



**QUEEN'S
UNIVERSITY
BELFAST**

Study of hybrid intralaminar carbon/glass composites

Almeida Júnior, J. H. S., Ornaghi Júnior, H. L., Amico, S. C., & Amado, F. D. R. (2012). Study of hybrid intralaminar carbon/glass composites. *Materials & Design*, 42, 111-117.
<https://doi.org/10.1016/j.matdes.2012.05.044>

Published in:
Materials & Design

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

Copyright 2021 the authors.

This is an open access manuscript distributed under a Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the author and source are cited.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: <http://go.qub.ac.uk/oa-feedback>

STUDY OF HYBRID INTRALAMINATE CURAUA/GLASS COMPOSITES

José Humberto Santos Almeida Júnior^{a*}, Heitor Luiz Ornaghi Júnior^b, Sandro Campos Amico^b,

Franco Dani Rico Amado^a

^aState University of Santa Cruz/Exact Science and Technology Department, Ilheus/Itabuna highway, km16. 45662-900, Ilheus/BA, Brazil. humberto.junior@ufrgs.br; franco.amado@gmail.com.

^bFederal University of Rio Grande do Sul/Materials Engineering Department, Av. Bento Gonçalves, 9500. 91501-970, Porto Alegre/RS, Brazil. ornaghjr.heitor@yahoo.com; amico@ufrgs.br.

* *Corresponding author:* E-mail: humberto.junior@ufrgs.br. Tel.: +55 51 3308 9419 Fax: +55 51 3308 9414.

Abstract

In this study, thermal, mechanical and dynamic mechanical analyses of hybrid intralaminar curaua/glass composites were carried out. Distinct curaua/glass fiber content ratio and overall fiber volume fraction (20, 30 and 40 vol. %) were studied. Thermal analysis showed higher thermal stability for the glass reinforcement. Mechanical properties showed, in general, higher impact strength and hardness with glass incorporation. Dynamic mechanical properties showed an increase in storage modulus whereas the glass transition temperature showed no significant trend with glass incorporation. Furthermore, a significant increase in overall properties can be obtained without significantly change the glass transition temperature. Finally, the composites containing more effective reinforcement were more successful in maintaining their properties along the range of temperature studied. Hybridization has been successful and the composite with 30% of curaua fiber replacing the glass fiber displayed similar properties than the pure glass composite.

Keywords: Intralaminar composites, natural fiber, dynamic mechanical analysis, viscoelastic properties.

1. Introduction

Composite materials are designed to combine desirable characteristics of two or more distinct materials. The reinforcement can be synthetic (e.g. glass, carbon, boron and aramid) or of natural sources (e.g. curaua, sisal, jute, piassava, hemp, coir, flax and banana). The main advantages of using natural fibers are: abundance and renewability, low cost, non-abrasiveness, easy processing, non-toxicity, high flexibility, acoustic insulation and low density [1,2]. On the other hand, there are some drawbacks such as their poor mechanical properties and high moisture absorption. The latter is due to their hydrophilic nature that is detrimental to many properties, including dimensional stability [3].

Nevertheless, some composite components (e.g. for the automotive sector), previously manufactured with glass fibers are now produced with natural fibers. Applications including door panels, trunk liners, instrument panels, interior roofs, parcel shelves, among other interior components, are already in use in European cars due to the more favorable economic, environmental and social aspects of the vegetable fibers [4].

The curaua plant (*Ananas erectifolius*) is well-known in the Amazon Water Basin in the Western region of the Para State of Brazil, where the first commercial plantations appeared. Compared to other lignocellulosic fibers, curaua still lacks deeper studies [3,4]. Nevertheless, these fibers are currently employed as raw material in the textile and automotive industries, as in bag manufacturing, thread production, brushes, bags, among others [5].

