu bulgular, nano-grafen takviyesinin karmaşık doğasını ortaya koyuyor ve çekme ve bükülme performansını dengelemek için özel formülasyonlara duyulan ihtiyacı vurguluyor. Yapısal uygulamalar için optimize edilmiş kompozit malzemelerin geliştirilmesi için nano-grafenin polimer matris içindeki arayüzey bağlanması ve dağılımına ilişkin daha fazla araştırma yapılması garanti edilmektedir.

Anahtar kelimeler: *Eğme, Nano-grafen, Polimer kompozit, Çekme*

*Filiz KARABUDAK; filizkarabudak@gumushane.edu.tr

1. Introduction

High-performance polymer composite materials that have lower weight compared to metallic materials; It is widely used as a structural material in engineering applications under working conditions in the automotive, aerospace and chemical industries (Bhong et al., 2023). To ensure economic efficiency and safety, low specific gravity, unique mechanical and tribological properties, and high resistance to degradation are required (Bello et al., 2015). Nano- or micro-sized inorganic particles added homogeneously to the polymer matrix contribute to the production of light and durable composite materials (Ray & Easteal, 2007).

Composite materials are materials created by combining two or more different materials, each of which preserves its own properties and works together to gain new and superior properties (Erdogdu, 2020).

Composite materials consist of two main components: reinforcement material and matrix material. The reinforcement material is a material with high tensile strength that increases the strength, stiffness and flexibility of the composite. The matrix material is the material that holds the reinforcement material together, distributes the load evenly and enables the shaping of the composite (Khakzad, 2017).

The key advantages of composite materials include high strength, low density, hardness, resistance to abrasion, efficient heat transfer, corrosion resistance, electrical conductivity, flexibility, and impact resistance (Adem & Uyaner, 2019).

Fiber materials such as glass, carbon, aramid and natural fibersfiber are generally used as reinforcement materials of composite materials. Fiber materials have properties such as high strength, low density, high flexibility and high thermal conductivity. The sizes of fiber materials can be classified as micro, nano and macro. Nano-sized fiber materials are called nanofibers. Nanofibers are fiber materials with a diameter of less than 100 nm (Murat et al. 2022, Akcan, 2023).

There are various studies in the literature in which different amounts of carbon nanotubes and nano-graphene particles are added to the matrix material to increase the durability of composite materials.

Graphene's unique 2D honeycomb lattice structure not only makes it the thinnest and strongest material in the universe (up to 100 times stronger than steel), but also gives it many excellent chemical and physical properties, such as high levels of flexibility (Li et al., 2016).

In Muharrem (2019) study; microstructure, hardness and wear were used to determine the mechanical properties of Al 2024 composites produced at different rates (0.5%-1.0%-2.0%-4.0%) reinforced with carbon nanotube (CNT) and nano graphene (G) made the analyses. In addition, machinability experiments were carried out with a cutting speed of 200 m/min, feed rates of 0.10 - 0.15 and 0.30 mm/rev and depth of cut of 1.0 mm. During the machining experiments, surface roughness was measured and the wear conditions of the cutting tools were examined under a microscope. According to the test results, the most appropriate values of nano material ratios in composites were determined. The study concluded that nanomaterial addition improved the hardness, wear and machinability properties of composites, but as the amount of nanomaterial increased, the surface roughness of the composites also increased.

İlhan & Feyzullahoglu (2019) investigated in their study how different natural fibers and fillers affect the properties of FRP composite materials. They concluded that the addition of natural fibers and fillers improves the properties of FRP composites, but can also have negative effects in some cases.

Aswathnarayan et al., (2020) investigated in their study how nano graphene affects the mechanical properties of glass-epoxy composites. In the study, pure epoxy and glass-epoxy composites containing 1% and 2% nano graphene were compared. These materials were prepared by the vacuum bag method. Mechanical performances were measured with tensile, bending and impact tests. Additionally, their crystal structures were analyzed by X-ray diffraction. As a result, nano-graphene additives significantly improved the mechanical behavior of glass-epoxy composites. It was concluded that this development is related to the homogeneous distribution of nano graphene and its good bonding with the glass fabric. This has made nanocomposites more durable. SEM images confirmed the compatibility between nano graphene and glass fabric.

