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Influence of Graphite Platelet Additions on The Mechanical Properties of Epoxy Resin

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Abstract
In this study, the effect of graphite platelet additions on the mechanical properties of the epoxy resin was investigated. The epoxy/graphite paltelet nanocomposites were fabricated using the mechanical mixing method by an electric blender. The graphite/epoxy nanocomposites were fabricated based on different weight fractions of graphite platelets, namely; 0, 3, 6, and 9 wt.%. The samples were self-cured at 25 °C for 24 hours before being post-cured at 100 °C for 4 hours. The mechanical properties of the neat epoxy and the epoxy/graphite nanocomposites were evaluated through tensile and hardness tests. Results showed that the graphite platelets have a positive impact on the stiffness and hardness of epoxy resin. For example, the stiffness and hardness increased by 20% and 5%, respectively, by adding 9 wt.% of graphite platelets. On the other hand, the fracture strength and the fracture strain were negatively impacted by the increased graphite addition. In conclusion, the study showed that the graphite platelets increased the nature of epoxy's brittleness, as indicated by the improvements in hardness and stiffness of the epoxy, but not its strength.
Keywords: *Graphite platelets, Epoxy, Polymer nanocomposites, Mechanical properties.*

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I. INTRODUCTION

Epoxy resins are increasingly being used in a wide range of applications, including tribology, electronic materials, adhesives, coatings, etc. [1–4]. This is attributed to their intrinsic properties such as rigidity, stability, flexibility, etc. [5]. However, thermoset polymers, including epoxy resins, are rarely used in their pristine forms. Hence, in order to widen their applications, polymers were used as matrix materials for producing polymeric composite materials, allowing them to modify their properties to meet the requirements of different engineering applications. Introducing nanoparticles is one of the most common techniques used to change the properties of polymers. Supported by a higher aspect ratio than microparticles, nanoparticles play a dominant role in the field of polymeric composites as they supply a large filler specific surface area [6]. Therefore, it is included as one of the distinct advantages that the performance improvement is often acquired at a relatively lower concentration of nanoparticles as compared to microparticles or normal fibers [7,8].

Graphite is widely used as an additive material to polymers in order to enhance their properties, including mechanical [9], wear [10,11], and thermal conductivity [12]. Interestingly, graphite sources are inexpensive and available in huge quantities (the world's inferred resources exceed 800 million tons of recoverable graphite). This motivated and opened a new trend in the field of materials science for developing a wide range of novel functional materials. Research into the potential of graphite as an additive material was conducted to improve the thermal, wear, and mechanical properties of thermoset polymers. For instance, Wang et al. (2015) [13] studied the effect of graphene nanoplatelets (GNPs) addition on the thermal conductivity of epoxy. The results showed that there is a significant increase in the thermal conductivity of epoxy, i.e., a 115% improvement was observed at the addition of 5 wt% of GNPs, compared with neat epoxy. Similar results were reported on the effect of graphite on the thermal conductivity of other types of thermoset polymers, for instance, high-density polyethylene [14] and polystyrene [15]. Tribological effects of graphite and its derivatives were also reported in the literature [16,17]. For example, G. Pan et al. (2010) [3] studied the effect of graphite as a coating on the tribological properties of polymers. Results showed that the graphite additions led to an improvement in the wear resistance of epoxy, accompanied by low friction. For instance, the addition of 50 wt.% of graphite reduced the friction by about 43% while the wear rate was positively reduced by 33%.

Mechanically, Results from published studies show that there is an improvement in the mechanical properties of polymeric composite materials. For example, B. Pan et al. (2012) [18] investigated the effect of a low concentration of graphene oxide (GrO) on the mechanical behavior of MC nylon. It was noticed that the tensile strength is directly proportional to the GrO content. For instance, the tensile strength increased by 35% at the addition of 0.05 wt.% of GrO. Similar observations have been reported on polyamide by Chen et al. (2018)

[19]. In contrast, other research studies reported different findings in which graphite and its derivatives, i.e., graphene, graphene oxide, etc., decreased the tensile strength of polymers [16,17,20]. The findings were mainly attributed to the agglomeration and aggregation phenomena, especially at the high rate of additives. This phenomenon promotes the value of stress, in other words, acting as a stress raiser, which reduces the load-bearing capacity of polymers. On the other hand, significant improvements in the modulus of elasticity and hardness of polymers were reported [16,21]. The concentration of the materials and their size could be regarded as the most important factors in determining the mechanical behavior of polymeric composites.