The positive characteristics of vegetable fibers in polymer composites can be potentialized when combined with synthetic fibers, i.e. using hybrid composites. Hybridization is the way to achieve a combination of tailor made properties [6]. Many factors determine the final performance of hybrid composites, such as matrix nature,

length and shape of the dispersed fiber (isotropic or anisotropic), fiber-matrix interface and vegetable/synthetic fiber ratio. Mishra et al. [7] studied the mechanical properties of pineapple leaf (PALF) and sisal fiber reinforced polyester composites containing low glass fiber volume content and Ahmed et al. [8] studied tensile, flexural and interlaminar shear properties of jute/glass/polyester composites. In addition, Idicula et al. [9] studied the dynamic mechanical properties of randomly oriented short banana/sisal/polyester hybrid composites and concluded that higher compatibility was obtained hybridizing these fibers, leading to higher stress transfer ability.

Dynamic mechanical analysis (DMA) is a technique that combines both mechanical and rheological characterization, and can determine the relaxation phenomena in an extensive range of temperatures [10]. This technique divides the dynamic modulus of the material in two parts: an elastic part (storage modulus – E') and a viscous component (loss modulus – E''). The ratio of E'' to E' gives the tangent of the phase ($\tan \delta$) known as damping factor [11]. DMA can be used to correlate macroscopic properties with microscopic deformations due to molecular rearrangement. Manikandan Nair et al. [12] studied the dynamic mechanical properties of sisal/polystyrene composites and noted that the addition of 10 vol.% fibers on matrix increases the storage modulus of the composites followed by a levelling of a higher loading.

Poathan et al. [13] studied the dynamic behavior of chemically banana fiber reinforced polyester composites and noted that the chemical modification has improved the storage modulus and the glass transition temperature due an improvement of the fiber/matrix adhesion. As a result, these composites can be used as substitute for building materials by the judicious control of the interphase chemistry.

Tatsumisago et al. [14] defined dynamic fragility as a way to characterize the anomalous non-Arrhenius transport behavior which develops in most glass-forming

liquids as they approach the ergodicity-breaking glass transition (T_g). According to Angell [15] the materials can be defined as strong or fragile, depending on the response of their dynamic properties such as relaxation time and viscosity. For composite materials, for example, dynamic fragility can be related (among other features) to the drop in the storage curve between the glassy region and the elastomeric one. A more abrupt drop indicates a fragile material whereas a smooth decrease means a strong material.

On this context, the aim of this paper is to investigate the performance of hybrid composites, focusing on the mechanical and viscoelastic properties of curaua, curaua/glass and glass composites, varying the overall fiber volume fraction ($\%V_f$) and the curaua/glass ratio.

2. Materials and methods

2.1. Materials

The raw materials used in this study were: curaua fiber rope purchased from Orsa foundation, glass fiber roving ME 3050 with linear density of 4000 tex from Owens Corning; commercial unsaturated and accelerated orthophthalic polyester resin ARAZYN® 13.0 (supplied by Ashland). Acetyl acetone peroxide (AAP), degassing agent A515 (BYK) and mold releasing agent (ChemLease 75*NEB) were also used.

2.2. Composite Molding

The curaua rope was disentangled, classified and chopped to the desired length (50 ± 2 mm). Then, a frame (with the same dimensions of the mold) was used to manually arrange the fibers aiming to produce a randomly distributed mat. The same process was used to produce the pure glass mat (the glass fiber roving was also cut to 50

± 2 mm) and, for the hybrid mat, both fibers were simultaneously used. The mat was compacted in the mold using a hydraulic press (Marconi – MA 098/A3030) for 30 min, using 3 ton (at room temperature). Besides, the mats were dried in an oven at 105 °C for 30 min (except for the pure glass mat) just prior to molding.

The resin was prepared by adding 2 wt.% curing agent and manually stirring for 2 min. Then, 2 wt.% of degassing agent was incorporated and kept at room temperature in an ultrasonic bath for 5 min. Compression molding of the composite was carried out under 6 ton, at 90 °C for 75 min, followed by post-curing at 80 °C for 120 min in an oven with air circulation. The studied composites were named using the overall fiber volume fraction (20, 30 or 40 vol.%) and the volumetric ratio between curaua and glass fiber. The fiber length was constant for all composites (50 mm). The Table 1 shows in detailed the composition of all composites studied.

