ANALYSIS OF THE MECHANICAL BEHAVIOR OF GRAPHENE COMPOSITES IN POLYMERIC MATRICES: A CASE STUDY

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ABSTRACT

In the recent years, polymeric nanocomposites have been widely studied due to their versatility and use in several industrial sectors. These studies include the use of reinforcements materials together with different polymeric matrices, which promote even more satisfactory resulting properties for automotive, aerospace, aeronautical, electronics, and other technological areas. Graphene is a carbon-based material in a flat, single-layer, and allotropic structure with atoms linked together. This material has proved to be a great ally in the development of new nanostructural technologies. Thus, recent studies promoting the use of graphene in the synthesis of polymers are promising. Thus, this work aimed to evaluate, based on the literature, the use of graphene as a reinforcement in polymeric matrices and its influence on mechanical properties, such as Young's modulus, tensile strength, and elongation at break. Therefore, after selecting recently published articles in this field, a comparative analysis of mechanical properties was developed by changing certain variables of the materials, such as the type of polymer in the matrix, the use of reinforcements, and the addition of compatibilizer. Based on the analyzes, it was observed that small changes in the fabrication process can cause significant changes in the properties of the composites. Therefore, the desired application of the composite will define which properties need to be improved by adjusting its composition and fabrication.

Keywords: *nanocomposite, graphene, graphene oxide, polymer, mechanical properties.*

INTRODUCTION

Graphene composites with polymeric matrices have shown promising mechanical properties, such as, hardness, Young's modulus, tensile strength and toughness[(1-4)]. These achieved properties are employed in various applications, such as packaging, membranes, adhesives, car and airplane parts, textile materials and electronic devices[(1,5)].
Thus, a bibliographic survey was carried out to analyze the mechanical behavior of graphene composites with polymeric matrices in the context here treated. There are different ways to synthesize composites with polymeric matrices. Therefore, this work presents a comparative analysis of the values of the mechanical properties when changing certain material variables, such as the type of polymer n the matrix, the use of reinforcements, the addition of compatibilizer, among others. It was chosen to evaluate three types of polymeric matrices: polypropylene (PP), polymethylmethacrylate (acrylic, PMMA) and epoxy. These three types

of matrices were chosen due to a greater availability of articles to gather extensive data and analyses.

METHODS

A literature review was carried out on which polymeric matrices are mostly used in the synthesis of polymeric nanocomposites reinforced with graphene or graphene oxide. Then, analyses of these processes, which use the melt mixing method, were carried out, evaluating their feasibility and scalability. After that, the variables that influence the synthesis of the nanocomposite were selected, namely the addition of compatibilizer, the matrix type and the graphene content. Young's modulus, tensile strength, and elongation at break were the mechanical properties chosen to be analyzed. Finally, a compilation and a comparative analysis of the mechanical properties were caried out by varying some desired synthesis parameters.

RESULTS AND DISCUSSION

The analyzes of selected properties of graphene composites are presented on the following sections, with three different polymer matrices (polypropylene, polymethylmethacrylate and epoxy).

Polypropylene composites

The articles of Natarajan[6], Oliveira[2], Achaby[7], Song[3] and Huang[8] were used as the basis for the analyses of PP composites reinforced with graphene. These articles were chosen because they have different characteristics in the composite synthesis process.
Table 1 shows the studied articles with PP, the composite synthesis method, and the articles identification in the following graphs. The mechanical properties compilation can be found in Figure 1, for the PP composites.

Table 1 - Identification of polypropylene composite works

Studied articles	**Synthesis summary**	**Identification**
Natarajan[6]	Melt mixing method; functionalized graphene.	Natarajan_PG
	Melt mixing method; functionalized graphene; carboxyl as a compatibilizer.	Natarajan_PMG
Oliveira[2]	Composite by solid-solid deposition; reinforcement by "Method L"	Oliveira_SSD
	Composite by liquid phase feeding; reinforcement by "Method L"	Oliveira_LPF
Achaby[7]	Melt mixing method; with preheating to 70ºC.	Achaby
Song[3]	Melt mixing method; with latex as a compatibilizer.	Song
Huang[8]	Melt mixing method.	Huang