Mishra et al., (2020) In their study, they investigated how glass/epoxy polymer composites can be improved with graphene. The research has shown that graphene is a nano-sized carbon material and shows wonderful properties such as high strength and flexibility. In his study, mechanical tests were carried out by adding 0%, 1%, 2% and 3% graphene to glass fiber epoxy composites. The tests were performed with two different layer layouts [(0/90)12s and (0/90/±45)6s]. It was applied on prepared glass/epoxy nano composite sheets. As a result of the test, it was observed that graphene-added composites provided a significant improvement in tensile, bending and impact strengths compared to composites without graphene. Additionally, it was found that the highest value of mechanical properties was reached with the addition of 2% graphene for both layer arrangements. Additionally, it was observed that the (0/90/±45)6s layer layout performed better than the (0/90)12s layer layout. His research has revealed that graphene is an effective nanofiller for glass fiber epoxy composites and may play an important role in the development of polymer composites.

Murat et al., (2022) experimentally investigated the mechanical properties and buckling behavior of E-glass fiber reinforced polymer composites by reinforcing them with Al2O3 and TiO2 nanoparticles. For this purpose, three types of pure, e-glass fiber reinforced composite plates with 2% Al2O3 addition and 2% TiO2 addition were prepared by vacuum-assisted resin infusion technique. The buckling behavior of the produced composite plates was determined by a four-point bending test. In addition, the hardness and tensile properties of the composite plates were measured. The article concluded that nanoparticle additive increases the buckling load, hardness and tensile strength of composite plates, but reduces the residual strength after buckling.

Seeli et al., (2023) focused on the mechanical and thermal behavior of E-glass fiber reinforced composites and prepared composites reinforced with nanographene and an E-glass layer at different weight ratios using mechanical mixing and hand-laying techniques. Nanocomposites have three different formulations: 1%, 2% and 3% by weight of nanomaterials. Mechanical parameters of nanocomposites such as bending strength, tensile strength, TGA, DTA, DSC and hardness were tested and the effect of nanofillers was compared. As a result, the results showed that nanographene (NG) composites are an effective method to increase mechanical performance, compared to plain E-glass composites, were obtained by experimentally examining the values of 1, 2 and 3% by weight of nanographene in the E-glass fabric reinforced composite. It was also found that the mechanical and thermal properties of nanographene decreased with the addition of nanomaterial after reaching the optimum weight ratio.

Recent studies have explored various aspects of nano-graphene reinforced composites:
Kumar et al. (2021) studied the effect of nano-graphene on the mechanical and thermal properties of epoxy-based composites. They found that adding 0.5% to 1% nano-graphene improved tensile strength and thermal conductivity, attributing this to the effective load transfer and thermal path networks created by the graphene.

Zhang et al. (2022) examined the impact resistance of carbon fiber composites with nano-graphene reinforcement. Their research demonstrated that the addition of 1% by weight nano-graphene enhanced the impact strength by 15%, primarily due to the graphene's ability to dissipate energy and prevent crack propagation.

Jiang et al. (2023) investigated hybrid composites containing both carbon nanotubes (CNTs) and nano-graphene. Their findings revealed that a combination of these nanomaterials resulted in synergistic effects, leading to improvements in tensile strength, modulus, and fracture toughness compared to using either reinforcement alone.

Zhao et al. (2020) focused on the electrical and mechanical properties of glass fiber/epoxy composites enhanced with nano-graphene. They reported a significant increase in tensile strength (by 25%) and electrical conductivity, suggesting that nano-graphene could be a promising additive for multifunctional composite materials.

Kumar & Kaur (2021) explored the fatigue behavior of nano-graphene reinforced epoxy composites and observed that the fatigue life of the composites increased by 30% with the incorporation of 0.75% nano-graphene. They attributed this to the improved crack-bridging and load-bearing capacity of the nano-graphene particles.

These studies illustrate the diverse benefits of incorporating nano-graphene into composite materials, such as improved mechanical properties, enhanced thermal and electrical performance, and increased durability under various loading conditions.

