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Enhancement of E-glass fiber/epoxy composite bending performance via graphene addition

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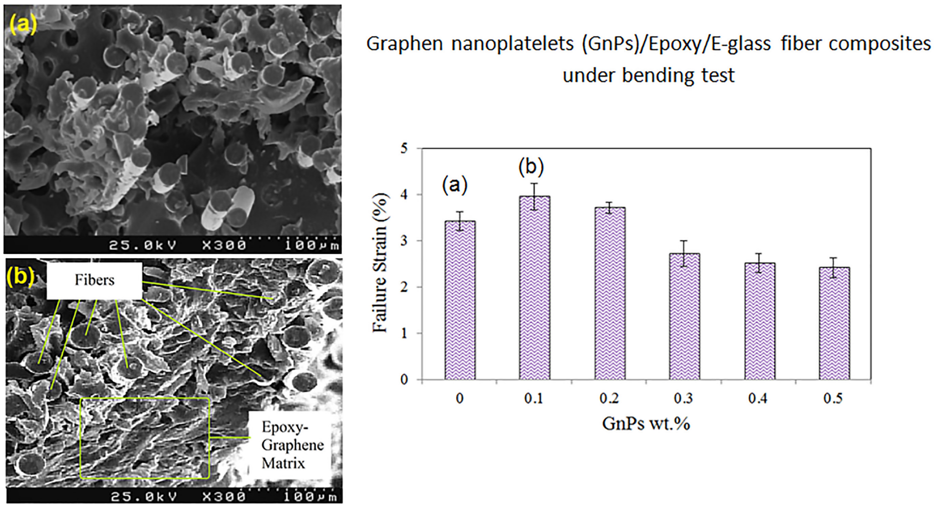
HIGHLIGHTS

- The bending performance of graphene/E-glass fiber/epoxy composites was studied.
- Maximum increases in flexural strength and modulus were observed for the composite containing 0.4 wt% graphene.
- The maximum flexural failure strain was obtained with the incorporation of 0.1 wt% graphene.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an experimental investigation using graphene nanoplatelets (GnPs) to enhance the bending performance of E-glass fiber/epoxy composites. Each specimen was prepared with two layers of E-glass chopped strand mat via the hand lay-up technique and using various contents of GnPs in the matrix (0.1, 0.2, 0.3, 0.4 and 0.5 wt%). Mechanical and ultrasonic stirring methods were employed to disperse the GnPs in the matrix. The obtained results demonstrated that the highest increases of 23% and 26% in the flexural strength and modulus, respectively, were observed for the composite containing 0.4 wt% GnPs. With the incorporation of 0.1 wt% GnPs, the flexural failure strain of the composite was enhanced by 16% compared to the control composite. The evaluation of the fractured surfaces clearly demonstrated that the interface between the glass fiber and polymeric matrix was improved when GnPs were added into the matrix.

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1. Introduction

Nowadays, the demand for fibrous composites with a very high specific strength is growing. These composites have other highly desirable properties such as high durability, damping properties, good corrosion resistance, and high impact properties. This broad range of properties has led to the wide application of composite materials in military, construction, aerospace, automotive, and marine industries [1,2].

Most recently, many efforts have been made to prepare polymer-matrix nanocomposites containing nanoclay [3], carbon nanotubes (CNTs) [4], carbon nanofibers (CNFs) [5], graphene [6], silica [7], alumina [8], zirconia [9], etc. Among these, graphene nanoplatelets are considered a good choice to reinforce the polymers due to its extremely high rigidity, large specific surface area (approximately 2630 $m^2.g^{-1}$), and two-dimensional structure [10,11]. The use of graphene nanoplatelets in the manufacture of multiscale composites has recently received much attention [12-16]. These types of composites are produced by dispersing nanofillers in the matrix or placing them on the surface of the fibers. In general, multiscale composites have better properties than un-reinforced fibrous composites. Recent researches have demonstrated that graphene nanoplatelets had a positive effect on the mechanical properties of fibrous composites. The bending performance of a basalt fiber reinforced graphene/epoxy composite was explored by Jamali *et al.* [12]. In another work, Jamali *et al.* reported that the wear resistance of the basalt fiber/epoxy sample having 0.4 wt% graphene was 62% greater than that of the control sample [13]. Kazemi-Khasragh *et al.* investigated the impact properties of basalt fiber reinforced epoxy composites filled with graphene nanosheets, and the maximum energy absorption was observed for the sample having 0.3 wt% nanofiller [14].

Kamar *et al.* reported a 29% increase in the bending strength of glass fiber/epoxy after adding only 0.25 wt% graphene [15]. Li *et al.* studied the interlaminar shear properties of carbon fibers/epoxy composites enhanced with graphene [16]. The results of their work showed that by adding only 0.1 wt% graphene oxide, an 11% improvement in interlaminar shear strength was achieved.

