

Mechanical and Dynamic Mechanical Analysis of Hybrid Composites Molded by Resin Transfer Molding

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Received 29 October 2009; accepted 1 March 2010

DOI 10.1002/app.32388

Published online 26 May 2010 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: This work aims to evaluate the performance of glass/sisal hybrid composites focusing on mechanical (flexural and impact) and dynamic mechanical analyses (DMTA). Hybrid composites with different fiber loadings and different volume ratios between glass and sisal were studied. The effect of the fiber length has also been investigated. The densities of the composites were compared with the theoretical values, showing agreement with the rule of mixtures. The results obtained in the flexural and impact analysis revealed that, in general, the properties were always higher for higher overall reinforcement content. By DMTA, an increase in the storage and loss modulus was found, as well as a shift to higher values for higher glass

loading and overall fiber volume. It was also noticed an increase in the efficiency of the filler and the calculated activation energy for the relaxation process in the glass transition region. The fiber length did not significantly change the results observed in all analyses carried out in this work. The calculated adhesion factor increased for higher glass loadings, meaning the equation may not be applied for the system studied and there are other factors, besides adhesion influencing energy dissipation of the composites. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 118: 887–896, 2010

Key words: resin transfer molding; hybrid composites; dynamic mechanical thermal analysis

INTRODUCTION

Polymer matrix composites are widely used nowadays because they may yield a unique combination of high performance, great versatility, and processing advantages at a reasonable cost.¹ The combination of a variety of fibers and polymers produces a wide range of composites, which are viable alternatives to conventional materials like metal and wood.

Among the techniques for the manufacture of thermoset polymer composites, resin transfer molding (RTM) is becoming very popular in the automotive and aerospace sectors because it is an eco-friendly process, as it is carried out in a closed mold.² RTM involves placing a fibrous preform in a cavity, followed by resin injection under preset pressure and temperature conditions, being then cured *in situ* to form the final part.³ The essential step in the RTM process is the fiber impregnation, to minimize undesirable effects like void content or non-uniform fiber wetting.⁴ During the course of the infiltration, the resin must wet the surface of the

reinforcement, eliminating voids and promoting intimate fiber/resin contact, which is vital for a strong adhesion between these phases. Adhesion is a major contributor to the performance of the composite, controlling the load transfer ability of the matrix/reinforcement interface. Usually, stronger interfaces result in stronger, but more brittle, composite materials. A variety of physical and chemical surface treatments for reinforcements may be found in the literature as a way of improving adhesion, especially for natural fibers.⁵

In the past two to three decades, thermoset composites with natural fibers have been extensively studied. However, their application is limited because of their generally poor mechanical properties and high moisture absorption compared with composites with synthetic fibers. Seeking to minimize these drawbacks, broadening the possible range of applications, research on the combined use of synthetic and vegetable fibers, i.e., on hybrid composites, is increasing.⁶ If the fibers are adequately combined, the resulting materials could be used in a variety of applications in different fields, for instance, the automotive sector, mostly in interior, but also in exterior components of cars, busses, and trucks.

As the fiber reinforced materials undergo various types of dynamic stressing during service, studies on their viscoelastic properties are of great

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Contract grant sponsors: UFRGS, UCS, CNPq, CAPES, FAPERGS.

importance. In fact, the dynamic properties of polymeric materials are of considerable practical significance, particularly if they are determined over a wide range of frequency and temperature.⁷ They can give insight into various aspects of the material structure, provide a convenient measure of polymer transition temperatures and may influence other properties such as flexural and impact strength.⁸ They are also of direct relevance to applications related to the isolation of vibrations or dissipation of vibration energy in engineering components.

Martínez-Hernández et al.⁹ carried out dynamic mechanical analysis of composites comprised of keratin biofibers from chicken feathers in a PMMA matrix. A shift in the glass transition temperature (T_g) to higher temperatures was observed for higher keratin content due to the constraints imposed on the polymeric molecules through the interface. The glass transition temperature, also known as α -transition for amorphous polymers, is the temperature at which energy dissipation reaches a maximum, as observed in DMTA analysis.

According to Hameed et al.,⁸ the activation energy required for the relaxation of the glass-fiber composites increased with fiber loading. An increase in storage modulus as well as a shift in T_g were noted and the stiffness imposed by the fiber was considered responsible for the higher activation energy. In addition, the effectiveness of the filler was calculated, showing lower values for higher fiber loading. Idicula et al.¹⁰ studied the peak width and the peak width at half height in DMTA and reported that the fiber to fiber contact increases with fiber volume fraction, decreasing the effective stress-transfer between fiber and matrix. Pothan et al.¹¹ concluded that maximum peak width is found for composites with maximum fiber content (in their case, 40%).

In fact, a considerable amount of work has been reported on the viscoelastic properties of polymer composites reinforced by a single type of reinforcement.^{7,12-14} However, the literature lacks works on the characterization of polymeric hybrid composites by DMTA, may be due to the complexity involved in such analysis. On this context, this work aims to evaluate the performance of glass/sisal hybrid composites focusing on mechanical testing (flexural and impact) and, particularly, dynamic mechanical analysis (DMTA) in order to contribute with the understanding of these hybrid systems.

EXPERIMENTAL

Materials

Commercial unsaturated polyester resin Polydyne 7001-041R (supplied by Cray Valley) was used to prepare the composites. Glass fiber roving, EC 2400

P207, was purchased from Vetrotex and sisal roving from Sisalândia Fios Naturais (Brazil). Commercial grade methyl ethyl ketone (MEK) peroxide (curing agent; Butanox M-50 from Akzo Nobel) and dimethylaniline (catalyst; Confibras) were also used. Sisal fibers are commonly known as much less rigid and strong and also to allow much weaker adhesion to polyester in comparison with glass fibers, whereas the latter shows lower strain at break.