In line with the literature research reviewed; It is seen that the durability of composite materials varies depending on the type and amount of nanoparticle powders.

The aim of this study is to investigate the effect of nano-graphene reinforcement at varying weight percentages (0.2%, 0.4%, 0.6%, 0.8%, and 1%) on the mechanical properties of glass fiber polymer composites, using tensile and three-point bending tests. The study seeks to understand how the addition of nano-graphene particles influences the tensile strength and bending strength of the composites, offering insights into the optimization of nano-reinforced polymer composites for engineering applications.

The novelty of this study lies in its detailed analysis of the mechanical behavior of glass fiber composites reinforced with nano-graphene particles at different concentrations. Unlike previous studies, this research provides a comprehensive comparison of tensile and bending properties, revealing a contrasting behavior—where tensile strength increases, and bending strength decreases with higher concentrations of nano-graphene. This unexpected behavior contributes to the broader understanding of the interactions between nano-reinforcements and polymer matrices, particularly in the context of mechanical performance under different loading conditions.

2. Materials and methods

2.1. Composite plate production

In this study, nano-particle reinforced glass fiber composite sheets were prepared with the hand lay-up technique, as seen in Figure 1. Hexion Epikote Resin MGSLR 635\Hexion Epikure Curing Agent MGH LH 635 epoxy hardener polymeric system (Tila Kompozit, Türkiye) was chosen as the matrix material. Spherical nano-graphene powders (Nanografi, Türkiye) of different amounts, 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight, were used as nanoparticle reinforcers (Table 1).

Figure 1. a) Preparation of nano-graphene particle reinforced resin/hardener polymeric system, b) brushing process and fiber laying

Table 1. Technical properties of the nanoparticles

Additive material	Grain size(nm)	Purity (%)	Diameter	Colour
Graphene powder	3 nm	99	1.5 µm	Black

To prepare 6-layer sheets, 6 pieces of 300gr/m² woven glass fiber fabric was cut into equal sizes with a cutting tool. The epoxy/hardener matrix material was obtained by mixing 70/30 by weight for 1 minute at room temperature. Then, in order to prevent agglomeration and obtain a homogeneous mixture, nano graphene powders were added to the epoxy hardener mixture we prepared by stirring in a 3000-rpm magnetic stirrer for 5 minutes, and the mixing process continued until a homogeneous mixture was obtained. Then, a transparent non-stick nylon fabric was placed on the marble plate. The nanoparticle reinforced epoxy resin mixture was first spread evenly on the nylon with a brush, and then it was reapplied with 1 piece of glass and 1 piece of glass fiber fabric resin in the determined proportions between nano graphene powders and 1 piece of glass fiber fabric, respectively, to prepare a total of 6-layer sheets. After brushing and fabric placement, the boards were covered with fireproof nylon. The boards were placed on a hard object to remove air bubbles and excess resin and were left to dry. This process; a total of 6 groups of reinforced polymer composite sheets were produced by repeating separately for the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% nano-graphene added glass fibers by weight. After the drying process was completed, as shown in Figure 1, the sheets were cleaned of resin residues and burrs.

2.2. Creating test samples

In this study, tensile test samples were cut in 25x250 mm dimensions according to ASTM D 3039/D standard (ASTM, 2008) and three-point bending test samples were cut in 12.7x125 mm dimensions in accordance with ASTM D790 standard (ASTM, 1997) by water jet cutting method (Figure 2). After the samples were cut, they were wiped clean with a dry, clean cloth. The thickness of each sample was measured to be approximately 3 ± 0.2 mm. After the samples were cut, they were arranged by wiping them with a dry, clean cloth.