In the current study, E-glass fiber/epoxy composites were filled with different amounts of graphene, and then the bending behavior of the fabricated samples were explored. Also, the fracture surface of the composites was evaluated.

2. Materials and experimental procedure

2.1. Materials

The employed polymeric matrix was a KER 828 epoxy resin with an amino-hardener (Kumho P&B Chemicals, Inc., Korea). As recommended by the manufacturer, the mixing ratio of resin to hardener was 100 to 10 (w:w). The E-glass chopped strand mat (Fig. 1), with a density of 450 $g.m^{-2}$ and filament diameter of 12 μm, was provided by the CNBM Company (China). The graphene nanoplatelets (GnPs) with the specifications given in Table 1 were purchased from US Research Nanomaterials, Inc., USA. Fig. 2 displays a SEM micrograph of the GnPs.

Table 1. Some specifications of the GnPs.

Property	Value
Diameter	μm 4-12
Thickness	nm 2-18
Layers	Less than 32 layers
Specific surface area	$m^2.g^{-1}$ 150-200
Purity	99.5%

2.2. Experimental procedure

To fabricate the multiscale specimens, the epoxy/GnPs mixture was first prepared. In order to achieve a desirable dispersion of GnPs in the matrix, the

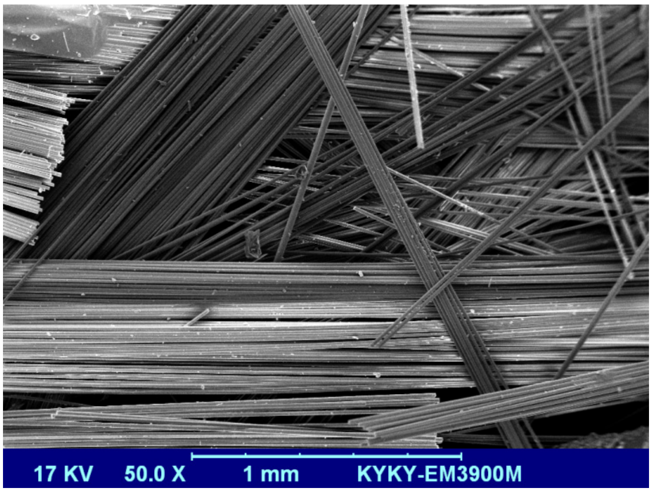

Fig. 1. SEM image of the E-glass fibers.

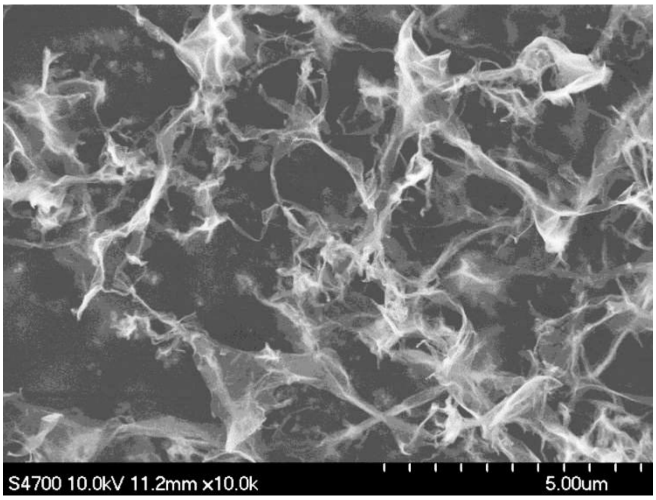

Fig. 2. SEM image of the GnPs.

mechanical and ultrasonication routes were employed. Various weight fractions of GnPs were added into pre-weighted quantities of epoxy resin and mixed for 20 min using a mechanical stirrer. Next, the suspension was exposed to 30 min ultrasonic stirring (150W, TOPSONICS Co.). The hardener was then hand-mixed for 5 min. The resulting suspensions were employed as a matrix to the prepared the E-glass fiber/epoxy/GnPs composites via the hand lay-up method. An E-glass fiber/epoxy composite was also prepared as a control.