Molding of the composites

Composites were prepared using the RTM technique. Both fibers (sisal and glass) were chopped to the desired length; the sisal was washed and then dried in an oven with air circulation (90°C, 40 min) before use. Mold-releasing agent (PVA) was applied to the mold before molding. The fibers were mixed and, after that, manually arranged in a premold of the required shape to produce a rectangular hybrid mat. After this, the mat was placed on the RTM mold and pressed. Orthophthalic polyester resin (100 mL) was mixed with 1 mL of MEK peroxide (curing agent) and 0.3 mL dimethylaniline (catalyst). In the RTM process, the resin mixture was injected into the closed mold under a positive pressure of 0.5 kg/cm² and allowed to cure *in situ* for 50 min and rest for 48 h at room temperature.

Composite sheets were prepared varying the fiber length (30 or 40 mm), overall fiber loading (10 or 20 vol %) and following different relative volume fractions between sisal and glass, i.e., 100 : 0, 75:25, 50 : 50, and 25 : 75, which were called 100% sisal, 75% sisal, 50% sisal, and 25% sisal, respectively. The samples were identified considering all these variations. For example, the composite prepared using 20 vol % overall fiber loading, 25% relative volume fraction of sisal and 30 mm fiber length was identified as (20/25/30). Table I shows the compositions of all studied composites.

Characterization

The density of the specimens was determined according to ASTM 792 in water. Flexural tests were carried out according to ASTM D790 using an EMIC DL 3000 testing machine. Five specimens were tested

TABLE I
Composition of the Composites

Total volumetric fraction of reinforcement (%)	Fiber length (cm)	Glass fiber content (%)	Sisal fiber content (%)
10 or 20	3 or 4	0	100
10 or 20	3 or 4	25	75
10 or 20	3 or 4	50	50
10 or 20	3 or 4	75	25

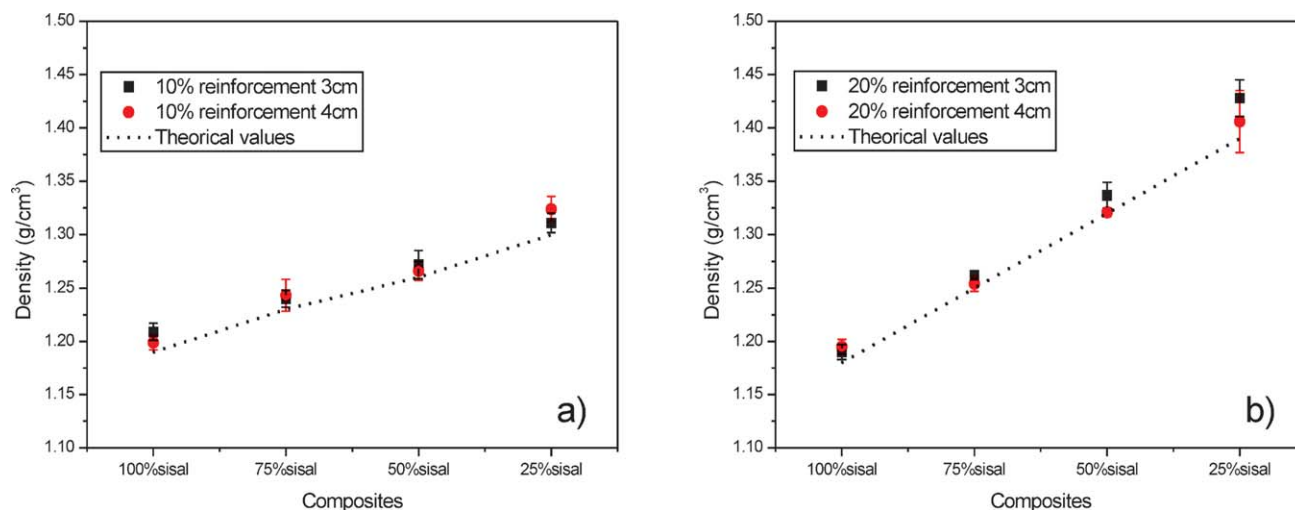


Figure 1 Specific gravity values for the sisal/glass composites vs. reinforcement content and fiber length. (a) 10% reinforcement, (b) 20% reinforcement. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

in each case and the average values are reported. Impact testing was carried out using a CEAST Resil 25 impact machine and impact strength was calculated following ASTM D256, with 5.5 or 7.5 J hammer. Five specimens were tested in each case and the average values are reported.

The viscoelastic properties of the composites were characterized using an Anton Paar Physica MCR 101 DMTA equipment and rectangular specimens $50 \times 10 \times 4$ mm. Tests were performed at the frequencies of 1, 3, 10, or 30 Hz. The specimens were heated from room temperature to 180°C at a heating rate of 3°C min^{-1} and the experiment was carried out in torsion mode at strain amplitude of 0.1%.

RESULTS AND DISCUSSION

General characterization

The density of the composites, both experimental and theoretical, are shown in Figure 1. As expected, specific gravity is higher for composites with higher fiber loading, as the fibers are heavier than the resin. Also, there was an increase in density for higher glass fiber content because the glass is heavier than the other components. There was no clear influence of the fiber length in the density of the composites studied and the variations observed were attributed to the heterogeneity of the vegetable fiber. Moreover, there was a reasonable agreement between the observed and the theoretical values considering again fiber heterogeneity and a possibly variable void content in the composites.

