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# Synergistic effect of exfoliated graphite nanoplatelets and short glass fiber on the mechanical and interfacial properties of epoxy composites



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# ABSTRACT

In this study, the properties of hybrid composites made by epoxy reinforced with short glass fibers (GF) and exfoliated graphite nanoplatelets (GNP) were determined as a function of the GF loading. The addition of GNP, either within the matrix or at the GF surface (GFc), promoted the formation of a stronger GF-epoxy interface, as evaluated by the single-fiber microdebonding test, resulting in an increase of the interfacial shear strength by ~60% exhibited by the hybrid epoxy composite reinforced with 5 wt% GNP. Quasi-static tensile tests and impact tests were performed in order to explore how the combined effect of the nano- and micro- size reinforcements affected the macroscopic mechanical properties under low and high strain rates. The improved tensile modulus, ultimate tensile strength and impact resistance exhibited by the hybrid composites revealed that it is possible to introduce the nano-materials at the fiber/matrix interface and significantly improve the interfacial properties, leading to lighter and stronger composites. Furthermore, the storage modulus and the viscoelastic behavior of GF/epoxy composites were remarkably enhanced upon addition of GNP, indicating strong GNP–polymer interactions and immobilization of the polymer chains. In conclusion, the combined effect of nano-materials and microsize reinforcements can be exploited to produce light-weight hybrid composites with enhanced mechanical properties.

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### 1. Introduction

Due to their low density and good adhesive and mechanical properties, epoxy resins are the most commonly used polymers for structural composites. As reported, the introduction of small amounts of nanomaterials (<10 wt%) in epoxy resins can remarkably increase their mechanical properties and thermal stability [1], dramatically enhance the electrical [2,3] and thermal [4,5] conductivity of the resulting composites and play a beneficial role on the interfacial properties of structural composites [6]. Addition of more than 10 wt% nanomaterials in polymers frequently leads to poor dispersion, difficult processability [7], and increased cost and density of the composite.

Short glass fiber reinforced polymers with 30–50 wt% fiber loading are commonly used as light-weight structural components due to their higher specific mechanical properties, superior corro-

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sion resistance and improved fatigue resistance with respect to conventional engineering materials. Because short-fiber reinforced composites are less resistant to mechanical load and fatigue damage than the corresponding continuous-fiber-reinforced composites, it is of great interest to explore whether combining two fillers of rather different size scales (i.e. micro- and nano-scale) would give the desired performance at low to intermediate filler loadings [8–10].

Therefore, the aim of this study is to investigate how the morphology and the mechanical properties of short glass fiber reinforced epoxy composites are affected by the presence of a carbonaceous nanofiller namely, graphite nanoplatelets (GNP). There are only very few studies reporting the effect of nanomaterials on the interfacial adhesion of fiber reinforced epoxy composites [6,11,12]. In this research, the mechanical behavior of hybrid epoxy composites was studied in order to determine the role of the fiber-matrix adhesion on the quasi-static, visco-elastic and impact properties of the resulting materials. The investigation of the interfacial strength, in order to characterize the adhesion between matrix and fibers, was carried out by microdebonding tests.

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# 2. Experimental section

## 2.1. Materials and fabrication of composites

A bicomponent epoxy resin, supplied by US Composites (West Palm Beach, FL), was used as matrix. The epoxy resin consisted of a mixture of 635 thin epoxy and a 556 slow aminic hardener at a weight ratio of 2:1. This specific epoxy resin is typically used in engineering applications for the large-scale production of composites components by sheet molding compound (SMC) used in the automotive industry. Exfoliated graphite nanoplatelets, xGnP<sup>®</sup>-M5 purchased by XG Sciences Inc., with an average diameter of  $\sim 5 \,\mu m$  and thickness in the range of 10-20 nm were used. E-glass fibers, with the trade name RO99 P319 supplied by Saint-GobainVetrotex were used asreceived. These GF are indicated as treated with a silane based coupling agent. Chopped strand glass fibers (single fiber diame $length = 6.50 \pm 0.44 mm$ ) ter =  $15.3 \pm 1.5 \mu m$ , average were obtained by chopping long glass fibers using a chopper gun CDA-08 provided by GlasCraft.