The flexural properties of the specimens were obtained based on the ASTM: D790 standard. A KOOPA apparatus was used to run the 3-point bending test at a speed of 4.3 mm.min^{-1}. For all tests, the support span (L) was fixed at 250 mm, and the ratio of support span-to-thickness (L/d) was 32:1. The tests were repeated five times for each specimen, and the averaged values were reported. The flexural strength (σ_f), flexural modulus (E_f), and failure strain (ε_f) were obtained from the following equations [9].

$$\sigma_f = \frac{3PL}{2bd^2} \tag{1}$$

$$E_f = \frac{L^3 m}{4bd^3} \tag{2}$$

$$\varepsilon_f = \frac{6Dd}{L^2} \tag{3}$$

In these equations, P and b represent the maximum load and the width of the sample, respectively, m is the slope of the straight-line part of the force-displacement curve, and D is the maximum deflection of the specimen center.

The tests were repeated three times and the averaged values were reported. An FESEM (HITACHI S-4160, 25 kV) was utilized to study the fractured surfaces of the samples after the bending test.

3. Results and discussion

Fig. 3 presents the results of the flexural modulus of the GnPs/E-glass fiber/epoxy composites in various GnPs loadings. Regarding the obtained results, a maximum enhancement on the flexural modulus of 26% was observed via the addition of 0.4 wt% GnPs. This result is expected because of the higher modulus of the GnPs as compared with the epoxy. It can also be explained by the fact that the GnPs in the matrix prevent the slippage of polymeric chains. The negligible difference between the flexural moduli for 0.4 and 0.5 wt% GnPs-enhanced specimens is probably attributed to the presence of GnPs agglomerates at higher nanofiller loadings [17].

Fig. 4 shows the variation of the flexural strength of the GnPs/E-glass fiber/epoxy samples in various GnPs loadings. One can clearly see that the flexural strength is enhanced by increasing the GnPs weight percent up to 0.4 wt% and declines afterward. The value of flexural strength for the specimen containing 0.4 wt% GnPs is 280 MPa, which shows an increase of 23% as compared to the GnPs-free specimen.

As reported in the literature, the matrix-fiber interfacial properties in FRPs have an undeniable effect on their mechanical properties [18,19]. Since the GnPs acted as a pinning agent between the fibers and the nanocomposite matrix in this study, a high friction coefficient is created between them. Moreover, the GnPs can tolerate a portion of the applied load, so,

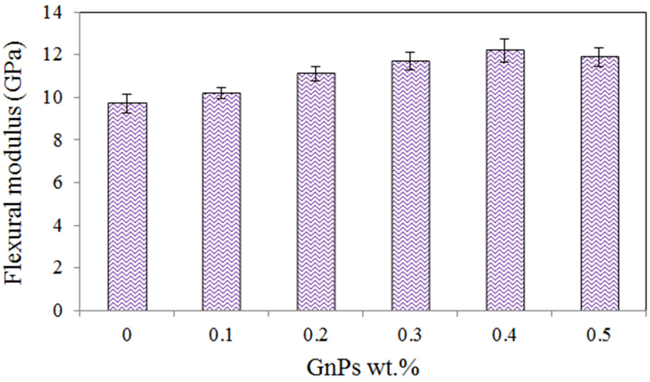

Fig. 3. Flexural modulus of GnPs/E-glass fiber/epoxy composites in various GnPs loadings.

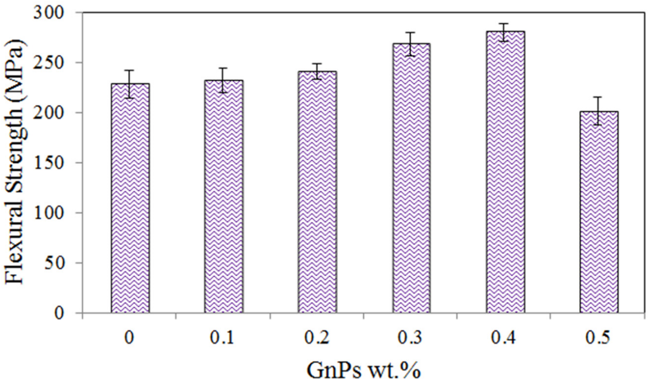

Fig. 4. Flexural strength of GnPs/E-glass fiber/epoxy composites in various GnPs loadings.

the necessary stress for fiber fracture increased. The drop in the flexural strength of the 0.5 wt% GnPs-filled composite is probably attributed to decreased matrix-fiber adhesion due to the formation of a discontinuous matrix network with some nanofiller agglomerates.

Fig. 5 displays the variation in the failure strain for the GnPs/E-glass fiber/epoxy composites containing various GnPs contents. Among these specimens, the 0.1 wt% GnPs-filled composite demonstrated a 16% enhancement in failure strain of the E-glass fiber/epoxy composite. We conclude that the presence of GnPs in the matrix creates strong barriers against crack propagation (deflection mechanism), resulting in enhanced failure strain. Similar to the flexural strength, a decrease in the failure strain with the addition of higher GnPs contents can be attributed to the unfavorable dispersion of GnPs.