The flexural modulus (Fig. 2) and strength (Table II) showed an increase with increasing overall fiber volume and glass loading, whereas the small variation in fiber length (from 3 to 4 cm) did not show a signifi-

cant and clear influence. This is an expected consequence of the better glass adhesion to polyester in comparison to the sisal adhesion and a consequently higher allowable degree of stress transfer to the fibers during loading. Table II also shows the elongation at break for all composites and the composites with $V_f = 10\%$ always showed lower values than those with $V_f = 20\%$, so there appears to be a minimum amount of fiber that enables a representative occupation of the whole volume of the sample in such a way that promotes better composite properties.

Increasing the overall fiber loading and the glass fiber content of the composites led to an increase in impact strength, as shown in Figure 3, whereas the small variation in fiber length did not show a significant influence. The fiber adhesion to the matrix plays a major role on impact strength of the composites and this increase can be attributed to energy dissipation at the interface in order to detach the fibers from the matrix. This mechanism is more prominent at the glass-matrix interface in comparison to the sisal-matrix one, that is why strength decreases with the sisal content in the composite.

Dynamic mechanical analysis

Storage modulus

The dynamic storage modulus (E') is defined as the stress in phase with the strain in a sinusoidal shearing deformation divided by the strain.¹⁵ The variation in the storage modulus as a function of temperature for the studied composites is given in Figures 4 and 5. As the temperature increases, E' decreases for all composites and this can be attributed to the increase in the molecular mobility of the polymer chains.¹⁶ A prominent increase in storage modulus of the matrix

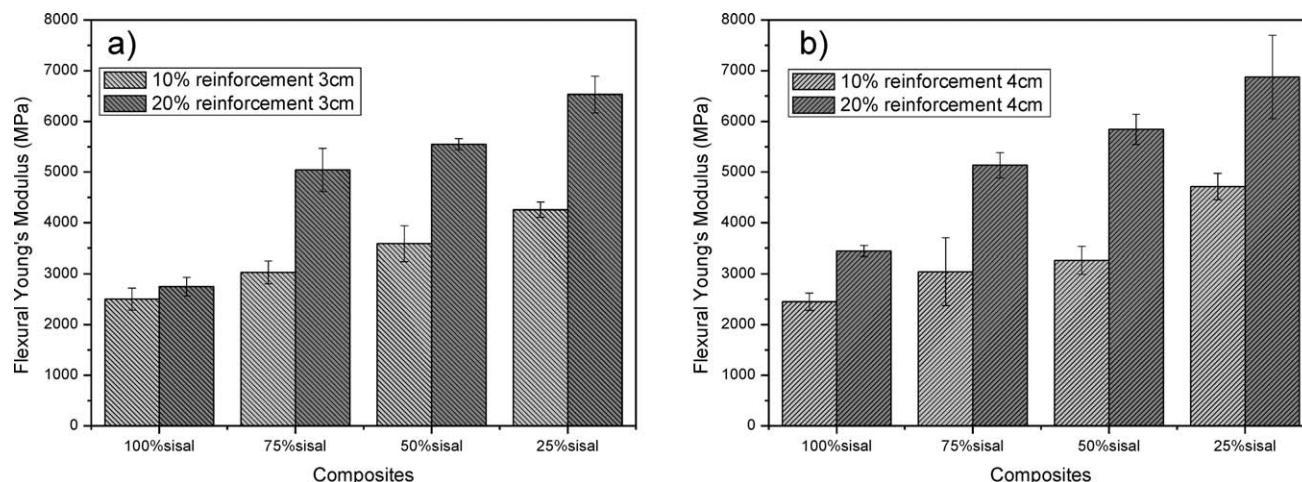


Figure 2 Elastic modulus for the composites vs. reinforcement content and fiber length. (a) 3 fiber length, (b) 4 fiber length.

in the elastomeric region with the incorporation of fibers is expected due to an increase in stiffness of the matrix with the reinforcing effect imparted by the fibers.⁸ There is a clear increase in E' with fiber loading and the maximum E' values were found for the composite with the highest glass fiber content of all samples (i.e., sample 20/25/3). This may be associated with the strong fiber/matrix interaction and the high elastic modulus of the glass fiber.^{11,15,16}

The drop in modulus around the glass transition region (in the 50–90°C range) is much smaller for composites with higher fiber loading and glass fiber content. In other words, the difference between E' values in the glassy and in the rubbery state is smaller for composites with higher glass fiber content than for the others or the neat resin, which clearly indicates the significant reinforcing effect of the glass fiber. The fiber effect on the modulus of the composite, i.e., its effectiveness, can be better represented by a coefficient “ C ”, shown in eq. (1).¹¹

$$C = \frac{(E'_g/E'_r)_{\text{composites}}}{(E'_g/E'_r)_{\text{resin}}} \quad (1)$$

where E'_g and E'_r are the storage modulus values in the glassy (set to 35°C) and rubbery region (set to

150°C), respectively. Thus, the C parameter is a relative measurement of the decrease in modulus when temperature increases and the material passes through its glass transition. A large fall for an unfilled system is expected as the stiffness at high temperature is determined by the amorphous regions, which are very compliant above the relaxation transition, i.e., there will be higher chain mobility and therefore less rigidity. It is important to mention that modulus in the glassy state is determined primarily by the strength of the intermolecular forces and the way the polymer chains is packed.¹¹ Furthermore, the expected drop in modulus for reinforced systems is comparatively less than for unreinforced ones. The specific shift in T_g in the glassy region is particular to each composite and a high C value in a reinforced system indicates a less effective fiber or filler.

