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Tensile behavior of lignocellulosic fiber reinforced polymer composites: Part I piassava/epoxy

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ABSTRACT

The fibers extracted from the piassava palm tree, scientifically known as *Attalea funifera*, are among the stiffest lignocellulosic fibers being considered for polymer composite reinforcement. Characterization of piassava composites have been carried out for different polymeric matrices and mechanical tests. In this work the tensile properties of DGEBA/TETA epoxy matrix composites reinforced with up to 30% in volume of continuous and aligned piassava fibers were evaluated. Tensile specimens post-cured at 60°C for 4 hours were room temperature tested and the corresponding fracture analyzed by scanning electrons microscopy. The results showed a decrease in both the tensile strength and the elastic modulus of the composites up to 30% with an increase at 40% of piassava fibers to values above those of the pure epoxy. The fracture analysis revealed a weak fiber/matrix interface, which could account for the comparative low performance of these composite in tensile tests up to 30% of volume fraction. The relatively large amount of stronger piassava fibers accounts for the better performance of the composite with 40% in volume fraction.

Keywords: Piassava fibers, epoxy composites, tensile properties, fracture analysis.

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1 INTRODUCTION

Natural fiber reinforced polymer composites are gaining considerable attention owing to environmental, economical, societal and technical advantages as compared with conventional synthetic, especially fiber glass, composites [1-4]. In particular, environmental issues such as the pollution caused by wastes that are non biodegradable or cannot be incinerated as well as climate changes due to CO_2 emissions associated with energy intensive processes are favoring the use of natural over synthetic fibers [5]. The automobile industry is a major productive sector in which many parts, traditionally made of pure plastic or glass fiber composites, are currently being replaced by natural fiber composite [6-8].

A great variety of natural fibers obtained from cellulose rich plants, from now on referred as lignocellulosic fibers, have been, in recent years, not only investigated but effectively applied in engineering composites [1, 4, 9]. Among theses the piassava fiber extracted from a palm tree (*Attalea Funifera*) native of Brazil and extensively used in simple items like brooms, is presently investigated as a possible composite reinforcement owing to its stiffer characteristic [10-14]. The mechanical behavior of polymer composites reinforced with continuous and aligned piassava fibers has been restricted to flexural and impact tests [14-15]. These tests have shown that the incorporation of up to 40% in volume of fibers into both epoxy and polyester matrices increases the composite resistance. Since tensile constraints are important for the structural response of the material, the present work investigated the tensile properties of post-cured epoxy matrix composites reinforced with continuous and aligned piassava fibers.

2 EXPERIMENTAL PROCEDURE

Piassava fiber were obtained as a bundle from a broom industry located in the city of Campos dos Goytacazes, state of Rio de Janeiro, southeast of Brazil.

From the as-received bundle, Figure 1(a), a lot of 100 fibers was individually separated, Figure 1(b), for a statistic analysis of their dimensions. The histogram of length distribution has been presented elsewhere [15]. It is worth mentioning that for the obtained piassava fibers an interval of length was found to vary from 200 to 900 mm with an average of 455 mm. Figure 2 shows the histogram of diameter distribution, which indicates an interval from 0.2 to 2.45, with an average of 1.1 mm.