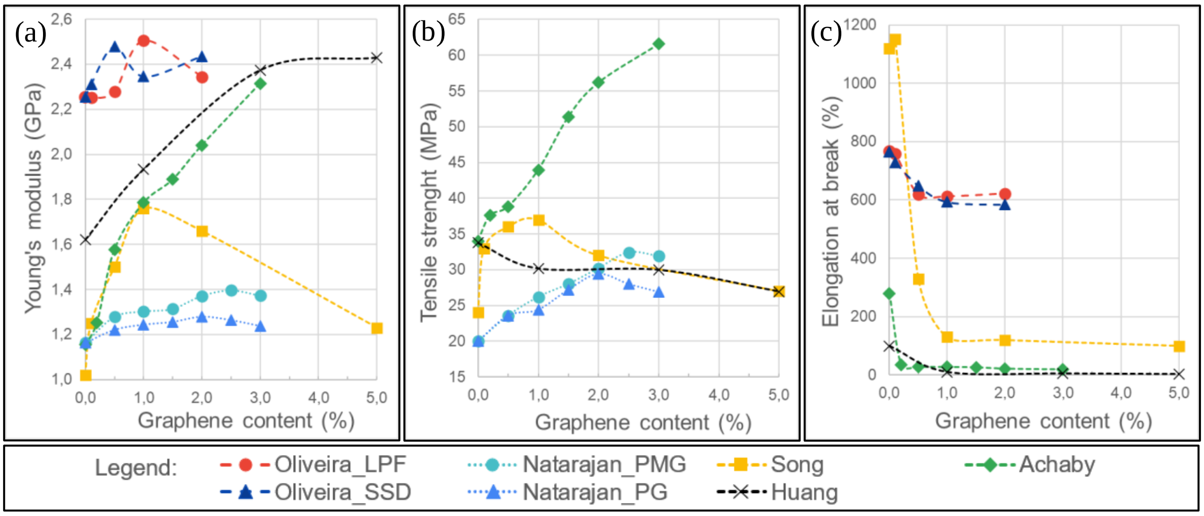

Figure 1: (a) Young's modulus, (b) Tensile strength and (c) Elongation at break by the graphene content in the PP composites.

It is recommended not to add another step in the synthesis in order to obtain a greater stiffness, if the melt mixing method is used (Figure 1-a). However, it is recommended to use SSD or LPF methods if a higher stiffness and ductility is desirable at the same time. Preheating is recommended to obtain a greater tensile strength, in the case of melt mixing method (Figure 1-b). Besides that, the use of compatibilizer is recommended to obtain a greater elongation at break (Figure 1-c). It was also analyzed that the graphene content increases the thermal and electrical conductivity.

Epoxy composites

The articles of Eqra[9], Tang[10], King[11], Bisht[12] and Salom[13] were considered for the study of epoxy composites reinforced with graphene. Table 2 shows the studied articles with epoxy, the composite synthesis method, and the articles identification in the following graphs. The mechanical properties compilation, for the epoxy composites, can be found in Figures 2 and 3.

Table 2 - Identification of polypropylene composite works

Studied articles	**Synthesis summary**	**Identification**
Bisht[12]	Composite with graphene nanoplates.	Bisht
Eqra[9]	Composite with 10 layers of graphene nanoplates.	Eqra - GNP10
	Composite with 30 layers of graphene nanoplates.	Eqra - GNP30
King[11]	Composite with graphene nanoplates.	King
Salom[13]	Composite with amine functionalized graphene (NH2) nanoplates.	Salom - NH2
	Composite with non-functionalized graphene nanoplates.	Salom - n
Tang[10]	Composite with high dispersion of graphene sheets.	Tang - A
	Composite with low dispersion of graphene sheets.	Tang - B