The values obtained from different systems at a frequency of 1 Hz are given in Table III. It can be observed that C decreases upon fiber loading and the lowest value was found for the 20/25/3 composite. Higher reinforcement content increases the constraints imposed to the matrix.¹⁷ When the fiber content is low, the distribution of the fibers throughout the matrix is less efficient, with many matrix-rich

TABLE II
Flexural Properties of the Composites

Sample	Flexural strength (MPa)	Elongation at break (%)	Sample	Flexural strength (MPa)	Elongation at break (%)
10/100/3	88.2 ± 24.2	3.3 ± 0.4	20/100/3	116.0 ± 11.2	4.9 ± 1.4
10/75/3	133.7 ± 12.1	4.3 ± 0.2	20/75/3	266.0 ± 2.9	8.3 ± 1.0
10/50/3	166.5 ± 9.5	4.5 ± 0.5	20/50/3	276.6 ± 52.9	6.3 ± 0.8
10/25/3	264.1 ± 11.7	5.1 ± 0.3	20/25/3	361.1 ± 32.1	6.9 ± 1.2
10/100/4	95.1 ± 15.6	4.3 ± 0.3	20/100/4	120.9 ± 49.5	5.1 ± 2.7
10/75/4	141.8 ± 36.1	4.3 ± 1.8	20/75/4	218.1 ± 15.6	7.5 ± 0.7
10/50/4	184.6 ± 18.0	5.0 ± 0.3	20/50/4	282.1 ± 23.9	6.4 ± 1.6
10/25/4	269.1 ± 31.6	5.2 ± 0.6	20/25/4	372.2 ± 41.3	6.5 ± 1.3

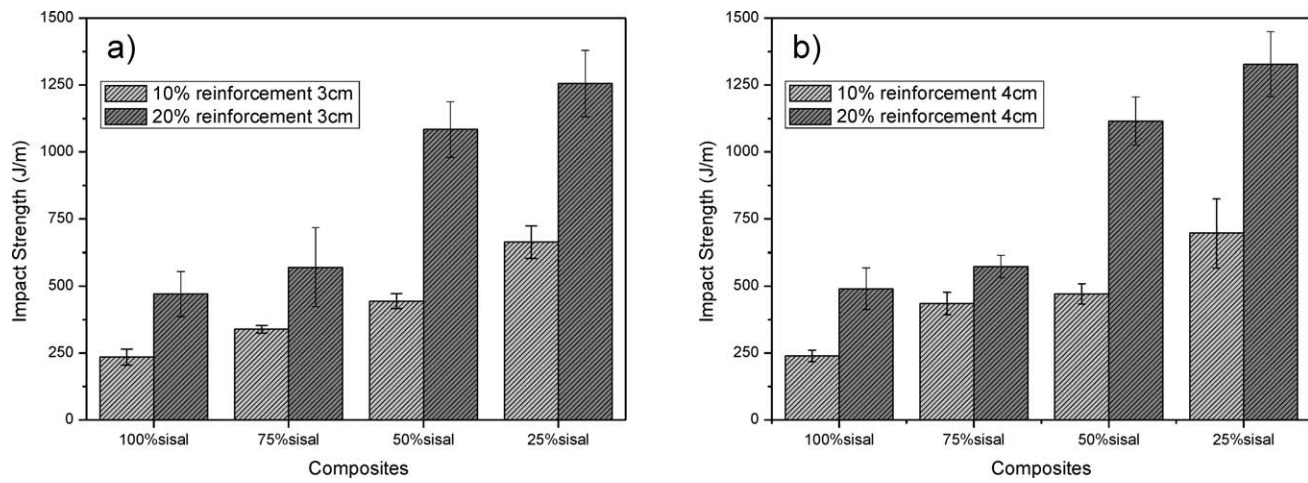


Figure 3 Impact strength of the composites *vs.* reinforcement content and fiber length. (a) 3 fiber length, (b) 4 fiber length.