GNP-coated glass fibers were prepared by sonication of xGnP-M5 in isopropanol with a filler concentration of 5 mg/ml. Sonication was carried out using a Misonix S-4000-010 for 1 h (30% amplitude, 8 W power) equipped with a probe of 12.5 mm diameter. After adding the GF to the solution, the sonication was continued for 1/2 h. Coated glass fibers were finally rinsed in isopropanol and dried at ambient temperature overnight. The GNP content added onto the GF surfaces, as measured by weighting the GF before and after the sonication and assuming homogeneous distribution of the graphite nanoplatelets on the fiber surfaces, was  $\sim$ 0.10–0.15 wt% with respect to the composite's weight. Specifically, the GF were weighted after complete solvent evaporation occurred under hood overnight. Glass fiber surfaces appear partially coated by graphite platelets, as observed by optical microscopy in Fig. 1 (Leica DMRM, Buffalo Grove, IL, USA). In particular, GNP are supposed to deposit onto the surfaces of GF by establishing weak interactions during sonication. The authors believe that no chemical bond is formed between graphite and GF, while physical adsorption and mechanical interlocking might occur.

The composites were made as follows: first the GNP were dispersed in isopropanol by sonication using the same conditions as mentioned above. Once the isopropanol was filtered away the GNP powder was mixed with the epoxy at 800 rpm and T = 60 °C for 40 min using a magnetic stirring plate. The GF were then added to the solution and stirring was continued for 20 min followed by addition of the curing agent and subsequent stirring at 800 rpm for 30 min. The mixture was degassed in a vacuum oven and cured in a mold at T = 80 °C for 1 h, followed by post-curing at T = 100 °C for 4 h. Post-curing as an accelerated thermal treatment was carried out according to the protocol provided by the epoxy supplier. Composites are designated by the amount and type of the filler, for example the composite containing 5 wt% of xGnP-M5 and 10 wt% GF is indicated as 5GNP/10GF/epoxy. Coated GF were indicated as GFc.

#### 2.2. Experimental techniques

The effect of the GNP on the fiber-matrix adhesion, was investigated through microdebonding tests on specimens consisting of an epoxy microdrop deposited onto a single fiber filament supported on a paper tab. Epoxy microdrops were distributed symmetrically around the filament while observing under an optical microscope. The drops were cured for 1 h at 80 °C followed by 4 h at 100 °C. Prior to testing, the samples were examined using an optical microscope (Leica DMRM, Buffalo Grove, IL, USA) in order to determine the fiber diameter (*d*), embedded fiber length (L), and the maximum droplet diameter (D), as indicated in Fig. 2a. Microdebonding tests were conducted at a crosshead speed of 1 mm/min by an Instron 33R 4466 tensile tester equipped with a 500 N load cell. During testing the paper tab attached to one end of the glass fiber was slowly pulled up, while the droplet was constrained by a shearing plate, fixed on a stationary support as shown in Fig. 2(b). The interfacial shear strength (ISS) was computed by Eq. (1):

$$ISS = \frac{F_c}{\pi dL}$$
(1)

where  $F_c$  is the critical applied load, recorded during the test, at which the fiber–matrix interface fails. Each value of interfacial shear strength is an average of at least ten measurements. The single fiber specimens were observed by SEM before and after the test.

The fracture surface of the composites was studied using a Phenom G2 Pro (Phenom-World BV) scanning electron microscope (SEM), at an acceleration voltage of 5 kV. A thin gold coating was applied onto the surface by plasma sputtering to minimize the charging effects. The rheological behavior of the composites was analyzed by an ARES-G2 rheometer (TA Instruments) under controlled strain conditions using parallel plate geometry. The test specimens were disks with a diameter of 25 mm and 1.5 mm thickness. Isothermal frequency sweep tests, in the 0.1–200 rad/s range, were carried out below and above the glass transition temperature of the epoxy ( $T_g$ ), at 25 and 100 °C, respectively (measured  $T_g$  = 64.8 °C). During the measurement, a small amplitude (10%) oscillatory shear strain, which was within the linear viscoelastic range, was applied to the samples. Each data point is an average of three measurements.

Tensile tests were performed according to ASTM D638 with an Instron model 33R 4466 tensile tester equipped with a 10 kN load cell at a crosshead speed of 5 mm/min. Each data point is an average of at least five measurements. Axial strain was recorded by using a resistance extensometer Instron<sup>®</sup> model 2630-101 with a gauge length of 10 mm. The elastic modulus was measured as a secant value between longitudinal deformations of 0.05% and 0.25%. Dynamic mechanical thermal analyses (DMTA) in tensile mode were carried out using a DMA Q800 (TA Instruments) over a temperature range of 20–160 °C, at a heating rate of 5 °C/min and a frequency of 1 Hz. A prestress of 0.2 MPa and a maximum strain of 0.05% were imposed on rectangular samples 25 mm long, 3.30 mm wide and 3.27 mm thick. Impact tests (Izod type) were



Fig. 1. Optical micrograph of (a) as-received GF and (b) GNP-coated GF.