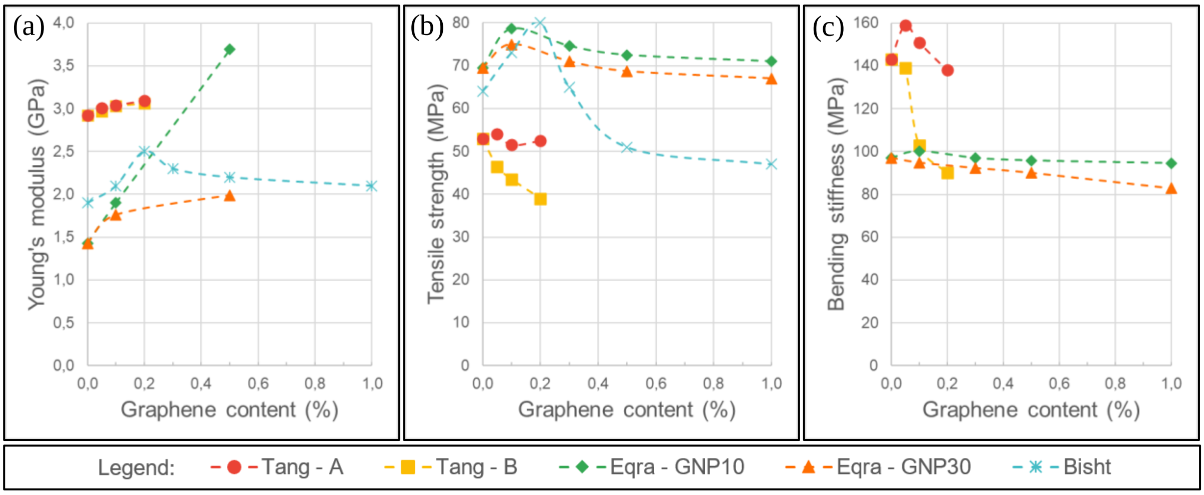

Figure 2: (a) Young's modulus, (b) Tensile strength and (c) Bending stiffness by graphene content (0% to 1%) in the epoxy composite.

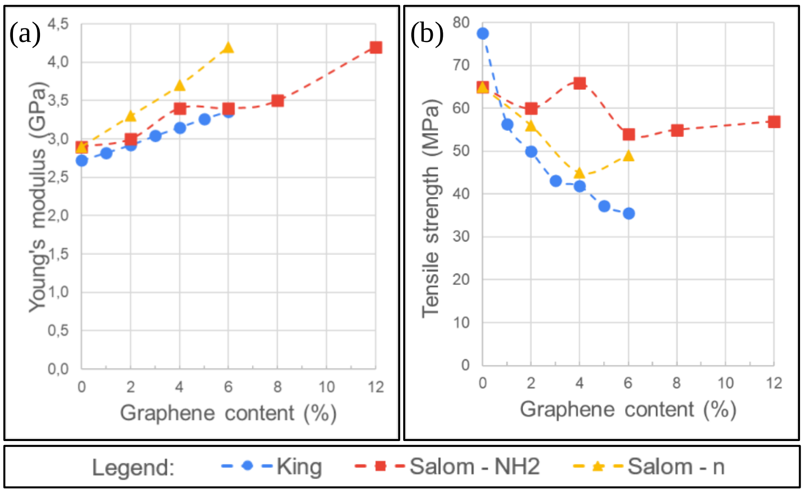

Figure 3: (a) Young's modulus and (b) Tensile strength by graphene content (0% to 12%) in the epoxy composite.

As seen in Figures 2-a and 3-a, a higher value of Young's modulus is obtained with nanoplates with 10 graphene layers, and Young's modulus tends to increase with values up to 12% of graphene content. Results with graphene sheets obtained minimal variations. Figures 2-b and 3-b show that a greater tensile strength is obtained with nanoplates with 10 layers of graphene, but it tends to worsen with values greater than 0.2% of graphene content. Composites with graphene sheets had a decrease in the tensile strength, mainly with a low reinforcement dispersion. In Figure 2-c, it is noticeable that only the composite with highly dispersed graphene sheets obtained a high bending stiffness, with a peak at 0.05% of graphene content. The composite with graphene sheets with low dispersion had a large bending stiffness drop.

Polymethylmethacrylate composites

For the study of PMMA composites reinforced with graphene, the articles of Gudarzi(14), Jiang(15), Morimune(16), Layek(17) and Tripathi(18) were considered. Table 3 shows the studied articles with PMMA, the composite synthesis method, and the articles identification in the following graphs. The mechanical properties compilation can be found in Figure 4, for the PMMA composites.