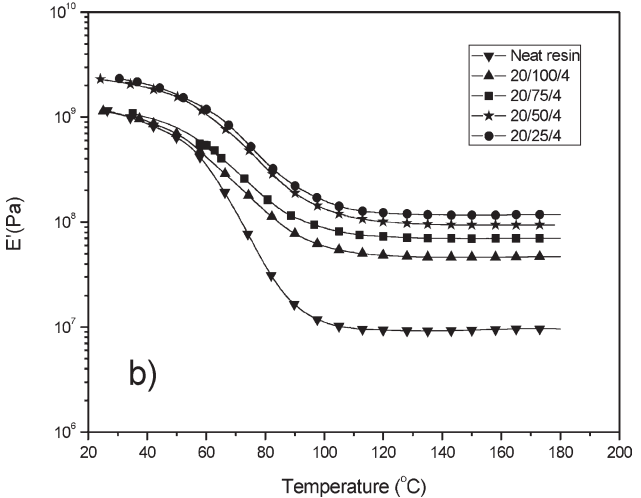
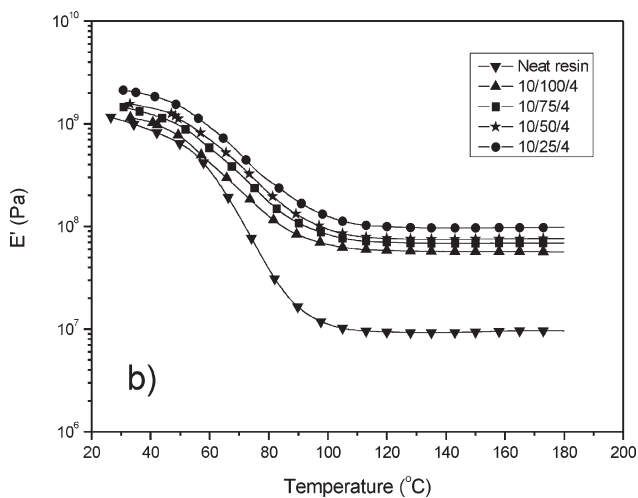
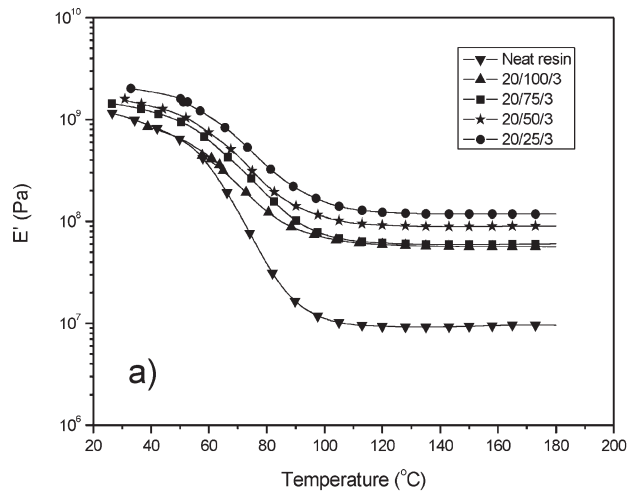
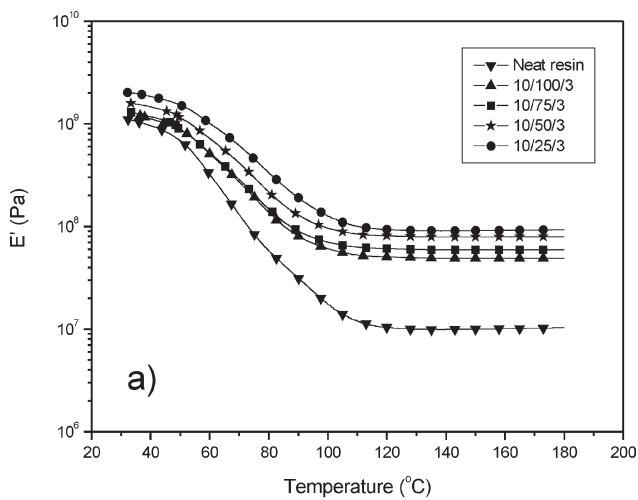


Figure 4 Storage modulus *vs.* temperature for composites with 10 vol% overall fiber reinforcement. (a) 3 fiber length, (b) 4 fiber length.

Figure 5 Storage modulus *vs.* temperature for composites with 20 vol % overall fiber reinforcement. (a) 3 fiber length, (b) 4 fiber length.

TABLE III
The Coefficient C for Different Sisal/Glass Composites

Sample	C	Sample	C
10/100/3	0.196	20/100/3	0.169
10/75/3	0.162	20/75/3	0.153
10/50/3	0.121	20/50/3	0.108
10/25/3	0.105	20/25/3	0.081
10/100/4	0.175	20/100/4	0.174
10/75/4	0.151	20/75/4	0.155
10/50/4	0.127	20/50/4	0.102
10/25/4	0.099	20/25/4	0.082

regions, resulting in higher C values.⁸ Another factor that may be associated with the increase in E' is the interference of neighboring segments, since there must be greater molecular cooperation for the relaxation process to occur.¹⁸

Loss modulus

The loss modulus (E'') is defined as the stress 90° out-of-phase with the strain divided by the strain. It

is a measure of the energy dissipated as heat per cycle under deformation, i.e., the viscous response of the material.¹⁵ Figures 6 and 7 show the variation in E'' with the temperature for the different composite systems. From these figures, it is clear that the incorporation of glass fiber causes a broadening of the loss modulus peak. This may be attributed to the inhibition of the relaxation process within the composites as a consequence of a higher number of chain segments upon fiber addition.⁸

There is an apparent shift in T_g toward higher temperatures on increasing the glass fiber content and the overall fiber loading. This is primarily attributed to the segmental immobilization of the matrix chain at the fiber surface.⁷ The loss modulus in the transition region is also higher for composites with higher glass fiber content and higher total fiber loading, which may be due to an increase in internal friction, promoting energy dissipation.