Fig. 2. (a) Schematic representation of a matrix drop deposited onto a rigid fiber and (b) schematic of the microdebonding test.

performed according to ASTM D256 standard, by a mechanical pendulum provided by Custum Scientific Instruments, Inc.

# 3. Results and discussion

# 3.1. Interfacial shear strength

An evaluation of the interfacial properties in the system CNT/ epoxy and glass fibers was investigated by Park et al. by micromechanical and wettability tests [11], finding a significantly greater ISS when using chemically-etched GF with respect to pristine GF due to their higher surface energy. In the same way, CNT/epoxy matrices exhibited higher surface energy than neat epoxy and the resultant work of adhesion between etched GF and CNT/epoxy was maximized in order to obtain higher adhesion. The ISS was also studied in GF/epoxy systems by microdebonding method, observing that the introduction of organo-modified clays led to the formation of a stronger fiber–matrix interface, with an increase of the ISS of about 30% [6]. However, to the best of our knowledge, no information is available in the scientific literature reporting the effect on of GNP homogeneously dispersed in epoxy resin on the fiber–matrix interfacial properties.

A micrograph of a microdebonding single fiber specimen is reported in Fig. 3a, evidencing that the neat epoxy microdrop with a diameter of around 570  $\mu$ m appears symmetrically centered with respect to the fiber axis. Magnifications of the microdrop interface were taken before and after the microdebonding test, as reported in Fig. 3b and c, respectively, in order to investigate the interfacial fracture mechanism occurring during debonding. Noteworthy, the droplet surface shows evident local deformation marks, ascribed to the contact with the shearing plate during testing. Moreover, the matrix appears detached from the fiber surface in correspondence to the interfacial region, confirming that debonding occurred. Although a significant difference on the interface could not be observed when using GNP-coated GF and unfilled epoxy, a different fracture mechanism was evidenced when taking into account as-received GF and epoxy incorporating GNP at 5 wt%. Specifically, the fracture occurring at the GF-5GNP/epoxy interface is characterized by a combined fiber debonding and radial fracture of the matrix, indicating the higher adhesion (Fig. 4). The incorporation of GNP results in a dramatic increase of the ISS evaluated at the interface, indicating a beneficial enhancement in the load transfer across the fiber/matrix interface (Fig. 5). Values of interfacial resistance confirm the superior tensile and viscoelastic properties exhibited by hybrid composites, in particular when considering the ultimate tensile strength and impact resistance.

Interestingly, improved interfacial strengths are also observed when the microdebonding test is performed on the system GFc/ epoxy, evidencing the beneficial effect of the fiber coating on the interfacial interactions. However, the best ISS values are obtained when combining nanomodified epoxy with coated fibers (i.e. 5GNP/GFc), showing an improvement of 58.9%. In particular, the higher ISS can be ascribed to (i) better mechanical and viscoelastic properties of the host matrix and (ii) greater chemical affinity between matrix and fiber, which is further promoted by the coex-



Fig. 3. SEM images of (a) neat epoxy drop deposited on a as-received GF for the microdebonding tests, (b) magnification at the fiber/drop interface before microdebonding, and (c) detail of the interface after debonding.



Fig. 4. SEM images of (a) 5GNP/epoxy drop deposited on a as-received GF for the microdebonding tests, (b) magnification at the fiber/drop interface before microdebonding, and (c) detail of the interface after debonding.



**Fig. 5.** Interfacial shear strength values of GF/epoxy composites, as a function of the GNP amount incorporated in the matrix, considering uncoated (full point) and coated (open point) GF. The GNP content deposited onto the GF is considered  $\sim$ 0.10 wt%.

istence of GNP in the matrix and on the fiber surface. Therefore, the fiber coating effectively enhances the fiber/matrix adhesion, as confirmed by the higher ultimate properties with respect to the composites incorporating uncoated fibers (see Section 3.3).

