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Performance of curaua fibers in pullout tests

**Sergio Neves Monteiro · Regina Coeli M. P. Aquino ·
Felipe Perisse D. Lopes**

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Abstract Natural lignocellulosic fibers are successfully replacing synthetic fibers as the reinforcement phase of composite materials in many engineering applications, including automobile parts. In addition to well-known conventional lignocellulosic fibers, others with promising properties, like that obtained from the leaves of the curaua plant (*Ananas erectifolius*) found in the Amazon region of Brazil, are now being considered. The present work investigated microstructural aspects associated with the performance of curaua fibers in pullout tests carried out to characterize the fibers interfacial strength with a polyester matrix. The results have shown that the naturally bonded filaments that constitute a curaua fiber present interspatial voids between them. These voids play an important role in providing adherence of the fiber surface to a polyester matrix, resulting in an effective reinforcement for a curaua-strengthened composite.

Introduction

Biodegradable and renewable lignocellulosic natural fibers have been considered as substitutes for energy-intensive synthetic fibers made of glass, aramid or carbon in many uses in which a high elastic modulus is not required [1–3]. In fact, traditionally cultivated fibers for textile such as cotton, sisal, jute, flax, hemp and ramie are, nowadays, being applied in several engineering systems from automotive parts to building construction elements [4–6]. In most of these applications, the natural fiber is used as a reinforcement phase for polymeric matrix composite materials. In particular, the low cost associated with low density and the fact that natural fiber reinforced composites can easily be recycled are economical advantages over synthetic fiber composites [3–6].

In order to further extend the use of lignocellulosic natural fibers, it is important to fully characterize the properties of the traditional fibers and to search out for new sources of this type of material. In developing countries with vast tropical areas, such as India and Brazil, technological research works are revealing promising lignocellulosic fibers from plants that were, so far, not applied as engineering materials. Examples of relatively unknown plants whose fibers could serve as reinforcement of engineering composites are piassava (*Attalea funifera*) [7–10], sponge gourd (*Luffa cylindrica*) [11–13] and curaua (*Ananas erectifolius*) [14–15]. Among these fibers, curaua is the one with greater potential to be used as an engineering material owing to its reported mechanical properties [16, 17]. According to Leao et al. [15], curaua is ranking in the top four among the common fibers for stiffness.

The possibility of using curaua fibers in polymeric composites has been investigated by Araujo [18]. Polyurethane and polypropylene composites incorporated with 20 wt.% of chopped, 6–20 mm, curaua fibers were characterized by thermal analysis techniques. In particular, the storage modulus obtained by dynamic mechanical analysis, DMA, showed that the incorporation of curaua fibers tends to increase the stiffness of both types of composites.

S. N. Monteiro (✉) · F. P. D. Lopes
State University of the Northern Rio de Janeiro, UENF,
Advanced Materials Laboratory, LAMAV, Av. Alberto Lamego,
2000, Campos dos Goytacazes 28013-602, Brazil
e-mail: sergio.neves@ig.com.br

R. C. M. P. Aquino
Federal Center for Technological Education, CEFET-Campos,
Brazil

Another relevant point regarding the mechanical behavior of curaua fibers is its soft characteristics associated with relatively small diameter. Consequently, the precise determination of a single fiber ultimate stress is a difficult task. In fact, detailed information on the experimental procedure used to measure the tensile resisting area of a single fiber has not been given in the works related to this subject [14–18].

In spite of the already performed investigation on the curaua fiber properties, no systematic evaluation of its behavior as reinforcement for polymeric matrix composites or microstructural characterization of its interfacial strength has been performed. Therefore, the results obtained from tensile tests and the characterization of curaua fibers by scanning electron microscopy were the objective of the present work.

Experimental procedure

Fibers of curaua (*Ananas erectifolius*) were obtained from the POEMA project in the state of Para, Amazon region, Brazil. Figure 1 illustrates, respectively, the aspect of the curaua plant (a) and a bundle of fibers extracted from the leaves (b). These fibers are known by their high strength, smoothness and low density [15].

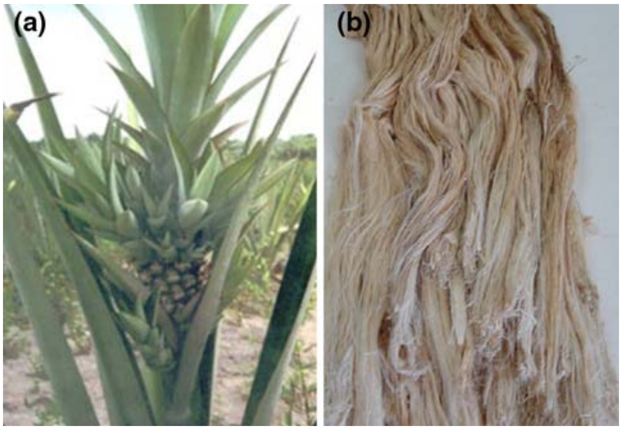


Fig. 1 Curaua plant (**a**) and fibers (**b**)

The curaua fibers were used in the as-received condition, without any surface treatment, except open air-drying. The length and the diameter of the fibers were statistically evaluated using the graphs in Fig. 2. From these graphs, an average length of 442 mm and an average diameter of 0.17 mm were obtained.