Fig. 6 shows SEM images of the fracture surface of the neat glass fiber/epoxy and multiscale 0.1 wt% GnPs-filled glass fiber/epoxy composites.

The fracture surface of the control sample (Fig. 6(a)) shows interfacial debonding between the fibers and matrix as the prevailing failure mechanism [20]. It can be also observed that the multiscale composite possesses improved glass fiber-matrix interfacial bonding as compared to the control sample (Fig. 6(b)). For this sample, matrix cracking is considered as the primary failure mechanism [20]. The SEM micrograph of the neat specimen shows that the matrix cleavage surface is smooth, demonstrating a brittle failure. On the contrary, the nanocomposite specimen indicates irregular cleavage due to the crack deflection mechanism resulting from the presence of GnPs in the matrix.

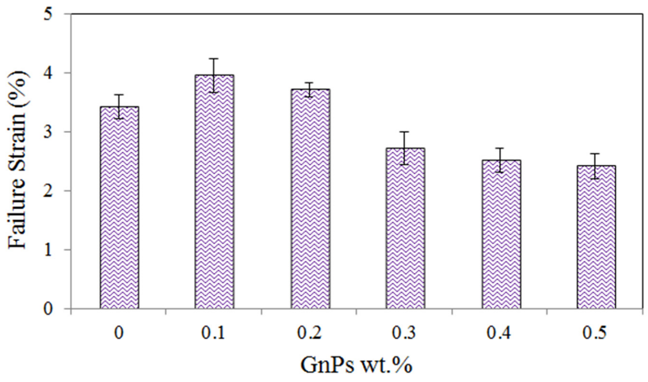

Fig. 5. Failure strain of GnPs/E-glass fiber/epoxy composites in various GnPs loadings.

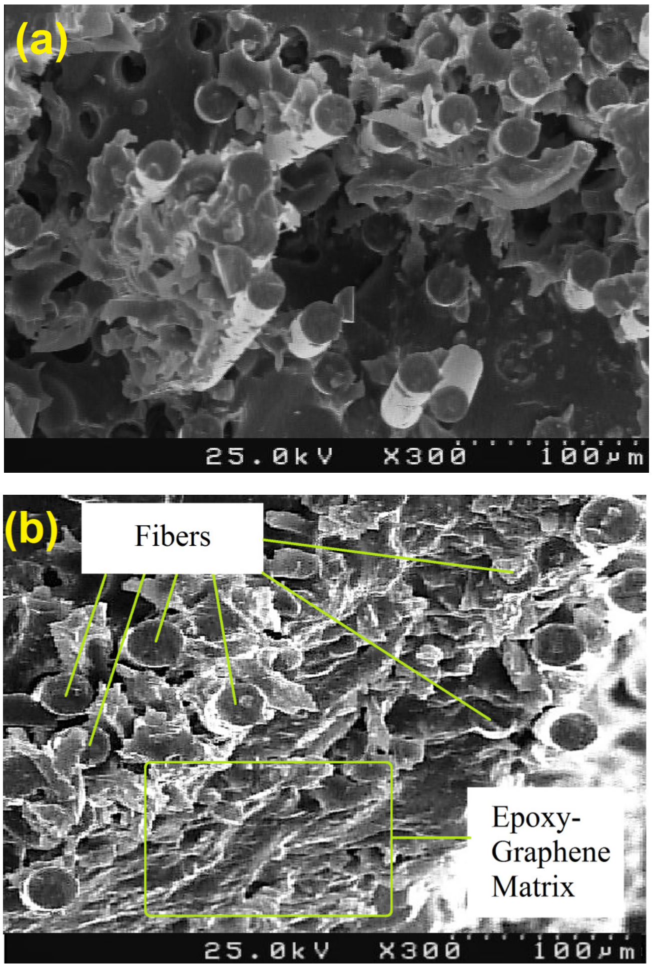

Fig. 6. SEM images of the fracture surface of the (a) neat glass fiber/epoxy and (b) multiscale 0.1 wt% GnPs-filled glass fiber/epoxy composites.

4. Conclusions

In this work, the effects of different GnPs wt% on the three-point bending properties of E-glass fiber/epoxy composites were explored experimentally. It was found that the maximum improvements in flexural modulus and flexural strength occurred in the sample having 0.4 wt% GnPs, while the maximum enhancement in failure strain was observed for the 0.1 wt% GnPs incorporation. The flexural strength and modulus of the 0.4 wt% GnPs/glass fiber/epoxy composite were 23%, and 26%, respectively, and were higher than those of the control. Also, the flexural failure strain of the glass fiber/epoxy specimen increased by 16% at 0.1 wt% GnPs content.

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