<< Insert Table 1 >>

2.3. *Characterization*

Density of the fibers was evaluated in a Helium Gas Pycnometer (MVP-1 Multipycnometer – Quantachrome), using 2 g of fiber (curaua or glass), according to ASTM D6093 [16], whereas density of the composites was obtained using the Archimedes approach (ASTM D792) [17], with distilled water. Barcol hardness was measured using a HPE Bareiss Durometer following ASTM D2583 [18] and an average of 20 measurements. Izod impact testing was carried out on unnotched specimens using a CEAST impact machine (Impact II model) according to ASTM D256 [19], with 11 J hammer. Seven specimens ($60 \times 12.7 \times 3$ mm) were used for each family of samples.

Thermogravimetric analysis (TGA) was carried in a 2050 TGA V5.4A (TA Instruments). The samples were heated from 20 to 1000 °C at a heating rate of 20 °C.min⁻¹, under N₂ atmosphere, according to ASTM E1131 [20]. For the dynamic mechanical analysis (DMA), a thermal analyzer 2980 DMA V1.7B (TA Instruments) was used. Specimen dimensions were 35 × 17 × 3 mm and the experimental conditions were: single cantilever mode, strain amplitude of 0.1%, frequency of 1 Hz, heating rate of 5 °C.min⁻¹ and temperature range from 25 to 200 °C.

3. Results and discussion

3.1. Mechanical properties

The Barcol hardness, impact strength and specific gravity (theoretical and experimental) of the composites are shown in Table 2. The theoretical density values were calculated based on the rule of mixtures and show an increase according to the content of incorporated glass fiber. This is expected since glass fiber has higher density than curaua ($\rho_{\text{glass}} = 1.84 \times \rho_{\text{curaua}}$). Density also increases for higher overall %V_f, since both fibers are more dense than the resin ($\rho_{\text{resin}} = 1.18 \text{ g.cm}^{-3}$).

Barcol hardness is mainly influenced by the material (fibers and resin) that is near the surface in which the test is performed [21], the relative fiber content and also the quality of the molding. Hardness increases for higher content of glass fiber (which is more rigid) or lower curaua/glass ratio. In general, it can be seen that for high overall fiber content and for composites with high curaua content, poorer results were obtained, being attributed to the lower quality of the molded part.

<< Insert Table 2 >>

Impact strength also increased with glass fiber incorporation since it shows better adhesion with polyester resin than the vegetable fiber. It also tended to increase for overall fiber content since there is relatively more energy dissipation at the fiber/matrix interface by pull-out/decoupling of fibers following an impact event [22]. However, this was not noticed for the pure curaua composites due to experimental difficulties at high % V_f , as mentioned above. The poor adhesion of natural fibers is a consequence of its polar character, weakening the fiber/matrix interface which may cause premature failure [10]. The mentioned experimental difficulties are due to curaua heterogeneity and non-homogeneous fiber distribution on hybrid composites.

3.2. *Thermal analysis*

The thermogravimetric analysis (TGA) of the curaua fiber (Fig. 1) evidenced weight loss related to the early release of moisture (c.a. 68 °C) and degradation of curaua fiber as a consequence of the pyrolysis of its lignocellulosic components, first, hemicelluloses and lignin (c.a. 217 °C), then cellulose (c.a. 377 °C), similar to what was discussed by Tomczak et al. [23]. The final decomposition occurred at 458 °C, related to the thermal-oxidation of the residues of the previous degradation stages [24].