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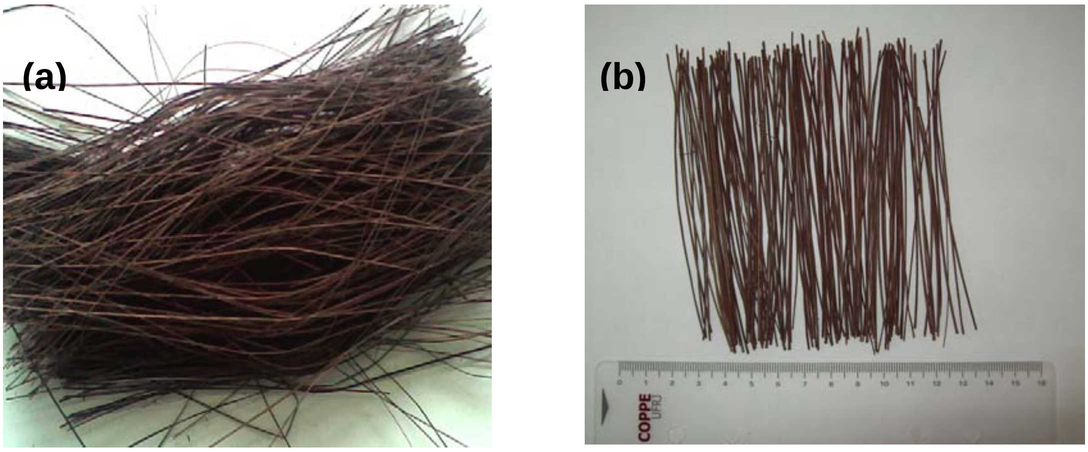


(a) (b)

Figure 1: Bundle of piassava fibers (a) l; and individual fibers with different diameters (b).

Composites were fabricated with different volume fractions of piassava fiber embedded in epoxy resin of the type diglycidyl ether of the bisphenol-A (DGEBA) hardened with phr 13 of triethylene tetramine (TETA). The as obtained piassava fibers were initially water cleaned and then dried at 60°C for 24 hours. Tensile composite specimens were individually prepared by laying down the fibers in an open dog-bone shaped silicone mold with 5.8 x 4.5 mm of reduced cross section and 35 mm of gage length. Fraction volumes up to 40% of continuous piassava fibers were aligned along the specimen's length, which corresponds to the tensile axis. Still fluid DGEBA/TETA epoxy resin was then poured onto the fibers inside the mold and allowed to cure for 24 hours at room temperature. This was followed by a post-cure at 60°C for 4 hours.

Seven composite specimens were fabricated for each volume fraction of piassava fiber. Each specimen was tensile tested in a model 5582 Instron machine at 25±2°C and a strain rate of 3 x 10^{-3} s^{-1}. The fracture surface of some representative specimens was attached to a support by conducting carbon tape and then gold sputtered to be analyzed by scanning electron microscopy (SEM) in a model SSX-550 Shimadzu equipment operating with secondary electrons at an accelerating voltage of 15 kV.

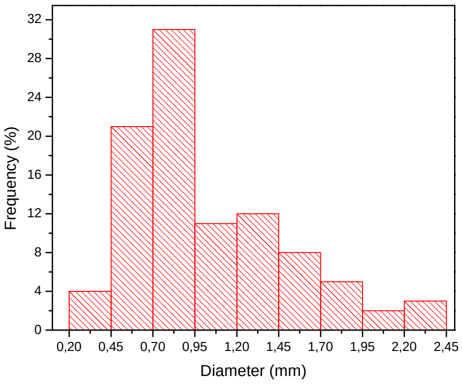


Figure 2: Histogram for the statistical distribution of diameter of the supplied piassava fibers.

3 RESULTS AND DISCUSSION

Figure 3 exemplifies the typical load vs. extension curves for different composites. These curves were recorded directly from the Instron machine and revealed that the piassava fiber reinforced composites apparently present limited plastic deformation. Consequently, these composites, in principle, may be considered as brittle materials