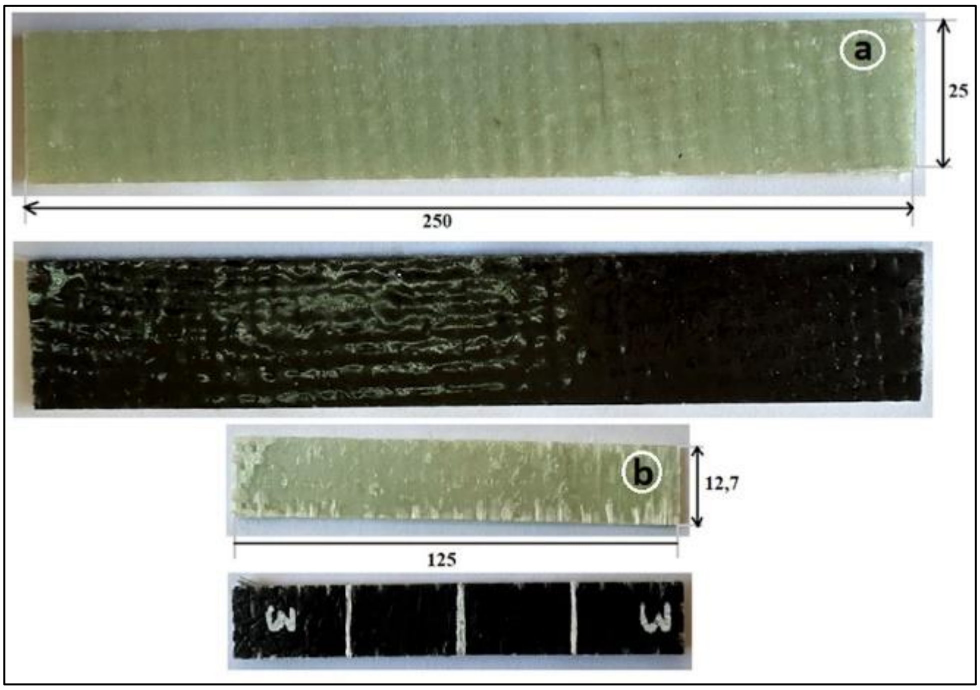

Figure 2. Cutting and classification of composite plates a) tensile b) three-point bending (dimensions in mm)

2.2.1. Tensile and three-point bending bending testing devices

In this study, tensile samples were tested with a Besmak Bmt 200es model testing machine with 12-480 bar hydraulic pressure and ± 20 kN tensile strength, at room temperature and 2 mm/min tensile speed. Bending tests were carried out at room temperature with a Shimadzu AGS-X universal testing device at a bending speed of 1 mm/min (Figure 3).

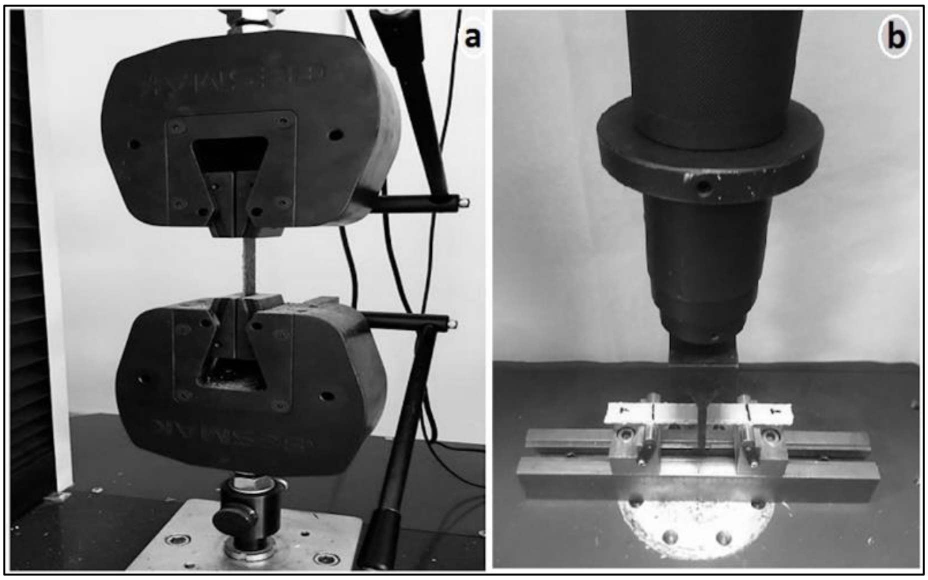

Figure 3. a) Tensile and b) bending testing devices

3. Results and discussion

The control group and composites reinforced with 0.2%, 0.4%, 0.6%, 0.8%, and 1% by weight of graphene nanoparticles were subjected to tensile and three-point bending tests. At least 6 samples of the same dimensions were produced from each plate group for tensile and bending tests.