#### 3.2. Morphology

Fracture surfaces of epoxy composites were analyzed and compared to that of neat epoxy (Fig. 6a). Noteworthy, black lines can be observed on the fracture surface of the neat resin as a result of the relatively brittle fracture occurred. In the SEM micrographs of 5GNP/epoxy sample it can be observed that GNP aggregates with dimension of ~5–10  $\mu$ m are quite well distributed within the matrix, while most of the graphite aggregates do not seem to be intercalated (Fig. 6b).

Morphological analyses conducted on GF composites revealed that the glass fibers are generally well dispersed in the unfilled epoxy matrix, and many fibers are pulled out from the matrix (Fig. 6c). The interfacial debonding appears to be the dominant failure mechanism, indicating low-adhesion condition. On the other hand, a different failure behavior is observed for composites based on epoxy matrix additivated with GNP (Fig. 6d), where fewer fibers are pulled out from the matrix and the matrix crack becomes a concurrent failure mechanism, showing a significantly better fiber-matrix adhesion. Furthermore, the substantial chemical affinity between fiber and matrix is evidenced by the presence of matrix residual on the fiber surface after pull-out. Specifically, previous research evidenced how the higher matrix wettability, which is an indicator of its affinity with respect to other materials, resulted in a greater fiber-matrix interfacial adhesion as measured by single-fiber microdebonding tests [6].

#### 3.3. Tensile mechanical properties and impact strength

As documented in Table 1, the tensile elastic modulus (E) and tensile strength ( $\sigma_B$ ) of the epoxy increase significantly with GNP content and even more in GF/epoxy composites, while the elongation at ultimate tensile strength ( $\varepsilon_{B}$ ) decreases. This trend is consistent with observations for adding fillers to a relatively brittle matrix. Interestingly, although the highest value in elastic modulus is exhibited by the 30GF/epoxy composite (increase by 46%), the greatest  $\sigma_B$  is exhibited by the 5GNP/15GF/epoxy hybrid composites, while maintaining a comparable elastic modulus to that of 30GF/epoxy (increase by 43% compared to neat epoxy). The higher  $\sigma_B$  exhibited by the hybrid composites with respect to the  $\sigma_B$  of GF/ epoxy composites, reflects the greater interfacial shear strength between fiber and matrix which promotes a better stress transfer across the interface, as reported in Section 3.1. The superiority of hybrid composites with respect to GF/epoxy composites is even more evident when the specific properties are taken into account (i.e., specific elastic modulus,  $E^*$ , and specific ultimate tensile strength,  $\sigma_{R}^{*}$ ). The specific properties were obtained as the ratio of each property to the material's density, with the density being calculated using the rule of mixtures. In particular, the  $\sigma_{B}^{*}$  of the hybrid composites is remarkably higher than that of GF/epoxy ones. Moreover, the  $\sim$ 4.6% increase of  $\sigma_{\scriptscriptstyle B}^*$  obtained in the 5GNP/ 10GF/epoxy hybrid composite is slightly greater than the 3.9% increase which is the sum of increase in  $\sigma_B^*$  in the 5GNP/epoxy and 10GF/epoxy composites, possibly indicating a synergistic effect due to the co-existence of the micro- and nano-fillers. Hybrid composites are thus lighter and stronger than GF reinforced epoxy composites.

The mechanical properties are also enhanced when GNP-coated GF are used. Specifically, the properties of the 10GFc/epoxy and 5GNP/10GFc/epoxy composites are better than the properties of the corresponding composites made using the as-received GF, reflecting stronger interfacial interactions and probably better adhesion between the coated GF and the epoxy resin.



Fig. 6. SEM micrographs of fracture surfaces of (a) neat epoxy, (b) 5GNP/epoxy, (c) 10GF/epoxy and (d) 5GNP/10GF/epoxy composites.

#### Table 1

Absolute and specific mechanical properties of epoxy composites.