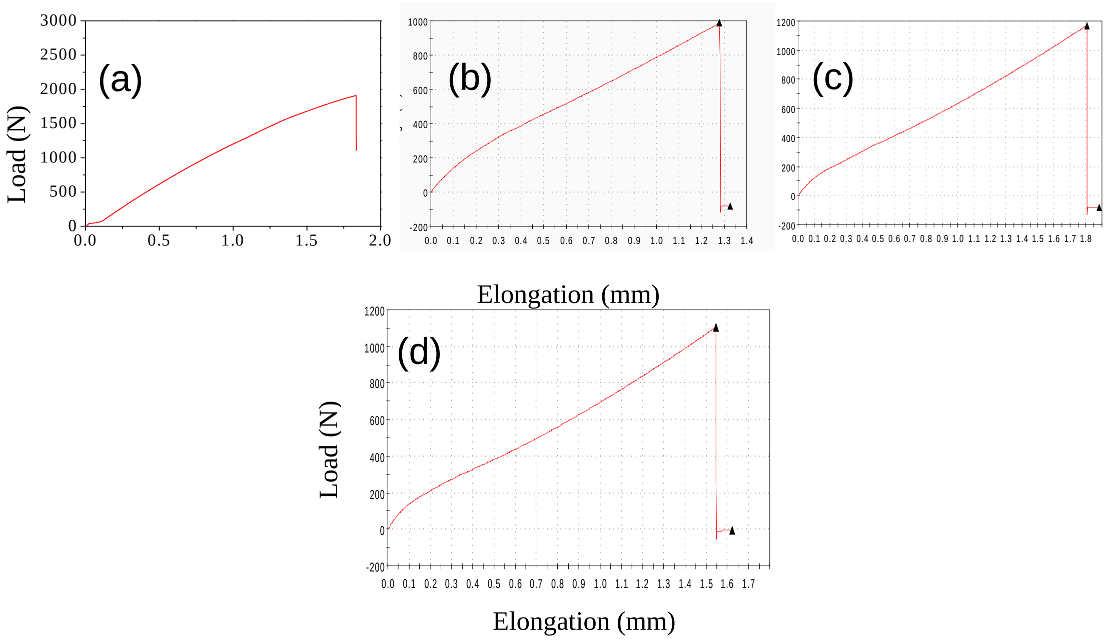


Figure 3: Load vs. elongation curves for epoxy composites reinforced with (a) 0%, (b) 10%, (c) 20% and (c) 30% of volume fraction of piassava fibers.

Figure 4 presents the macro aspect of representative tensile ruptured specimens corresponding to each volume fraction of piassava fiber considered for composite reinforcement. An increase non-uniform rupture can be noticed at the fractured tips of composites with more than 10% of piassava fibers. This will be discussed further with the fracture analysis.

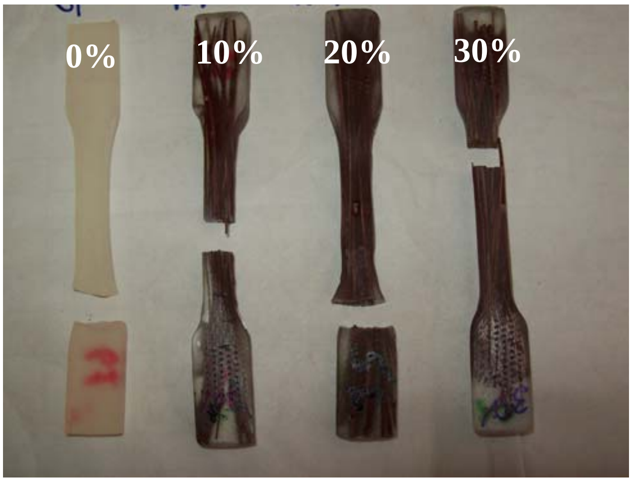


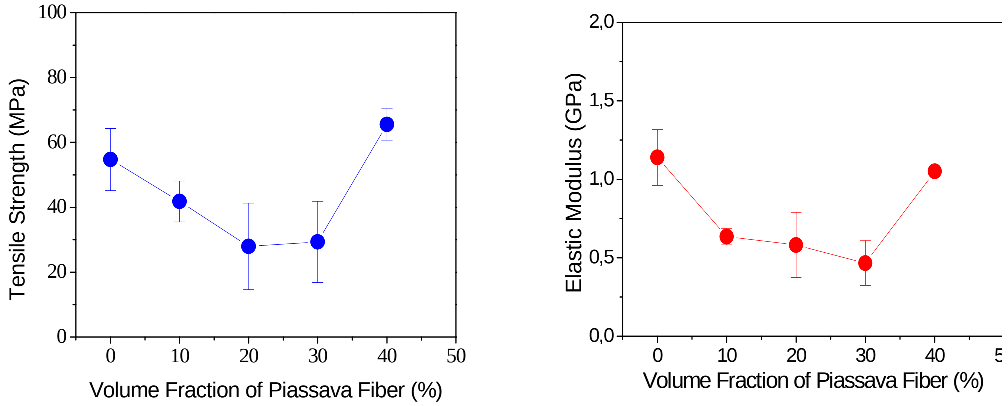
Figure 4: Tensile ruptured specimens for each volume fraction of piassava fiber incorporated into the epoxy matrix.