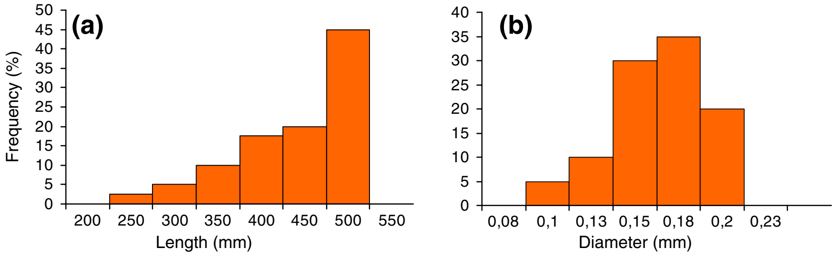
Tensile tests were performed in more than 100 single fibers using a mechanically driven Instron machine with pneumatic action grips. The tests strain rate was 5×10^{-3} s^{-1} and a grip holding pressure of 0.15 MPa was applied to the fibers extremities.

Before each tensile test, the fiber diameter was measured both with a profile projector and a micrometer caliper. It was found that measurements done by a metallic caliper, in which one needs to feel the touch of the metal against the fiber surface, underestimated the correct value of the diameter. Consequently, the fibers' cross-section area was also underestimated, and unrealistically greater values for the tensile strength were consequently determined [19]. This effect was more accentuated the smaller the fibers' diameter. Figure 3 presents the correction curve that needed to be considered to obtain the correct value for the curaua fiber diameter, whenever a metallic caliper is used.

Pullout tests were performed according to the schematic drawing shown in Fig. 4a. The embedded length L in this figure was varied from 3 to 50 mm in order to generate a pullout tensile stress versus L curve. The single curaua fiber was mounted on cylindrical polyester socket, Fig. 4a, with 6 mm in diameter. Each pullout test was conducted on a mechanically driven Instron machine with pneumatic action grips at a strain rate of 5×10^{-3} s^{-1}. A holding pressure of 0.15 MPa was experimentally determined to provide reliable test results. The polymeric resin used as the embedding material, simulating the composite matrix, was a commercially available orthophtalic polyester mixed with 0.5 wt.% of methil-ethil-ketone catalyst. The fiber/polyester socket was cured at room temperature for at least 24 h. A minimum of 20 specimens were tested for each value of the embedded length and a stress versus L curve for the curaua/polyester composite system was obtained [20]. This pullout curve is shown in Fig. 4b.

The structural analysis of the curaua fibers was performed by scanning electron microscopy, SEM,

Fig. 2 Statistical distribution of curaua fiber dimensions



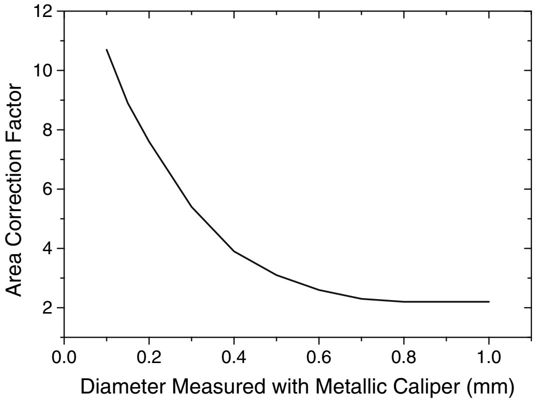


Fig. 3 Correction curve for the curaua fiber diameter when using a metallic caliper (factor to be multiplied by the measured cross section area)