Sample	<i>E</i> (MPa) <i>E</i> <sup>*</sup> (MPa/(g/cm <sup>3</sup> ))	$\sigma_B$ (MPa) $\sigma_B^*$ (MPa/(g/cm <sup>3</sup> ))	$\varepsilon_B$ (%)	Izod impact strength (J/m)
Ероху	2917 ± 37	59.6 ± 0.7	4.1 ± 0.1	26.5 ± 2.1
	(2537)	(51.8)		
5GNP/epoxy	3543 ± 76	$62.4 \pm 0.2$	3.5 ± 0.1	$28.6 \pm 1.4$
	(3023)	(53.2)		
10GF/epoxy	3793 ± 40	63.7 ± 0.3	3.1 ± 0.2	80.5 ± 2.3
	(3122)	(52.4)		
30GF/epoxy	4266 ± 80	$67.8 \pm 0.2$	$2.0 \pm 0.2$	116.2 ± 2.4
	(3111)	(49.5)		
5GNP/10GF/epoxy	3907 ± 74	$67.0 \pm 0.6$	$3.0 \pm 0.2$	$92.4 \pm 1.9$
	(3156)	(54.2)		
5GNP/15GF/epoxy	4178 ± 91	$70.4 \pm 0.7$	$2.2 \pm 0.2$	107.5 ± 1.9
	(3282)	(55.3)		
10GFc/epoxy	3818 ± 65	$64.7 \pm 0.2$	$3.0 \pm 0.2$	$86.4 \pm 1.4$
	(3140)	(53.2)		
5GNP/10GFc/epoxy	3949 ± 47	67.9 ± 0.2	$2.8 \pm 0.2$	101.4 ± 1.1
	(3189)	(54.8)		

 $E, E^*$ : elastic modulus and correspondent specific value.

 $\sigma_{\rm B},\,\sigma_{\rm B}^*$  : tensile strength and correspondent specific value.

 $\varepsilon_B$ : strain at break.

GFc indicates GNP-coated GF.

The impact strength of the epoxy composites including the hybrid systems is also reported in Table 1, where the synergistic effect due to the presence of both fillers is clearly evidenced. Results show that addition of 5 wt% GNP in epoxy improves the impact resistance by ~8%, indicating the beneficial effect of well-dispersed GNP on the resins' impact toughness. In case of GF/epoxy composites the impact strength noticeably increased with the GF content, and the results show a significant dependence on the GF-epoxy interfacial interactions as indicated by the higher impact strength of the composites containing GNP-coated GF. Owing to

the GF surface modification and the beneficial presence of the nanofiller within the matrix, hybrid composites exhibit a considerable improvement in impact strength when compared to nonhybrid composites at the same GF loading.

## 3.4. Viscoelastic behavior under dynamic shear and tension

The effect of the GF addition on the dynamic shear storage modulus (*G'*) and complex viscosity  $(|\eta^*|)$  of epoxy composites as a function of frequency is reported in Fig. 7a and b, respectively. As



**Fig. 7.** (a) Storage modulus (*G*) and (b) complex viscosity  $|\eta^*|$  of epoxy composites evaluated below (open point) and above  $T_g$  (full point) with respect to angular frequency ( $\omega$ ).

expected, both *G*' and  $|\eta^*|$  significantly increase with the GF loading across the whole frequency range. Moreover, a further increase is recorded upon incorporation of GNP in the 15GF/epoxy composite, mainly because of a pseudo solid-like transition caused by the dispersed fillers [13,14]. Furthermore, the viscosity of the neat resin decreases sharply with frequency due to shear thinning, while the viscosity of composites exhibits a plateau behavior at high frequencies. This frequency independent fluid properties (i.e., Newtonian-type flow) are usually observed in nanocomposites at low filler contents [15].

In addition to the frequency sweep, the viscoelastic rheological properties of the composites were also evaluated at two different temperatures, specifically below and above  $T_g$ . The results are shown in Fig. 7a and b, respectively. As the temperature increases, both the storage modulus and the viscosity decrease as expected due to polymer chain relaxation at high temperatures [16]. The decrease in the storage modulus above  $T_{g}$  can be ascribed to a transition from elastic-solid to viscous-liquid behavior. Considering the results obtained at 25 °C, the effect of GNP on the viscoelastic properties can be isolated from that of the polymer chains, as the last are frozen at temperature below  $T_g$ . Quite in the contrary, the effect of restriction of polymeric chain motion due to GNP-polymer physical interactions significantly contribute in the increase in G'when the rheological properties are evaluated above  $T_{g}$ . Moreover, the 5GNP/15GF/epoxy composite exhibits values of G' comparable with those of 30GF/epoxy (i.e. the typical industrial reference composite), while when the viscosity is taken into account, the hybrid system shows slightly lower values. Noteworthy, the pinning effect

of the nanofiller onto the polymeric chains [17,18] might also pla	łУ
a key role in increasing the viscosity in hybrid composites.	