3.1. Tensile test

Figure 4. Damage images of tensile test samples of a) control group and b) 0.2%, c) 0.4%, d) 0.6%, e) 0.8% and f) 1% graphene nano-particle reinforced composites by weight

Figure 4 shows the damage mechanisms seen in the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight graphene nanoparticle reinforced polymer composite under tensile load. It is observed that there are matrix and fiber fractures in all six groups. Fiber grooves, which are predicted to occur by the separation of epoxy and fiber in line with the literature, indicate a sawtooth damage mechanism (Hu & Zhang, 2004; Gao et al., 2022; Fan et al., 2024).

Saw teeth are damage mechanisms that occur perpendicular to the fiber direction and are one of the most important fractographic features seen in composites (Brockmann & Salviato, 2023; Abdullah et al., 2024).

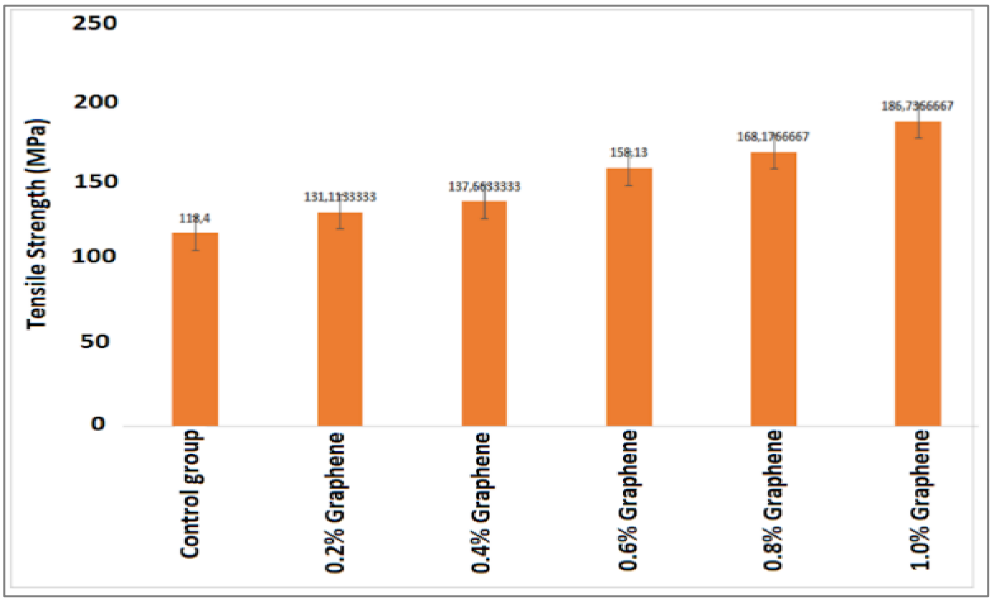

Figure 5. Average tensile strengths of the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight graphene nano-particle reinforced composites

The average tensile strengths of the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight graphene nanoparticle reinforced composites are given in Figure 5. According to this; The average tensile strengths of the control group, 0.2%, 0.4%, 0.6%, 0.8% and 1% Graphene nanoparticle reinforced composites were determined as 118.4, 131.11, 137.66, 158.13, 168.17, and 186.73 MPa, respectively. The highest contribution to tensile strength occurred in 1 wt% Graphene nanoparticle reinforced composites, as predicted.
When evaluated compared to the control group, there was an increase of 10.98%, 16.52%, 33.84%, 42.03% and 57.71%, respectively, in 0.2%, 0.4%, 0.6%, 0.8% and 1% Graphene Nanoparticle reinforced composites, and as the weight amount of graphene nanoparticle reinforcement increased, the tensile strength of the composites increased. A significant increase in strength was observed.

Representative tensile stress and displacement curves of these samples are shown in Figure 6.