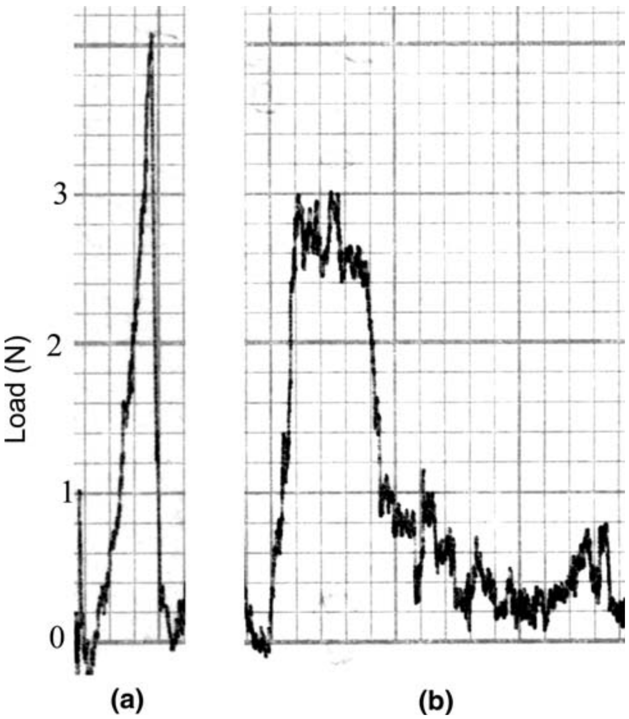


Fig. 5 Examples of the typically registered load versus extension curves for curaua fiber: (**a**) sudden rupture; (**b**) successive rupture of filaments

observations in a model JSM 6460 LV Jeol microscope operating with a beam voltage of 15–20 kV.

Results and discussion

Figure 5 illustrates the two general types of load versus extension curves typically registered by the Instron machine.

Most of the single curaua fibers, when tensile tested, presented a sudden rupture after the linear elastic extension, as shown in Fig. 5a. Few other fibers, Fig. 5b, undergo a successive process of rupture of the individual filaments that constitute the fiber structure. These microstructural aspects, which will be shown ahead in the present work by SEM. In this latter case, each discontinuous drop in the curve in Fig. 5b could be associated with a broken filament. Here it is important to remark that fibers that undergo a sudden rupture, Fig. 5a, display a relatively higher ultimate stress than the ones, Fig. 5b, that suffer a successive rupture of their filaments.

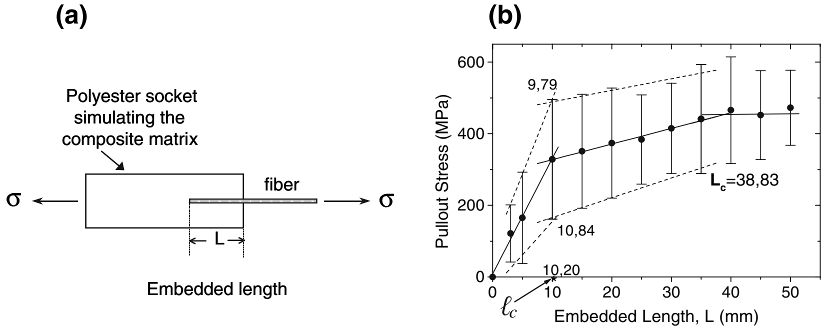
From the more of 100 curves, such as those shown in Fig. 5, a mean value and corresponding standard deviation was obtained for the tensile strength of curaua fibers:

$$\sigma_{\mathrm{m}} = 404 \pm 141\,\mathrm{MPa} \quad (1)$$

Regarding the value presented in Eq. 1, it is relevant to mention that, owing to the different cases of rupture illustrated in Fig. 5, a large dispersion in the strength value given in Eq. 1 can be justified. Indeed, among all tensile tests performed, one fiber presented a maximum value of 729 MPa whereas a minimum of 158 MPa was also found.

Another point worth mentioning is that the mean value of 404 MPa obtained in the present work is significantly smaller than that of 502 MPa previously reported [17]. A possible explanation for this discrepancy could be the way of measuring the fiber diameter, as above discussed in the Experimental Procedure. In fact, a recently obtained unrealistic average value for the curaua fiber strength of

Fig. 4 Pullout test of curaua fibers: (**a**) schematic procedure and (**b**) stress versus embedded length curve



559 ± 314 MPa [19], in which the fibers' diameters were measured with a metallic caliper, confirmed this explanation.

Based on the pullout curve of Fig. 4b, in which the fiber cross section area was calculated using the correction curve in Fig. 3, both the fiber's critical length, ℓ_c, and its interfacial strength with the polyester matrix, τ_c, were evaluated by means of the Kelly and Tyson equation [21].

$$\ell_c = \frac{d\sigma_f}{2\tau_c} \tag{2}$$

where ℓ_c = 10.20 mm is the critical length in Fig 4b, d = 0.17 mm the average fiber diameter in Fig. 2b, σ_f = 404 ± 141 MPa the fiber strength in Eq. 1 and τ_c calculated as

$$\tau_c = 3.4 \pm 1.2\,\text{MPa} \tag{3}$$

Among the lignocellulosic fibers like the piassava [9] this interfacial strength is relatively high and could represent a comparatively good adherence between the curaua fiber and the polyester matrix.