In conclusion, graphite and its derivatives exhibited a clear positive impact on the thermal conductivity of polymers and their tribological properties as well. However, it was noticed that there was no specific mechanical behavior, which could be attributed to the different aspects that affect the final behavior of the polymeric composite material, such as the content and size of the fillers. In conclusion, there is still a need to explore the effects of the different derivatives of the various additive materials, including graphite, on the mechanical properties of polymeric matrices.

In the current study, the effect of different concentrations of graphite platelets on the mechanical properties of epoxy will be investigated. The general purpose of this study is to determine the relationship between concentrations, mechanical characteristics, and the compatibility of epoxy-graphite platelets.

II. Materials and experimental procedures

2.1 Materials

Epoxy is a common resin used in a variety of industrial applications. It is ideal for a variety of applications, including casting, tooling, composites, and automotive parts, and offers numerous benefits [11]. This includes, but is not limited to, the infusion technique, which is cost-effective and simple to use at room temperature, and it allows for the production of large-sized laminates [22].

Graphite is derived from natural graphite sources, which are inexpensive and available in huge quantities. The world's inferred resources exceed 800 million tons of recoverable graphite [23]. In addition to the advantages of their lack of flammability and thermal resistivity, graphite fillers have a significant effect on the tribological and mechanical behavior of polymeric composites. In the current study, epoxy thermoset polymer was chosen as a polymer matrix, and graphite platelets were used as an additive filler.

In the current study, epoxy resins (R246TX) with the corresponding (H160) curing hardener with a ratio of (1: 4) were supplied by Australian Calibrating Services Pty Ltd, Australia. The Graphite platelets with average surface areas of 7.2 m^2/g and ash of less than 4% was purchased from Chem-Supply Pty Ltd, Australia. The properties of epoxy resin and graphite platelets presented in Table 1 and Table 2, respectively.

Table 1: The properties of the epoxy resin (according to the supplier).

Density (g/cm^3)	*Glass-transition temperature (T_g)*	*Tensile strength (MPa)*	*Compressive strength (MPa)*	*Thermal conductivity W/(m·K)*
1.07	65 ℃	72	13.8 - 55.16	0.2

Table 2: The properties of graphite platelets (according to the supplier).

Density (g/cm^3)	*Melting point*	*Surface area (m^2/g)*	*Tensile strength (MPa)*	*Compressive strength (MPa)*	*Thermal conductivity W/(m·K)*
2.09-2.3	2820 ℃	7.2	2.7-13.8	13.8-55.16	2-90

2.2 Sample preparation

Figure 1 illustrates the fabrication steps of epoxy/graphite nanocomposites. For neat epoxy, the epoxy resin with its corresponding hardener was mixed at a constant ratio of 1:4, which also applied to the all of the fabricated composites. In order to fabricate the epoxy-graphite, graphite platelets with different concentrations, namely, 0, 3, 6, and 9 wt.% were gradually added to the resin (see Table 3). The mixture was stirred by using an electrical blender at a speed of 250 rpm for 2 minutes, ensuring optimal homogeny of the mixture. After that, the hardener was then added and mixed with the mixture in the same way for one minute. In order to get rid of the air bubbles that appeared after the mixing process, the mixture was degassed inside a vacuumed chamber oven at 40 ℃ and -70 kPa for 30 minutes. The mixture was then poured inside special steel molds (see Figure 2-[a]) for fabricating the tensile samples in the form of dog-bone shapes in accordance with the ASTM D638-99 standard test. The dimensions of the tensile samples are illustrated in Figure 2-[b].

Table 3: Details and the compositions of the fabricated samples

	Epoxy	**Graphite platelets (wt.%)**
Neat epoxy	Epoxy (100)	0.0
Epoxy/graphite-3%	Epoxy (97.0)	3.0
Epoxy/graphite-6%	Epoxy (94.0)	6.0

Epoxy/graphite-9%	Epoxy (91.0)	9.0

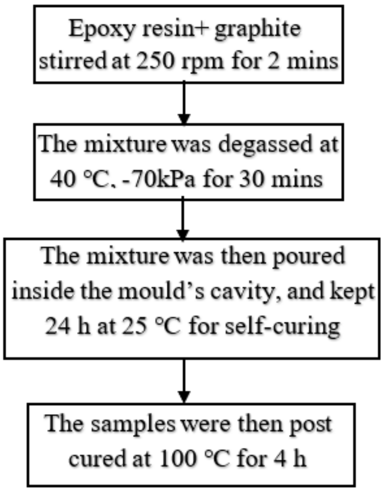

Figure 1: The sample preparation flowchart of the epoxy/graphite nanocomposites.