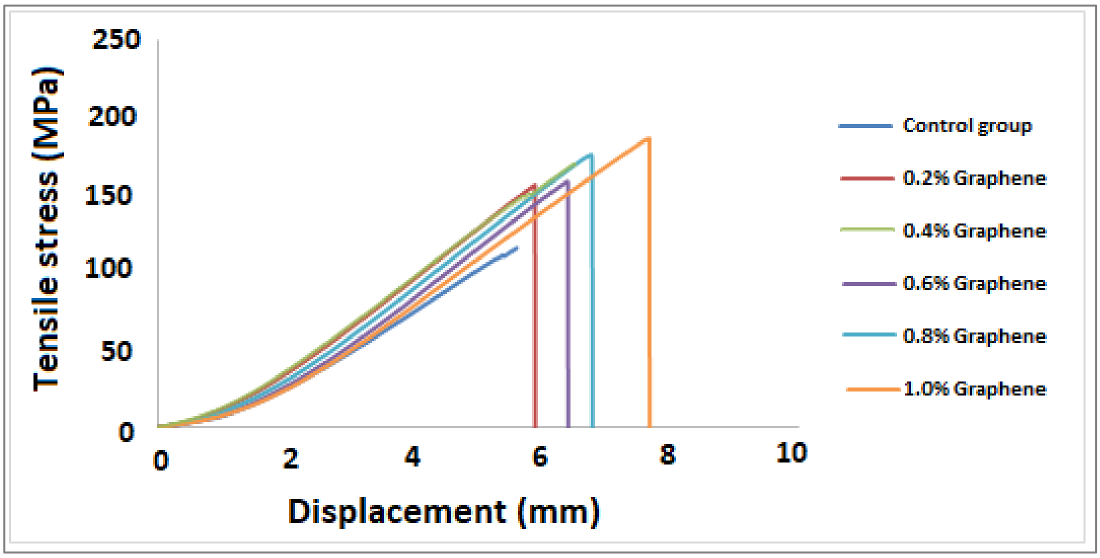

Figure 6. Tensile stress/Displacement diagram of control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight Graphene Nanoparticle reinforced composites

3.2. Three-point bending test

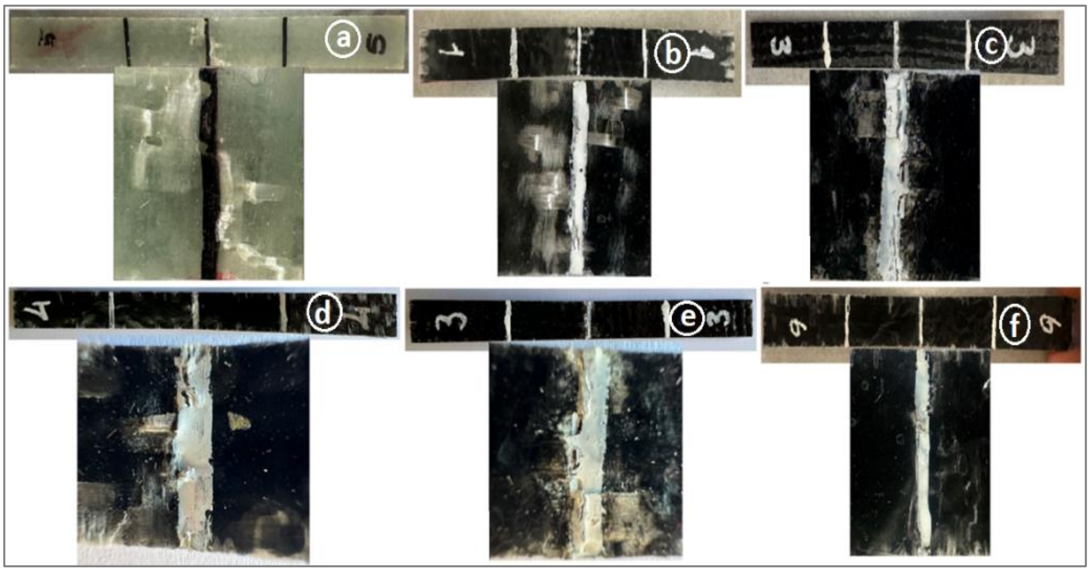

Figure 7. Damage images of bending test samples of a) Control group and b) 0.2%, c) 0.4%, d) 0.6%, e) 0.8% and f) 1% Graphene Nanoparticle reinforced composites by weight

Figure 7 shows the damage mechanisms seen in the polymer composite with graphene nanoparticle addition at different weight ratios under bending load. In all 6 groups, including the control group, plate integrity was lost as a result of sudden breakage after carrying some more load with the breakage of the matrix at the middle interface. Under the stresses occurring in all plates, first the upper layer and then the lower layer broke.