The role played by the microstructure of the curaua fiber on its interfacial strength with the polyester matrix was revealed by SEM analysis. Figure 6 shows the typical aspect of a curaua fiber broken in tension. In this figure one should notice that a single curaua fiber is formed by several filaments that participate, individually, in the rupture process. Actually, during this process, some filaments could be breaking, while others are still intact and resisting the applied load.

Figure 7 depicts a single curaua fiber, as a bundle of parallel filaments, which has been pulled out from the polyester socket during the test. In this figure, it is important to observe the patches of resin still covering the fiber.

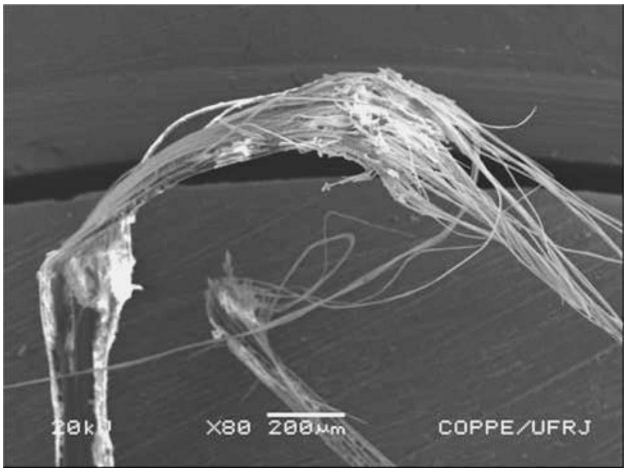


Fig. 6 Tensile fracture of a curaua fiber

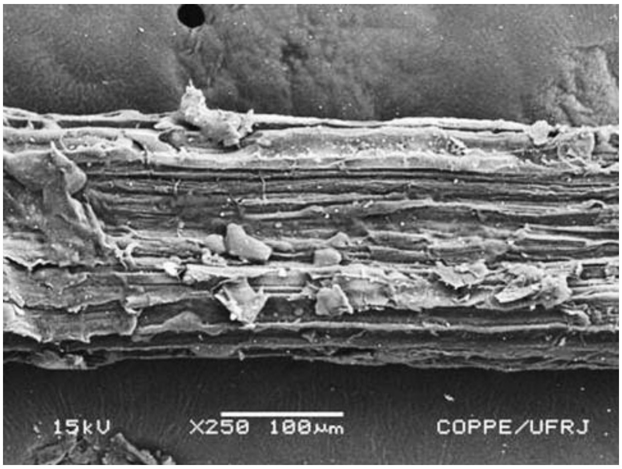


Fig. 7 Curaua fiber after being pulled out from the polyester socket

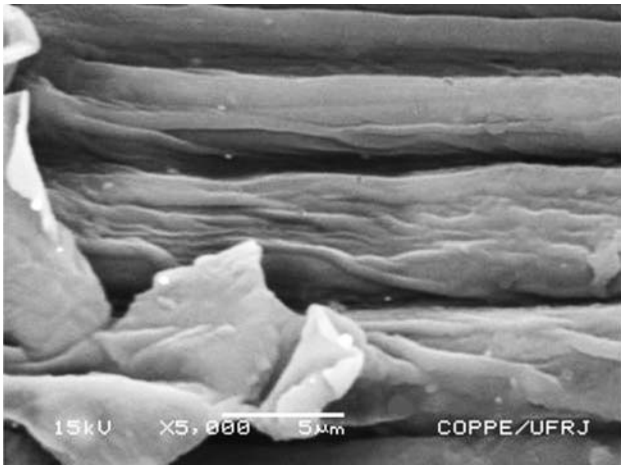


Fig. 8 Interaction of filaments and polyester resin in a single curaua fiber

Figure 8 reveals, with larger magnification, the polyester resin interaction with the filaments' surface. One could then regard the curaua fiber as a natural mini-composite in which the space in between the filaments may be penetrated by the resin, while it is in the liquid state. Consequently, as shown in Fig. 8, the curaua fiber tends to develop a strong adherence to the polymeric phase and thus efficiently transfer mechanical strength to the composite matrix. In conclusion, the heterogeneous characteristics of the curaua fiber are associated with naturally bonded filaments presenting interspatial voids between them. These voids could help the adherence of a polymeric resin matrix, resulting in an effective reinforcement for a curaua fiber composite.

Conclusions

Curaua fibers are among the strongest natural lignocellulosic fibers with a tensile strength above 400 MPa. However, owing to heterogeneous characteristics, which result in large statistic dispersion, tensile strength greater than 700 and smaller than 200 MPa may eventually be found in individual fibers.

In a microstructural scale, the heterogeneous characteristics of the fiber are associated with naturally bonded filaments presenting interspatial voids between them. These voids could help the adherence of a polymeric resin resulting in an effective reinforcement for a curaua fiber composite.

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