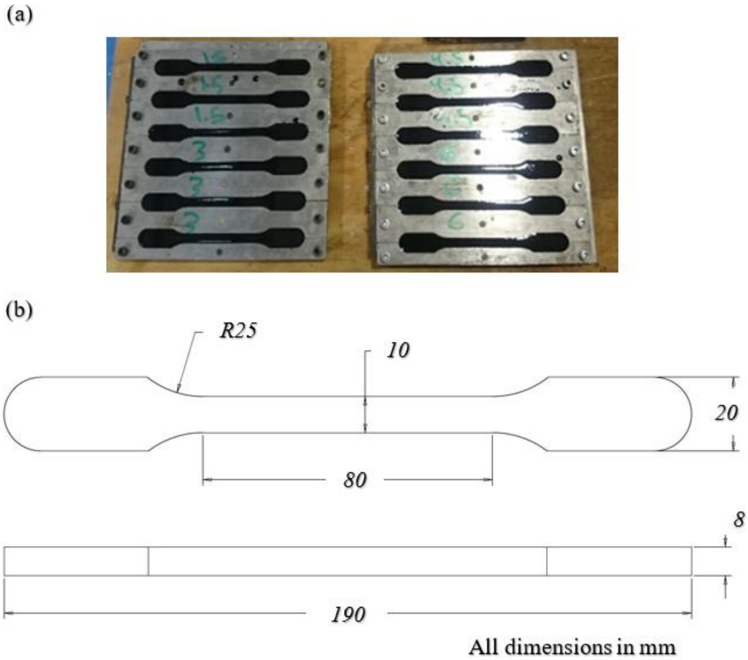

Figure 2: (a) tensile molds, and (b) tensile specimen geometry.

2.3 Testing procedures

Tensile strength, stiffness and elongation at break of neat epoxy and epoxy/graphite nanocomposites were obtained through the tensile test which conducted using MTS 810 tensile testing machine (shown in Figure 3-[a]) in accordance with ASTM D638-99. The test was conducted at a head speed of 1 mm/min. The hardness test of the developed composites was also measured using Dial Shore Type Durometer-D (Figure 3-[b]) following ASTM D2240. To ensure the results of the experiments, i.e., reliability and reproducibility, three samples were tested under the same conditions for each test and then the average values were obtained.

(a) (b)

Figure 3: (a): Tensile testing machine and (b) Shore D hardness tester

III. RESULT AND DISCUSSION

The mechanical characteristics of graphite/epoxy nanocomposites were tested through tensile and hardness tests. The tensile strength, stiffness, and fracture strain were obtained from the results of the tensile test in accordance with ASTM D638-99. Figure 4 illustrates the stress-strain curves of the neat epoxy and graphite/epoxy nanocomposites. Neat epoxy exhibited the highest fracture strength of 60.7 ± 3.5 MPa, however, it recorded the lowest value of stiffness of 1.08 ± 0.05 GPa. The results are in good agreement with the previously published studies in which the tensile strength was in the range of 58-94 MPa and the stiffness was in the range of 0.6-2.7 GPa [13,16]. Regarding the graphite platelet additions, it is obvious to notice the contradiction between the behaviors of strength and stiffness. Visibly, the stiffness of epoxy increases as the content of graphite platelets decreases. On the other hand, both tensile strength and fracture strain decrease. Howevre, signifcant changes were noticed in the mechanical proprties of epoxy by adding the graphene platelets. For instance, compared with neat epoxy, 6 wt.% addition of graphite platelets (epoxy/graphite-6%) exhibited an increment of 21 % in the stiffness, howevere, the fracture strength and its fracture strain reduced by 35 % and 20 %, respectively.