The high modulus glass fibers introduce constraints on the segmental mobility of the polymeric molecules at the relaxation temperatures, but,

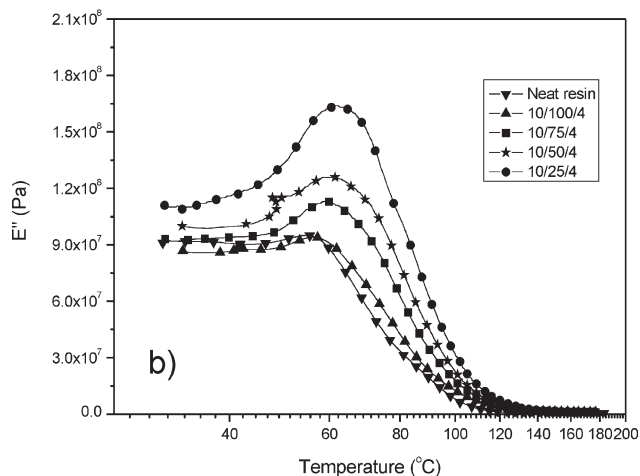
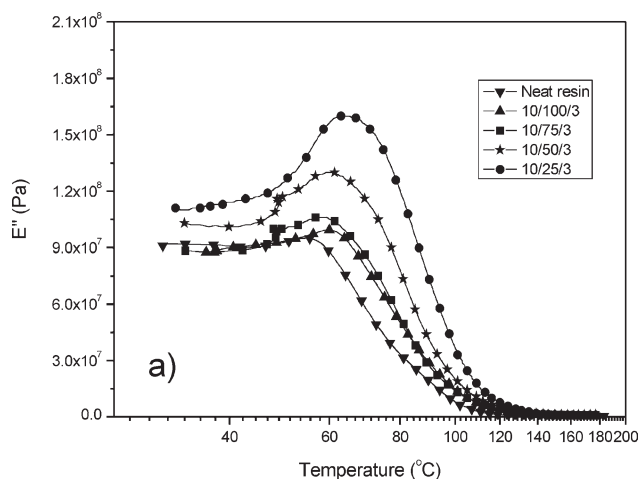


Figure 6 Loss modulus vs. temperature for composites with 10 vol % overall fiber reinforcement. (a) 3 fiber length, (b) 4 fiber length.

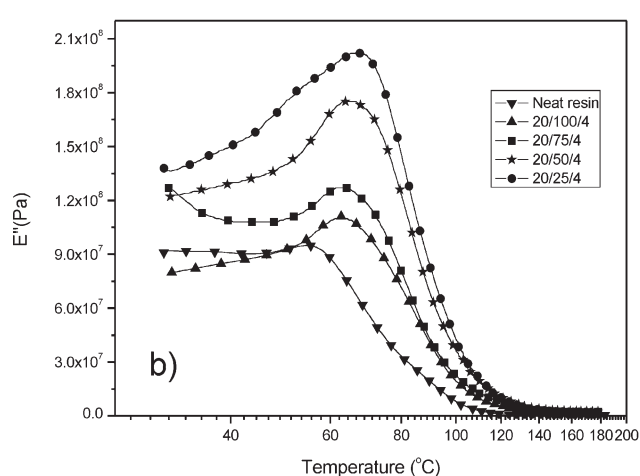
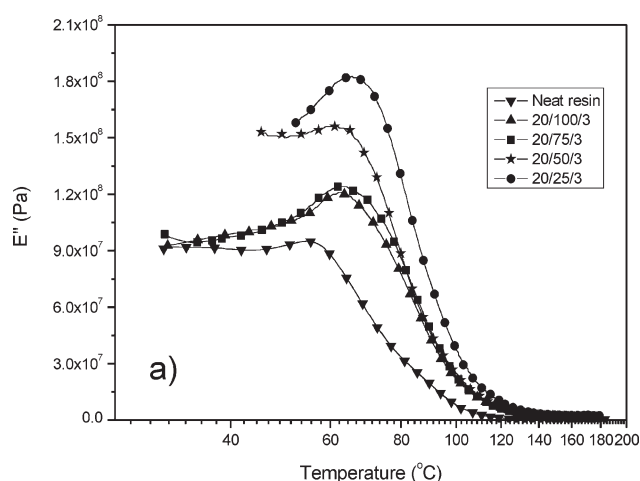


Figure 7 Loss modulus vs. temperature for composites with 20 vol % overall fiber reinforcement. (a) 3 fiber length, (b) 4 fiber length.

TABLE IV
Tan δ Peak Height and Width at Half Height for Different
Sisal/Glass Fiber Composites

Sample	Peak height	Peak width at half height	Sample	Peak height	Peak width at half height
Neat resin	0.540	13.205	Neat resin	0.540	13.205
10/100/3	0.314	9.414	20/100/3	0.271	9.183
10/75/3	0.310	8.975	20/75/3	0.304	9.006
10/50/3	0.340	9.422	20/50/3	0.355	9.305
10/25/3	0.345	9.452	20/25/3	0.326	9.305
10/100/4	0.283	8.906	20/100/4	0.299	10.029
10/75/4	0.317	9.096	20/75/4	0.283	10.472
10/50/4	0.335	9.293	20/50/4	0.336	9.903
10/25/4	0.341	9.393	20/25/4	0.355	10.560

probably, there are also other factors that lead to energy dissipation.¹⁹ It can be observed that, for higher fiber content, the loss modulus curve spreads over a wider distribution and shows a higher peak. This effect can be a consequence of the inhibition/restriction of the relaxation process of the chain segments in the composites or due to an increase in the rigidity of chain segments, increasing material heterogeneity.¹⁰

A higher peak height may be associated to a poor interface.⁹ However, in general, it may also be attributed to an increase in the mobility of the polymer chains.²⁰ The width of the relaxation curve is characterized by the β factor of the Kohlrausch-Williams-Watts equation (KWW). A low β value implies a wider distribution, whereas a β value close to the unity means a perfectly narrow relaxation spectrum.^{21,22} An increase in free volume usually results in a decrease in the number of cross-linking sites of the polymeric matrix, because there is less cross-linked space between fiber and resin. Also, a tendency toward an α -transition shift is noted for higher temperatures increasing the glass content.