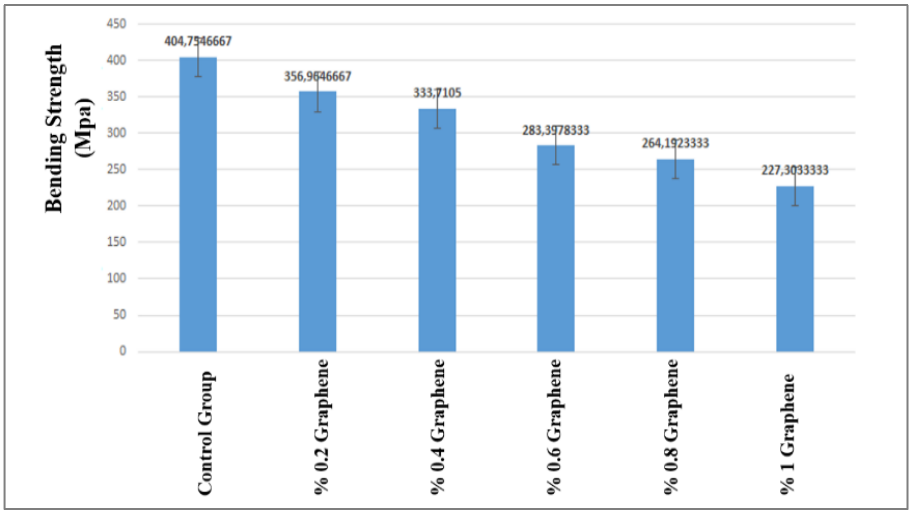

Figure 8. Average bending strengths of the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight Graphene Nanoparticle reinforced composites

The average flexural modul of graphene nanoparticle reinforced composites are shown in Figure 8. According to this; The average bending strengths of the control group 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight Graphene Nanoparticle reinforced composites were found to be 404.75, 356.96, 333.71, 283.39, 264.19 and 227.30 MPa, respectively.

It should be noted that different amounts of graphene nanoparticle reinforcement resulted in a significant decrease in the average bending strength of the composites. In this context; When evaluated compared to the control group, there was a decrease of 11.80%, 17.55%, 29.98%, 34.72% and 43.84%, respectively, in 0.2%, 0.4%, 0.6%, 0.8% and 1% Graphene Nanoparticle reinforced composites. As the weight amount of graphene nanoparticle reinforcement increased, the bending strength of the composites decreased, contrary to expectations (Seeli, 2023). In their study, they concluded that the bending strength decreased with nano graphene reinforcement to glass fiber. They explained this by saying that Nano-graphene's huge surface area, atomic structure and lack of functionality are likely responsible for this phenomenon. Representative force and displacement curves of these samples are shown in Figure 9.