From the literature, similar observations were reported in the published works. For exampel, Eayal Awwad et al. (2021) [16] investigated the impact of different weight fractions of GNPs on the mechanical properties of epoxy resin. At an additon of 4.5 wt.%, an improvement of 15% in stiffness was recorded compared with pure epoxy. Contradictory, the tensile fracture and fracture strain decreased by 22% and 45%, respectively.

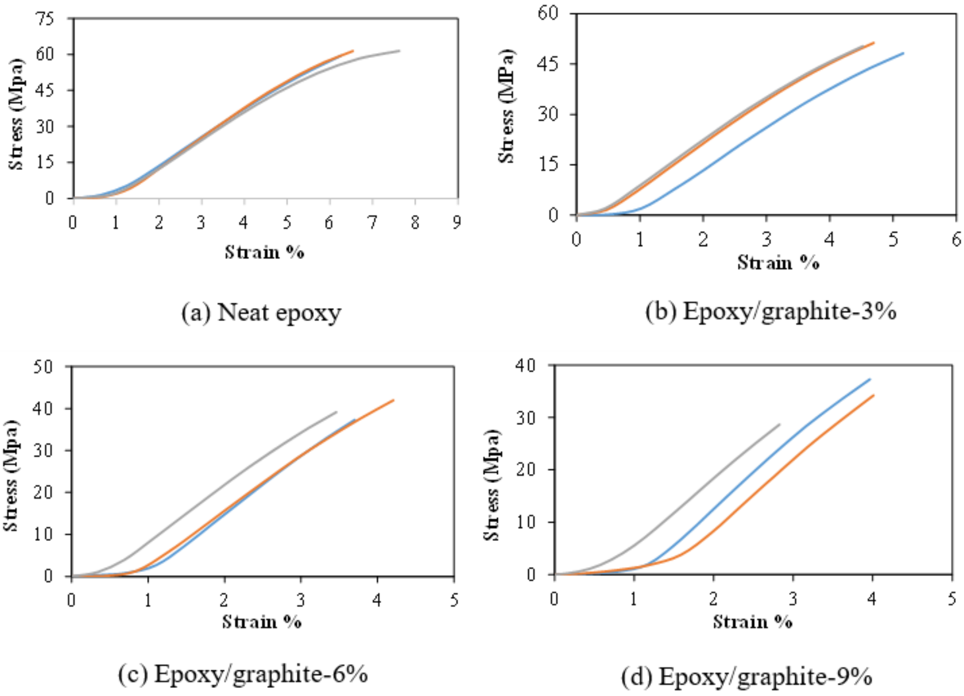

Figure 4: Stress-strain diagrams for epoxy and epoxy/graphite nanocomposites based on different percentages of graphite platelets, where three samples were performed for each composite.

The effect of the different weight fractions (0–9 wt.%) of graphite platelets on the tensile strength and stiffness of epoxy is presented in Figure 5. It can be noticed that the tensile strength decreases with the increase in graphite content. In contrast, the stiffness is directly proportional to the content of graphite platelets. The stiffness improvement could be attributed primarily to the high stiffness of graphite platelets (1,000 GPa) [16]. In addition, the huge surface area that can be provided by the nano-size particles, for instance, is about 7.2 m2 in this study. This can also explain the significant improvements in the stiffness and hardness of epoxy. However, the strength reduction could be mainly attributed to the aggregation/agglomeration phenomena of nanoparticles, which act as stress risers [16,24], hence leading to a reduction in the fracture strength and its corresponding strain fracture as shown in Figure 5. These phenomena can also lead to reduce bonding strength, i.e., the interfacial adhesion between the graphite layers and the epoxy matrix. It is worthwhile to mention here that the graphite platelets tend to aggregate due to the van der Waals forces and π−π interactions between their layers [25]. This force usually makes the dispersion process a challenge inside the polymer matrices, especially with high viscosity resins like epoxy.