Table 3 - Identification of works on polymethylmethacrylate composites

Studied articles	**Synthesis summary**	**Identification**
Gudarzi[14]	Graphene by Hummer's method; Pickering emulsion polymerization;	Gudarzi
Jiang[15]	Graphene by Hummer's method; composite by latex technology and melt blending.	Jiang_p-FGN
	Graphene by Hummer's method; composite by melt blending alone.	Jiang_FNG
Morimune[16]	Graphene by Hummer's method; soap-free emulsion polymerization.	Morimune
Layek[17]	Graphene by Hummer's method; composite by atom transfer radical polymerization (ATRP) and reducing with hydrazine hydrate.	Layek
Tripathi[18]	Graphene by Hummer's method; *In situ* polymerization of MMA in presence of reduced graphene oxide (RGO).	Tripathi_InSitu
	MMA polymerization in presence of PMMA/RGO beads.	Tripathi_Beads
	In situ polymerization of MMA in presence of RGO followed by sheet casting.	Tripathi_Sheet

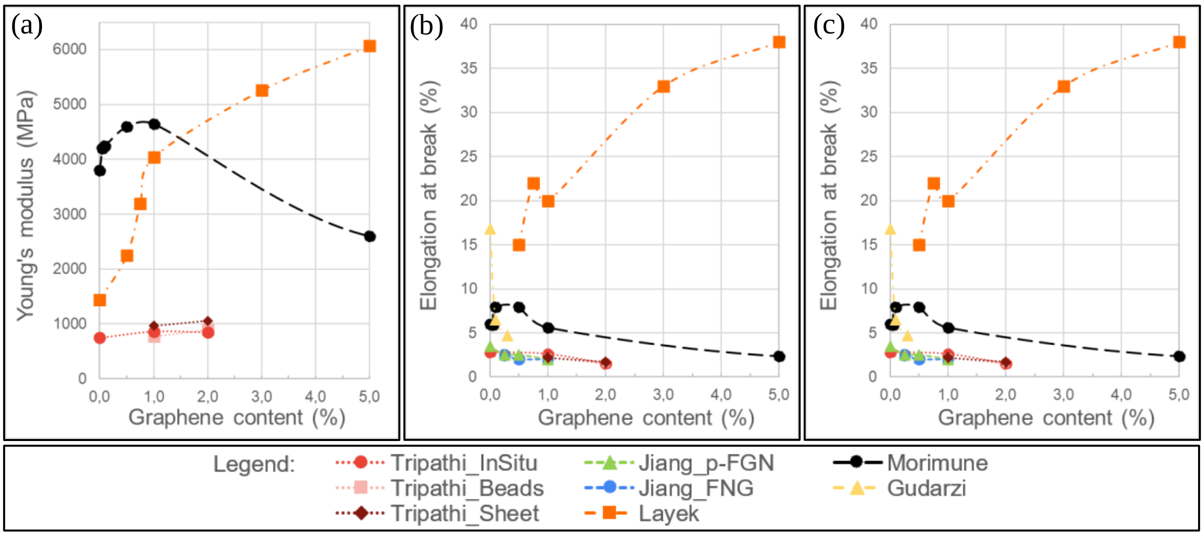

Figure 4: (a) Young's modulus, (b) Tensile strength and (c) Elongation at break by the graphene content in the PMMA composites.

When analyzing Figure 4, it is initially noted that the composite with the highest Young's modulus, tensile strength, and elongation at break was obtained with composite with synthesis by atom transfer radical polymerization (ATRP) and reduction with hydrazine hydrate.

CONCLUSIONS

The literature review made it possible to analyze the mechanical properties of the graphene composites with polypropylene, polymethylmethacrylate, and epoxy, by varying the graphene content in their composition. The main properties analyzed were the Young's modulus, the tensile strength, and the elongation at break.

Initially, it was concluded that the main variables that changed the composite properties are: the type of matrix, the reinforcement and its the dispersion, the presence of compatibilizer, the number of layers of graphene nanoplates, as well as the synthesis method.

In general, it was noticeable that it is possible to obtain different mechanical properties, for the same composite, with small changes in the melt mixing method. As an example, it was observed that the use of compatibilizer resulted in a gain in ductility at a cost of stiffness loss. However, if a greater tensile strength is sought, preheating the materials is a recommended alternative.

Finally, when comparing the three polymers, it was observed that the composite with PMMA presented the best overall results, due to its better interactivity with graphene.

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