The dynamic mechanical properties of the composites under investigation were significantly influenced by the fiber weight fraction: as expected, the tensile storage modulus (E') increases with higher GF contents (Table 2), while the loss tangent  $(\tan \delta)$ decreases. In addition, the incorporation of GNP in the epoxy matrix produces a considerable increase of E' and a concurrent decrease of the loss tangent (Fig. 8). Moreover, the glass transition temperature  $(T_g)$ , as evaluated at the tan  $\delta$  peak during DMA experiments, significantly increases in both GNP nanocomposites and GF composites. In particular, the increase in  $T_g$  observed in the nanocomposite can be attributed to a chain-pinning mechanism promoted by polymer-GNP physical interactions. Therefore GNP reinforces the epoxy matrix not only because it is stiffer but also because it remarkably alters locally the physical properties of the polymer. As GNP and GF are filled in the epoxy matrix, the synergistic effect of both fillers could further reduce and restrict molecular motions, and thus enhance the restriction on the rate of relaxation, leading to higher  $T_g$  [18]. Lower values of tan  $\delta$  recorded upon nanofiller addition in hybrid composites (Table 2) can be attributed not only to the stiffening effect and enhanced fibermatrix adhesion, but also to greater physical interactions occurring between polymer and GNP, resulting in lower viscous modulus and improved elastic modulus. With this regard, the storage modulus of the composites was considered below and above  $T_g$  (i.e. at  $T = 25 \circ C$  and  $T = 80 \circ C$ , respectively). In particular, the elastic behavior observable below  $T_g$  better describes the stiffening effect,

Table 2	
Thermal and viscoelastic properties of epoxy composites.	

Sample	<i>E'</i> (25 °C) (MPa)	<i>E'</i> (80 °C) (MPa)	$T_g$ (°C)	$\tan(\delta)_{Tg}$
Ероху	786 ± 16	6 ± 2	$64.8 \pm 0.2$	$1.17 \pm 0.06$
5GNP/epoxy	862 ± 21	15±3	$65.2 \pm 0.3$	$1.07 \pm 0.04$
10GF/epoxy	1032 ± 29	84±6	$66.2 \pm 0.2$	$0.78 \pm 0.04$
30GF/epoxy	1581 ± 32	161 ± 11	$66.8 \pm 0.4$	$0.48 \pm 0.08$
5GNP/10GF/epoxy	1221 ± 24	119±8	67.7 ± 0.3	0.53 ± 0.06
5GNP/15GF/epoxy	1311 ± 35	138 ± 12	67.7 ± 0.3	$0.45 \pm 0.04$
10GFc/epoxy	1062 ± 20	89 ± 9	$66.3 \pm 0.2$	$0.75 \pm 0.03$
5GNP/10GFc/epoxy	$1240 \pm 14$	122 ± 8	$67.9 \pm 0.3$	$0.49 \pm 0.04$

E' (25 °C): storage modulus at 25 °C.

E' (80 °C): storage modulus at 80 °C.

 $T_g$ : glass transition temperature as evaluated in tan  $\delta$  plot.

 $tan(\delta)_{Tg}$ : value of  $tan \delta$  peak.

GFc indicates GNP-coated GF.



**Fig. 8.** Dynamic mechanical properties of epoxy composites (frequency = 1 Hz): storage modulus (E') and loss factor (tan  $\delta$ ) as a function of temperature.

while the elastic behavior investigated above  $T_g$  takes into account the restriction of polymer chain mobility. As a representative example, the storage modulus of the composite 5GNP/10GF/epoxy, normalized with respect to that of 10GF/epoxy, corresponds to 1.18 and 1.42 when considered below and above  $T_g$ , respectively, confirming the chain blocking mechanism due to GNP incorporation.

# 4. Conclusions

In this study, hybrid composites made of epoxy reinforced with GNP and short GF were characterized in terms of their mechanical and viscoelastic properties and the effect of GNP, on these properties and the interfacial shear strength of the GF/epoxy composites, was determined. It was found that the addition of GNP, either dispersed in the epoxy or as a coating of the GF, to GF/epoxy composites significantly increases the elastic modulus without compromising the impact strength and enhances the viscoelastic behavior. The determination of the interfacial shear strength through micro-debonding tests and morphological study indicated that the higher ultimate tensile strength of hybrid composites is ascribed to not only matrix nanomodification, but also to the stronger interfacial interactions between matrix and GF, which are enhanced by the GNP coating of GF.

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