From the results of the load *vs.* elongation curves, the ultimate stress (tensile strength), elastic modulus, and total strain were calculated. Table 1 shows the average values for these tensile properties for the different amounts of piassava fiber investigated. In this table, it should be noted that the incorporation of piassava fibers fail to reinforce the epoxy composites up to 30% of volume fraction. The value of the tensile strength for 40% piassava fiber, however, is higher than that of the pure epoxy (0% fiber) specimens. The ductility measured by the total tensile strength is slightly increased with the amount of the piassava fiber in the composites.

Figure 5 plots the results of tensile strength and elastic modulus, shown in Table 1, as a function of the volume fraction of the piassava fibers. In this figure, it is observed that both the strength and stiffness decrease with the amount of piassava fiber incorporated into the epoxy matrix up to 20-30% of volume fraction. Similar results were found for the flexural properties of the same piassava fibers incorporated into epoxy composites [16]. An alkali treatment of the piassava fibers [17] failed to improve these flexural properties. It was then concluded that piassava fibers do not provide a reinforcement effect to the relatively stronger epoxy matrix up to 30% of volume fraction.

Table 1: Tensile properties for the piassava fiber reinforced epoxy composites.

Volume Fraction of Piassava Fiber (%)	*Tensile Strength (MPa)*	*Elastic Modulus (GPa)*	*Total Tensile Strain (%)*
0	54.70 ± 9.58	1.14 ± 0.18	5.15 ± 1.74
10	41.81 ± 6.33	0.63 ± 0.05	5.38 ± 0.067
20	27.96 ± 13.13	0.58 ± 0.20	5.86 ± 0.51
30	29.33 ± 7.43	0.46 ± 0.14	5.88 ± 0.54
40	65.56 ± 5.02	1.05 ± 0.15	6.26 ± 1.26



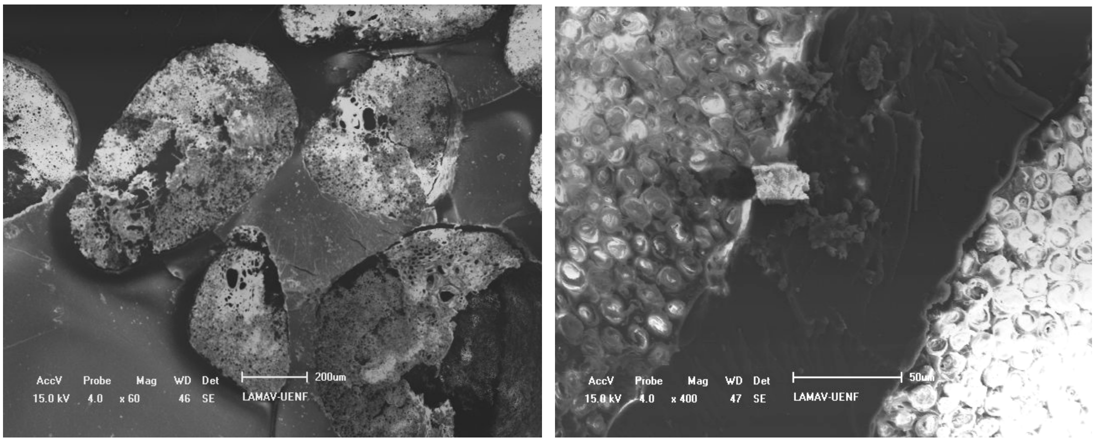
(a) (b)

Figure 5: Variation of the tensile strength (a) and elastic modulus (b) with the volume fraction of piassava fiber reinforcing epoxy composites.