<< **Insert Fig. 1** >>

Fig. 2 shows the TGA results for the studied composites. The composites showed good thermal stability up to about 200 °C (Fig. 2a), followed by an abrupt thermal degradation up to approximately 450 °C. In this temperature range, the lowest weight loss was found for the 30/0/100 composite, whereas the 30/100/0 sample shows about 95% of weight loss, which can be attributed to fiber depolymerization. In the

DTG curve (Fig. 2b), the 30/0/100 sample (pure glass) shows weight loss ratio of just 0.5 %. min^{-1} , whereas the other composites show within 0.9-1.3 %. min^{-1} , due to presence of –OH groups that characterize the natural fiber as hydrophilic [25].

<< Insert Fig. 2>>

3.3. *Dynamic mechanical analysis*

Dynamic mechanical analysis is of great importance to the academic and industry fields since it can predict long term mechanical behavior in a wide range of temperature/time, allowing also correlation between microscopic and macroscopic properties [26]. It is observed in Fig. 3 that storage modulus of the composites in the glassy state increased with glass incorporation. This is due to the rigidity and the glass fiber/matrix adhesion that contributes for higher modulus value in this region.

<< Insert Fig. 3>>

The main transition for amorphous polymers from the glassy state to the elastomeric plateau comprises different types of molecular motion, including cooperative short-range diffusional motion of the chain segments [22], sub-Rouse and Rouse models [27]. It is important to add that from the local motion to the Rouse model, the mobile unity becomes larger, i.e. only a small number of bonds in the main chain for the former, to Gaussian sub-molecules for the latter (each sub-molecule is understood to be a bead and is considered to follow an ideal distribution probability, i.e., Gaussian distribution).

To better visualize the results reported in Fig. 3, a normalized modulus was calculated from the modulus values in the glassy (30 °C) and in the elastomeric regions (180 °C) (Table 3). The parameters E_{c30} and E_{m30} mean the storage modulus observed at 30 °C for the composite and the matrix, respectively, providing a quantitative evaluation of the reinforcement effect.

<< Insert Table 3 >>

As mentioned before, the reinforcement effect is more pronounced in the glassy region than in the elastomeric one. For all composites, the modulus values in the glassy region were higher upon glass incorporation. The same was not found in the rubbery state, which can be related to the natural fiber heterogeneity and non-uniformity in fiber distribution.

In the elastomeric region, modulus is also expected to be higher for the samples containing higher glass fiber content and, some discrepancies found were attributed to the heterogeneity of the system and the particular regions from where the specimens were collected in the composite plate. Variation in the content of amorphous and crystalline components of natural fiber can also occasionate these changes.

In Fig. 4, it is clear that there is an increase in storage modulus with overall fiber content in the entire temperature range studied. This can be explained by the more pronounced mechanical constraints imposed by the presence of the fibers to higher energy levels required for the cooperative motion. In all, the composites containing greater fiber fraction and higher effective reinforcement content display a less abrupt fall from the glassy state to the elastomeric one.

<< Insert Fig. 4>>

Equation (1) can be used to allow better appreciation of the fiber effect on the storage modulus of the composite [28]:

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

where: E'_g and E'_r are the storage moduli in the glassy and rubbery regions, respectively. The obtained C coefficient represents the reinforcement effectiveness and a lower value means a more reinforced system, i.e. the difference among the values obtained in all regions of the storage curves is smaller, as cited earlier. Table 4 and Table 5 show the C results obtained for all composites. In general, it is noted that the system tends to show more efficiency in stress transferring due to a better glass fiber/matrix adhesion when the glass reinforcement is incorporated.

<< Insert Table 4>>

<< Insert Table 5>>

Another consequence of the fiber incorporation is the flattening of the loss peak, as can be seen in Fig. 5. This can be attributed to the inhibition of relaxation processes in the composites, decreasing mobility at the surface of the fiber and a higher number of chain segments upon fiber addition [22]. Higher energy dissipation leads to an increase in internal friction. Energy incorporation also increases with glass addition, which is expected since the resin/glass interface dissipates more energy than the resin/curaua interface [28,29].