Damping parameters

The ratio between the loss modulus and the storage modulus is called the mechanical loss factor, or tan δ . The damping properties of the material give the balance between the elastic and viscous phases in a polymeric structure.²³ In composites, damping is influenced by the incorporation, type and distribution of fibers, as well as the fiber/matrix interaction and the void content.^{13,24-27}

All materials exhibit a relaxation process, which is associated with the glass-rubber transition of the matrix. It has been observed that as the temperature increases, the damping values pass through a maximum in the transition region and then decrease in the rubbery region. This relaxation process, denoted as α , involves the release of cooperative motions of

chains between crosslinks. Below T_g , damping is low because, in this region, the chain segments are in the frozen state. Hence, the deformations are primarily elastic and the molecular slips resulting in the viscous flow are low. Also, in the rubbery region, the molecular segments are quite free to move and hence damping is low and thus there is no resistance to flow.^{8,28} However, in the transition region, the molecular chains begin to move and every time a frozen segment begins to move its excess energy is dissipated as heat. In fact, a frozen-in segment in the glassy state can store more energy for a given deformation than a rubbery segment, which can move freely. In a region where most of the chain segments take part in a cooperative motion under a given deformation, maximum damping will occur.^{8,11,14}

The position and height of the tan δ peak are indicative of the structure and properties of a particular composite material. Generally, composites have considerably less damping in the transition region compared to neat resin because the fibers carry a greater amount of the load and allow only a small part of it to strain the interface.⁷ Therefore, energy dissipation will occur in the polymer matrix at the interface and a stronger interface allows less dissipation. This may be due to a restriction of the movement of the polymer molecules due to the incorporation of the stiff fibers.¹⁰

The tan δ peak height and peak width at half height data obtained are summarized in Table IV. As in the case of the E'' curves, the tan δ curves of the composites shift towards higher values for higher overall and glass fiber content. In general, this is indicative of a poor interface. Since a lower peak height indicates a good interfacial adhesion,²⁹ according to the results shown in this study other factors contribute to the softening of the interface. Generally, composites containing less fiber content exhibit higher peak heights. One reason for this may be that there is less matrix by volume with higher glass content, and there is more energy at the

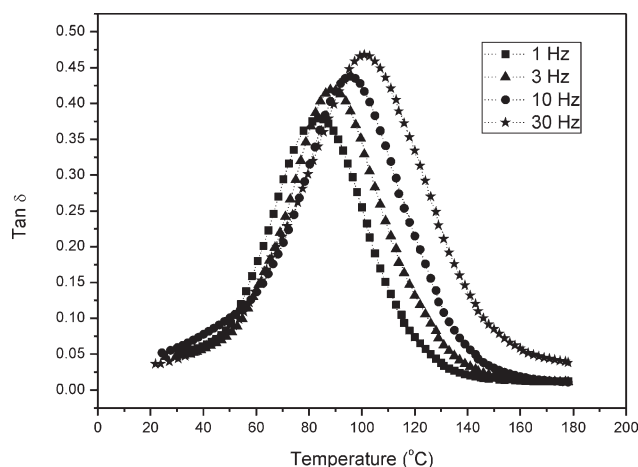


Figure 8 Variation of $\tan \delta$ with temperature at different frequencies for the 10/25/4 composite.

interface because of the increase in the interfacial area. The matrix dissipates more energy than composites, because the fibers carry a greater amount of the load, dissipating a small part of it to strain the interface.

The width of the $\tan \delta$ peak of the composites also becomes broader upon fiber addition. At lower fiber concentrations, the packing of fibers will become inefficient leading to matrix-rich regions and therefore the matrix is not restrained by sufficient fibers and highly localized strains will occur.¹⁰ Higher value was obtained for the matrix more crosslinking sites, as a consequence, a more heterogeneous system is obtained.

The effect of frequency

The viscoelastic properties of a material depend on the temperature and the frequency (time), and because of that dynamic mechanical tests are usually performed over a temperature range at constant frequency or vice versa.³⁰ Any material subjected to a constant stress over a period of time, undergoes a decrease in its elastic modulus due to its molecular rearrangement in order to minimize the localized stresses.¹¹ Modulus measurements performed over a short time (high frequency) result in higher values³¹ and this behavior is clear in Figure 8. The variation in $\tan \delta$ with temperature at different frequencies shows that the $\tan \delta$ peak height increases with frequency.

The T_g of the composite is also shifted towards higher temperatures for higher frequencies. This can be explained by the Arrhenius relationship.¹⁴ The shift in the transition temperature allows the estimation of the apparent activation energy of the relaxation (E_a) for each of the composites assuming a linear equation of the type shown in eq. (2)

TABLE V
Activation Energy (E_a) of Different Sisal/Glass Fiber Reinforced Composites and the Determination Coefficient (R^2) of the Respective Fitting Curves Used

Sample	E_a (kJ/mol)	R^2	Sample	E_a (kJ/mol)	R^2
Neat resin	248.9	0.974	Neat resin	248.9	0.974
10/100/3	176.9	0.990	20/100/3	201.6	0.968
10/75/3	223.9	0.996	20/75/3	238.4	0.974
10/50/3	234.8	0.998	20/50/3	243.0	0.996
10/25/3	237.6	0.991	20/25/3	254.3	0.994
10/100/4	161.8	0.939	20/100/4	205.6	0.955
10/75/4	217.5	0.994	20/75/4	235.4	0.934
10/50/4	231.5	0.998	20/50/4	246.0	0.986
10/25/4	235.6	0.999	20/25/4	260.5	0.952

$$\log f = \log f_0 - \frac{E_a}{2.303 R T} \quad (2)$$

where f is the measured frequency, f_0 is the frequency when the temperature approaches infinite, T is the $\tan \delta$ maximum temperature and R is the universal gas constant. The slope of the plot obtained from plotting $\log f$ vs reciprocal temperature will give the activation energy (E_a) for the relaxation process. The E_a values obtained along with the determination coefficient (R^2) of the respective fitting curves are given in Table V. The activation energy of the composites increases upon fiber loading. The stiffness imposed by the rigid glass fiber accounts for the higher activation energy. For the resin, higher values were obtained due to the more regular reticulate system in relation to the other samples.