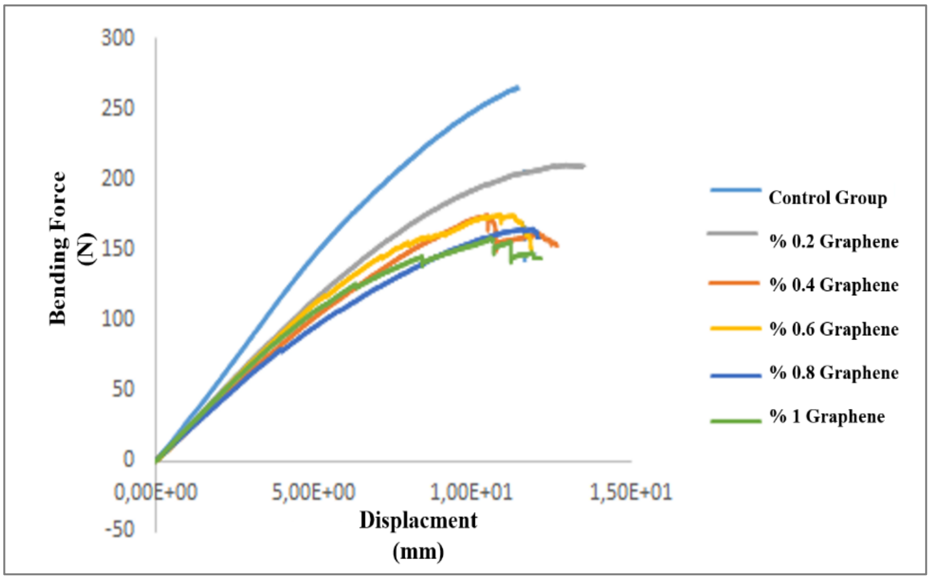

Figure 9. Bending Force/Displacement diagram of the control group and 0.2%, 0.4%, 0.6%, 0.8% and 1% by weight Graphene Nanoparticle reinforced composites

This study investigated the effect of nano-graphene reinforcement on the mechanical properties of glass fiber polymer composites. Nano-graphene particles were added at varying weight percentages (0.2%, 0.4%, 0.6%, 0.8%, and 1%) to analyze changes in tensile and bending strengths. The tensile test results showed a significant enhancement in tensile strength with increasing concentrations of nano-graphene. The composites with 1% nano-graphene exhibited the highest tensile strength of 186.73 MPa, a 57.71% improvement compared to the control group (118.4 MPa). Each increase in the concentration of nano-graphene led to a proportional increase in tensile strength, indicating a strong reinforcing effect.

Conversely, the three-point bending test revealed an unexpected trend where the bending strength decreased with higher nano-graphene content. The highest bending strength was observed in the control group (404.75 MPa), while the composites with 1% nano-graphene showed the lowest strength (227.30 MPa), marking a 43.84% decrease. This decline suggests that the addition of nano-graphene may have impacted the integrity of the composite under bending stress, leading to early failure.

The contrasting behaviors observed in tensile and bending tests underscore the complexity of interactions between nano-reinforcements and polymer matrices. While nano-graphene significantly improves tensile properties by enhancing load transfer and crack resistance, its influence on bending performance may be attributed to changes in the stress distribution and potential microstructural weaknesses. Future studies could explore optimizing the dispersion and bonding of nano-graphene within the matrix to mitigate the decline in bending strength, enabling more effective use of nano-reinforcements in composite materials.

4. Conclusions

The following results were obtained based on the tensile and 3-point bending test values of 0.2%, 0.4%, 0.6%, 0.8% and 1% Graphene Nanoparticle reinforced composites by weight:

The maximum enhancement in tensile strength was seen in composites with 1% by weight graphene reinforcement, achieving 186.73 MPa—an increase of 53.71% compared to the control group.

In the bending test, unlike the tensile test, the highest increase was observed in the glass fiber control group composites at 404.75 MPa. It has been shown that bending strength decreases with increasing weight percentage of nano-graphene reinforcement.

According to the findings of the tensile test damage images, interlayer separation (delamination) along with matrix and fiber fractures were observed in all plate types.

When the three-point bending test damage images findings were evaluated, plate integrity was lost as a result of sudden fracture after carrying some more load with the breakage of the matrix in the middle interface in all 6 groups, including the control group.

As a result, it has been determined that graphene reinforcement at different weight ratios causes a significant increase in tensile strength but a decrease in bending strength, in parallel with the increase in weight.

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Author contribution

FK: supervision, article administration, and resources. FK and OKA; methodology and writing-original draft preparation. OKA and HZ; writing, reviewing, and editing.

Declaration of ethical code

The authors declare that all of the rules stated to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" were followed, and none of the actions specified under the title of "Actions Contrary to Scientific Research and Publication Ethics" have been carried out.

Conflicts of interest

The authors declare that they have no conflict of interest.

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