<< **Insert Fig. 5**>>

Besides, there is some evidence of a relaxation peak, probably related to the bulk polymer. In composite materials, two relaxation peaks may appear as reported by Sreekala et al. [30]. The first peak would occur due to short-range diffusion of the chain segments immobilized at the boundaries of the solid (fibrous) surface, and the second would be associated with the polymer molecules in the bulk phase. In addition, if a second peak is located after the maximum energy dissipation temperature, it may imply the existence of entrapped resin-rich regions close to the boundary, producing a different network structure that promotes this shifting to higher temperatures. Finally, the loss modulus peak should be wider for stronger polymer composites due to the same reason cited earlier. Indeed, as the fiber is incorporated, it can be noted in Fig. 6 that the curves become broader.

<< **Insert Fig. 6**>>

In composites, damping is influenced by content, type and fiber distribution, viscoelastic nature of the matrix and/or fiber, matrix/fiber interface as well as fiber/matrix interactions and void content [31-33,28]. Furthermore, damping also originates from the slipping at the boundary regions in the fiber/matrix interface or delamination, and from the dissipation energy in the matrix cracks, broken fibers, among others.

According to Fig. 7 and Fig. 8, as the temperature increases, damping passes through a maximum in the transition region and decreases in the elastomeric region.

Below T_g , damping is low because the chain segments are frozen-in. So, deformations are mainly elastic and the molecular slipping from the resulting molecules in the viscous flow is small. Furthermore, in the glassy region, the molecular segments are free to move, i.e. there is no resistance to flow, so damping is low. In fact, frozen-in segments can store more energy in the vitreous state for a particular stress than a segment located in the elastomeric state that can move more freely. In the transition region, the earlier frozen segments become free to move and the exceeding energy is dissipated.

Also, it can be noted that damping is lower for the composites than for the neat polyester matrix. This can occur if the fibers carried a greater amount of the load, dissipating only a small amount of it at the interface. Comparing composites with distinct reinforcements, lower energy dissipation is characteristic of a stronger fiber/matrix interface [34].

<< **Insert Fig. 7**>>

<< **Insert Fig. 8**>>

Systems containing more restrictions and a higher degree of reinforcement tend to show higher T_g values. However, in this study, the glass transition temperature did not follow a particular trend and only the pure curaua composite showed a clearly distinct (lower) T_g (Table 6). This may have occurred due to the high void content of the sample or even due to lower than expected fiber content in that particular sample. Higher T_g values represent a more reticulated system, which yields higher network degree density. The networking promotes more restrictions by decreasing the number of structural units between crosslinkings and increasing the average crosslink density [35].

Another interesting feature is that better overall mechanical properties can be obtained without significant variation in T_g . The glass transition temperature is a well-established and convenient reference point that indicates the reinforcement effect (as cited earlier) of a polymeric composite material through the peak maximum, in a way that higher molecular restriction at the fiber boundaries leads to higher hindrance and, as a consequence, the temperature to begin the cooperative motion shifts to higher values [36].

<< Insert Table 6 >>

From the dynamic fragility point of view, a stronger polymer should present larger distribution in relaxation times which causes broadening of the tan delta curve. This heterogeneity can be better characterized observing the peak width at half-height [28], which is associated with the β factor of the Kohlrausch-Williams-Watts equation, and a low β value implies wider distribution [33].

The Cole-Cole interaction can be used to evaluate homogeneity of the system and also, in this case, to study structural changes yielded by the fiber inclusion [29,32]. The Cole-Cole graph consists in plotting the loss modulus data ($\log E''$) as a function of the storage modulus ($\log E'$). According to Fig. 9, as the fiber is incorporated in the system, narrowing of the curves is observed, meaning that the system becomes more homogenous, according to this approach. In this case, homogeneity can mean a smaller difference in the relaxation times between the components of the composite.