The activation energy in the α -transition gives an approximation of the energy required to promote the initial movement of some molecular segments in the polymer backbone.³² On increasing the reinforcement, more energy is needed to initiate this movement. The activation energy values are in agreement with the storage modulus, where higher values indicate higher matrix/fiber interaction.¹¹

Table VI gives the T_g values obtained at 1 Hz frequency. A shift to higher temperatures can be

TABLE VI
 T_g Values (at 1 Hz) for the Various Composites Obtained from $\tan \delta$ Data

Sample	T_g (°C)	Sample	T_g (°C)
Neat resin	80.1	Neat resin	80.1
10/100/3	80.8	20/100/3	82.0
10/75/3	82.6	20/75/3	83.2
10/50/3	83.6	20/50/3	84.7
10/25/3	84.9	20/25/3	85.3
10/100/4	79.9	20/100/4	82.2
10/75/4	82.2	20/75/4	83.5
10/50/4	83.2	20/50/4	84.4
10/25/4	85.0	20/25/4	86.1

TABLE VII
Adhesion Factor Values at T_g for the Different Composites Calculated from DMTA

Sample	A	Sample	A
10/100/3	0.121	20/100/3	0.280
10/75/3	0.146	20/75/3	0.298
10/50/3	0.160	20/50/3	0.322
10/25/3	0.178	20/25/3	0.331
10/100/4	0.108	20/100/4	0.283
10/75/4	0.140	20/75/4	0.303
10/50/4	0.154	20/50/4	0.317
10/25/4	0.179	20/25/4	0.344

observed with the increase in overall fiber and glass content. The latter is because of the decrease in the number of comparatively more fragile regions (sisal) and because a higher energetic contribution is required to promote the initial cooperative segmental movement. The incorporation of the glass fiber decreases the flexibility of the material introducing constraints on the mobility of the polymeric molecule segments at the relaxation temperatures, which confirms the effectiveness of the glass fiber as a reinforcing agent.

Adhesion factor

An adhesion factor (A) may be determined from the mechanical damping ($\tan \delta$) of the composite and the neat resin as a function of the reinforcement content and the temperature.¹⁴ Furthermore, in this work, the adhesion factors shown in Table VII were determined at T_g , according to Correa et al.¹⁷ Higher degree of interaction between the fiber and the matrix, i.e. lower adhesion factor, yields reduced molecular mobility in the neighborhood of the fiber surface compared to the matrix. Thus, damping tends to reduce at the interface whenever there is a higher degree of interaction or adhesion between the constituents.³³ Indeed, according to Giraldi,³³ there is an increase in molecular mobility near the interface, as the degree of fiber/matrix adhesion decreases.

However, Table VII shows an increase in A values with the incorporation of more reinforcement or a more adherent reinforcement. Thus, these results did not follow the same trend reported by Correa,¹⁷ perhaps indicating that energy dissipation may not be only associated with fiber/matrix interaction when this methodology is applied to hybrid composites, which are a more complex system.

CONCLUSIONS

In this article physical, mechanical, and dynamic mechanical properties of sisal/glass fiber reinforced polyester composites are described. The density of the composites varied as expected, and a close

agreement with the predicted values was obtained. The flexural and impact properties of sisal/glass reinforced polyester composites were observed to improve with the incorporation of glass fibers, whereas the small variation in fiber length did not showed a clear effect on the flexural properties of the composites.

The effect of hybridization on the dynamic mechanical properties was studied in detail. As expected, the storage and loss modulus decreased with the increase in temperature, which is associated with a softening of the matrix at higher temperatures. The storage modulus increased with increasing fiber loading and this was due to the reinforcement effect imparted by the fibers which are more rigid than the matrix.

The loss modulus curves were found to distribute over a wider range and reach higher peak values for higher fiber content. These curves, which are indicative of the dissipated energy, were found to be shifted to higher positions following the incorporation of more glass fibers into the composites. The incorporation of glass fibers also caused a broadening of the loss modulus peak which was attributed to the inhibition of the relaxation process within the composites. The higher loss modulus at the relaxation temperature was associated with an increase in internal friction which enhances energy dissipation. Additionally, despite the presence of high-modulus glass fibers, which introduce constraints on the segmental mobility of the polymeric molecules at the relaxation temperature, there are other factors that lead to energy dissipation.

There was a shift in the glass transition towards higher temperatures on increasing the overall fiber loading and the glass fiber content. This is because of restrictions imposed on the mobility of the polymer molecules at the interface. The highest activation energy values were obtained for the composites with higher glass fiber content. The glass transition temperature increased with increasing frequency of the analysis due to the dephasing response of the composite at higher frequencies. The adhesion factor increased for higher fiber contents, suggesting that, for hybrid composites, energy dissipation is not associated only with fiber/matrix adhesion being of more complex analysis when more than one type of fiber is present in the system.

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