The weak piassava fiber interface with the epoxy matrix acts, up to 40% of volume fraction, as a preferential site for crack nucleation at flexural stress levels below that necessary for the rupture of the pure epoxy [16]. By contrast, the tensile tested epoxy composites with 40% of piassava fibers in Fig. 5 display a marked increase in strength and stiffness. This recovery in strength was enough to surpass the corresponding value of the pure epoxy matrix. In other words, the incorporation of 40% of continuous and aligned piassava fibers provides an effective tensile reinforcement for the epoxy matrix. The reason for this reinforcement is apparently a consequence of the relatively higher tensile behavior of the piassava fiber. In fact, piassava fibers can reach tensile strengths of the order of 160 MPa and elastic modulus of 4.6 GPa [9] in comparison to the epoxy resin with 40/90 MPa and 2.4 GPa, respectively [18].

As shown in Fig. 5, for composites with 40% of volume fraction, the total fiber resisting cross-section area provides a tensile stress above that of the epoxy matrix. Even with cracks propagating through the weak fiber/matrix interface, the large amount (40%) of piassava fibers will not break in tension until a relatively higher strength, around 66 MPa in Table 1, is attained. Evidences that support this reinforcement mechanism are provided by the SEM fracture analysis.

Figure 6 shows typical SEM fractographs, with different magnifications, of a tensile rupture specimen corresponding to an epoxy composite reinforced with 40% of piassava fiber. With lower magnification, Figure 6(a), one should notice the fracture surface of several piassava fibers that are still embedded in the epoxy matrix. These fibers are sticking out of the flat and brittle epoxy fractured surface.



(a) (b)

Figure 6: Fracture of a composite with 40% of volume fraction of piassava fiber, with different magnifications: (a) 60x and (b) 500x.

It is suggested that fracture initiates at interfacial flaws and defects such as the decohesion void between two fibers, shown in Figure 6(b) with higher magnification. The fracture then proceeds transversally through the brittle epoxy matrix. The associated cracks are obstructed by the piassava fibers. For the 40% fiber composite, Figure 6(a), this obstruction is effective and generates decohesions at the interface. This type of flaw nucleates another crack, Figure 6(b), which separates longitudinally the fiber from the matrix. At this point, only the loosen piassava fibers are holding together the two parts of the specimen, the final rupture occurs with the tensile collapse of piassava fibers. This corresponds to a stress level of approximately 40% of the average tensile strength of a piassava fiber. One should bear in mind that a 40% volume fraction of continuous and aligned fibers corresponds to 40% of resisting cross section area of these fibers in the specimen.

The suggested mechanism proposed in this work is in agreement with the results shown in Table 1 and Figure 5. This mechanism justifies the decrease in strength and stiffness up to 20-30% of piassava fibers, Figure 5, followed by an increase at 40% of volume fraction. Moreover, the proposed mechanism also explains the non-uniform rupture shown in Figure 4, where individual piassava fibers are detached from the matrix at the specimen's fractured tips.

4 CONCLUSIONS

Tensile tested epoxy composites incorporated with continuous and aligned piassava fibers show a reinforcement associated with higher strength only for 40% of volume fraction. Lower amounts of piassava fibers result in values of tensile strength and elastic modulus below those for the pure epoxy matrix.

The piassava fibers act as barrier to transversal crack propagation through the epoxy matrix. This also causes decohesion due to the weak fiber/matrix interface and separates longitudinally the fiber from the epoxy matrix. Loosen continuous and aligned piassava fibers represent the final resisting cross-section area to the tensile rupture.

Since the piassava fiber is stronger and stiffer than the epoxy resin, composites with 40% of volume fraction present enough cross-section area to undergo rupture at a tensile stress higher than that of the pure epoxy.

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