<< Insert Fig. 9 >>

4. Conclusions

In this study, thermal, mechanical and dynamic mechanical properties of curaua/glass hybrid composites were investigated. The density results showed an increase in density of the composites for higher glass content and overall fiber volume fraction, as expected. Barcol hardness and impact strength followed the same trend due to the intrinsic characteristics of the glass fiber such as stronger adhesion to the matrix and higher energy dissipation at the interface in comparison with the vegetable fiber.

The storage and loss moduli increased for higher glass fiber content. This is probably due to a greater degree of restriction imposed by the glass fiber to the matrix, which allows a greater stress transfer through the matrix/reinforcement interface. In addition, the glass transition temperature did not display a significant variation, suggesting that so many variables as fiber/fiber interaction, fiber/matrix interphase among others must be accounted.

Acknowledgments

The authors would like to thank the FAPESB and CNPq for the financial support. Also, to Marcia Cardoso of Ashland/Brazil for supplying the polyester resin used in this study.

References

- [1] Taj S, Munawar MA, Khan S. Natural fiber-reinforced polymer composites. Proc Pakistan Acad Sci 2007;44:129-44.
- [2] Saheb DN, Jog JP. Natural fiber polymer composites: A review. Adv Polym Tech 1999;18:351–63.

- [3] Silva RV, Aquino EMF. Curaua Fiber: A new alternative a polymeric composites. *J Reinf Plast Compos* 2008;27:103-12.
- [4] Zah R, Hischer R, Leão AL, Braun I. Curauá fibers in the automobile industry – a sustainability assessment. *J Cleaner Prod* 2007;15:1032-40.
- [5] Gomes A, Matsuo T, Goda K, Ohgi J. Development and effect of alkali treatment on tensile properties of curaua fiber green composites. *Composites Part A* 2007;38:1811-20.
- [6] Cicala G, Cristaldi G, Recca G, Ziegmann G, El-Sabbagh A, Dickert M. Properties and performances of various hybrid glass/natural fibre composites for curved pipes. *Mater Des* 2009;30:2538-42.
- [7] Mishra S, Mohanty AK, Drzal LT, Misra M, Parija S, Nayak SK, et al. Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Compos Sci Technol* 2003;63:1377–85.
- [8] Ahmed KS, Vijayarangan S. Tensile, flexural and interlaminar shear properties of woven jute and jute-glass fabric reinforced polyester composites. *J Mater Process Technol* 2008;207:330–5.
- [9] Idicula M, Neelakantan NR, Oommen Z, Kuruvilla J, Thomas S. A study of the mechanical properties of randomly oriented short banana and sisal hybrid fiber reinforced polyester composites. *J Appl Polym Sci* 2004;96:1699-709.
- [10] Gregorova A, Hrabalova M, Kovalcik R, Wimmer R. Surface modification of spruce wood flour and effects on the dynamic fragility of PLA/wood composites. *Polym Eng Sci* 2011;51:143-50.
- [11] Gu H. Dynamic mechanical analysis of the seawater treated glass/polyester composites. *Mater Des* 2009;30:2774-7.

[12] Manikandan Nair KC, Thomas S, Groeninckx G. Thermal and dynamic mechanical analysis of polystyrene composites reinforced with short sisal fibres. *Compos Sci Technol* 2001;61:2519-29.

[13] Pothan LA and Thomas S. Polarity parameters and dynamic mechanical behaviour of chemically modified banana fiber reinforced polyester composites. *Compos Sci Technol* 2003;63:1231-40.

[14] Tatsumisago M, Halfpap BL, Green JL, Lindsay SM, Angel CA. Fragility of Ge-As-Se glass-forming liquids in relation to rigidity percolation, and the Kauzmann paradox. *Phys Rev Lett* 1990;13:1449-52.

[15] Angell CA. Formation of glasses from liquids and biopolymers. *Science* 1995;267:1924-35.

[16] ASTM D6093 – 97(2011): Standard test method for percent volume nonvolatile matter in clear or pigmented coatings using a helium gas pycnometer. American Society for Testing and Materials, 2011.