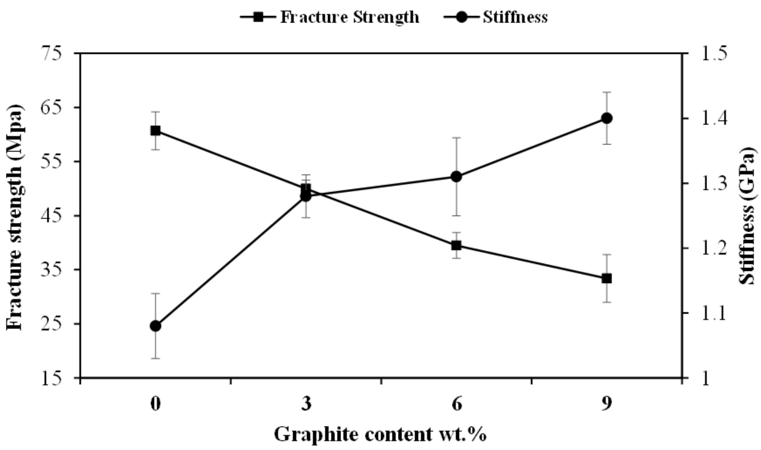

Figure 15: Effect of graphite platelet concentration on the stiffness and fracture strength of epoxy.

The effect of the graphite platelet additions on the hardness of epoxy was studied, and the results are displayed in Figure 6. The results are represented by three readings for each composite. The test was conducted by a Shore D hardness tester in accordance with ASTM D2240. From the results, there is a tendency for improvements in the hardness of epoxy as the concentration of the graphite platelet increases. This behavior can be mainly explained by the brittle nature of both epoxy thermoset resin and graphite platelets. Epoxy is a brittle material in its nature [26]. Graphite also has a brittle nature, as indicated by the high value of stiffness, as mentioned above. Regardless of the advantages of stiffness improvement, thermoset epoxy resin is considered as a brittle material. In wide range of applications, this is considered as one of the major problems limiting the applications of such materials by reducing the load-bearing capacity of structural components because of the fast growth of any crack that can happen under the loads.

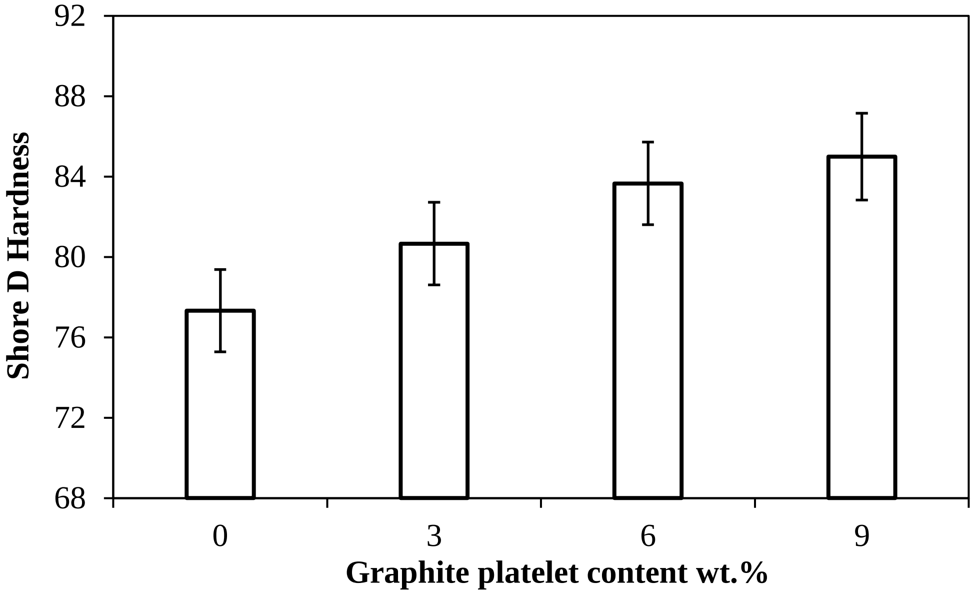

Figure 6: Effect of graphite platelet concentration on the stiffness and fracture strength of epoxy.

IV. CONCLUSION

The current study was conducted in order to investigate the mechanical properties of epoxy resin with the addition of different weight fractions of graphite platelets. Fundamentally, the results were basically compared with the mechanical properties of neat epoxy. In conclusion, the findings of the current study can be summarized through following two points:

- The addition of graphite platelets improve the stiffness and the hardness of epoxy, i.e., as the graphite content increases, the stiffness and the hardness of the epoxy increase.

- Graphite platelet additions exhibited different trends when compared with stiffness and hardness. The addition of graphite platelets reduced the fracture strength of epoxy and its fracture strain.

Conflict of Interests
The authors state that there are no conflicts of interest in the publishing of this paper

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