[17] ASTM D792 – 08: Standard test methods for density and specific gravity (relative density) of plastics by displacement. American Society for Testing and Materials, 2008.

[18] ASTM D2583 - 07: Standard test method for indentation hardness of rigid plastics by means of a Barcol impressor. American Society for Testing and Materials, 2007.

[19] ASTM D256 - 10: Standard test methods for determining the Izod pendulum impact resistance of plastics. American Society for Testing and Materials, 2007.

[20] ASTM E1131 – 08: Standard test method for compositional analysis by thermogravimetry. American Society for Testing and Materials, 2008.

[21] Reddy GV, Naidu SV. A study on hardness and flexural properties of kapok/sisal composites. *J Reinf Plast Compos* 2009;28:2035-44.

- [22] Ornaghi Jr HL, Silva HSP, Zattera AJ, Amico SC. Hybridization effect on the mechanical and dynamic mechanical properties of curaua composites. *Mater Sci Eng A* 2011;528:7285-9.
- [23] Tomczak F, Satyanarayana KG, Sydenstricker THD. Studies on lignocellulosic fibers of Brazil: Part III – Morphology and properties of Brazilian curauá fibers. *Composites Part A* 2007;38:2227-36.
- [24] Santos PA, Spinacé MAS, Feroselli KKG, Paoli MA. Efeito da forma de processamento e do tratamento da fibra de curauá nas propriedades de compósitos com poliamida-6. *Polímeros* 2009;19:31-9.
- [25] Sreekumar PA, Thomas PS, Saiter JM, Unnikrishnan G, Thomas S. Viscoelastic and thermal properties of eco-friendly composites fabricated by resin transfer molding. *J Reinf Plast Compos* 2011;30:1509-16.
- [26] Cassu SN, Felisberti MI. Comportamento dinâmico-mecânico e relaxações em polímeros e blendas poliméricas. *Quim Nova* 2005;28:255-63.
- [27] Jinrong W, Huang G, Liangliang Q, Zheng J. Correlations between dynamic fragility and dynamic mechanical properties of several amorphous polymers. *J Non-Cryst Solids* 2009;355:1755-9.
- [28] Ornaghi Jr HL, Bolner AS, Fiorio R, Zattera AJ, Amico SC. Mechanical and dynamic mechanical analysis of hybrid composites molded by resin transfer molding. *J Appl Polym Sci* 2010;118:887–96.
- [29] Idicula M, Malhotra SK, Joseph K, Thomas S. Dynamic mechanical analysis of randomly oriented intimately mixed short banana/sisal hybrid fibre reinforced polyester composites. *Compos Sci Technol* 2005;65:1077-87.

- [30] Sreekala MS, Kumaran MG, Joseph R, Thomas S. Stress-relaxation behavior in composites based on short oil-palm fibres and phenol formaldehyde resin. *Compos Sci Technol* 2001;61:1175-88.
- [31] Chandra R, Singh SP, Gupta K. Damping studies in fibre-reinforced composites - a review. *Compos Struct* 1999;46:41-51.
- [32] Pothan LA, Oommen Z, Thomas S. Dynamic mechanical analysis of banana fibre reinforced polyester composites. *Compos Sci Technol* 2003;63:283-93.
- [33] Nishar H, Sreekumar PA, Bejoy F, Yang W, Thomas S. Morphology, dynamic mechanical and thermal studies on poly(styrene-co-acrylonitrile) modified epoxy resin/glass fibre composites. *Composites Part A* 2007;38:2422-32.
- [34] Joseph PV, Joseph K, Thomas S. Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites. *Compos Sci Technol* 1999;59:1625-40.
- [35] Qazvini NT, Mohammadi N. Dynamic mechanical analysis of segmental relaxation in unsaturated polyester resin networks: Effect of styrene content. *Polymer* 2005;46:9088-96.
- [36] Pinheiro A, Mano JF. Study of the glass transition on viscous-forming and powder materials using dynamic mechanical analysis. *Polym Test* 2009;28:89-95.