Original Article

Bending test in epoxy composites reinforced with continuous and aligned PALF fibers

Gabriel Oliveira Glória, Maria Carolina Andrade Teles, Anna Carolina Cerqueira Neves, Carlos Maurício Fontes Vieira, Felipe Perissê Duarte Lopes, Maycon de Almeida Gomes, Frederico Muylaert Margem, Sergio Neves Monteiro

a Universidade Estadual do Norte Fluminense – UENF, Campos dos Goytacazes, RJ, Brazil
b Instituto Federal Fluminense – IFF, Campos dos Goytacazes, RJ, Brazil
c Faculdade Redentor – FAC, Itaperuna, RJ, Brazil
d Military Institute of Engineering, IME, Rio de Janeiro, RJ, Brazil

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A B S T R A C T

Sustainable actions aiming to prevent increasing worldwide pollution are motivating the substitution of environmentally friendly materials for conventional synthetic ones. A typical example is the use of natural lignocellulosic fiber (LCF) as reinforcement of polymer composites that have traditionally been reinforced with glass fiber. Both scientific research and engineering applications support the use of numerous LCFs composites. The pineapple fiber (PALF), extracted from the leaves of Ananas comosus, is considered a LCF with potential for composite reinforcement. However, specific mechanical properties and microstructural characterization are still necessary for this purpose. Therefore, the objective of this short work is to evaluate the flexural properties, by means of three points, bend tests, of epoxy composites incorporated with up to 30 vol% of PALF. Results reveal that continuous and aligned fibers significantly increase the flexural strength. Scanning electron microscopy disclosed the fracture mechanism responsible for this reinforcement.

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1. Introduction

Owing to adverse impacts caused by human activities, particularly industrial pollution and excessive consumption of energy [1], our modern society is searching for environmentally friendly materials such as the natural lignocellulosic fibers (LCFs) extracted from plants. LCFs are renewable, biodegradable, cheaper, less abrasive to processing equipment and lighter than glass fiber [2]. These advantages are motivating the substitution of LCF reinforced composites for the long time...
commonly used fiberglass [3]. An escalating number of papers are today being dedicated to LCF’s and their related composites, as emphasized in several review articles published since past decade [4–10]. In addition, many LCF composites are already being applied in the automotive industry [11,12].

In spite of these scientific investigations and engineering applications, many LCF composites are still needing specific characterization for practical use. This is the case of polymer composites reinforced with pineapple leaf fiber (PALF) extracted from the plant Ananas comosus.

In fact, PALF contains a high amount of cellulose (83%) associated with tensile strength (748 MPa) and elastic modulus (36 GPa) convenient for composite reinforcement [13]. A limited number of works has investigated PALF composites [14–19] and additional ones are needed to explore their reinforcing potential. Therefore, the objective of this short communication is to investigate the flexural strength of epoxy composites incorporated with continuous and aligned PALF by means of three points bend tests. Weibull statistical analysis was applied to the results and scanning electron microscopy (SEM) identified the rupture mechanisms associated with reinforcing.

2. Experimental procedure

The PALFs in this work were supplied by the firm Desigan Natural Fibers, Brazil, as a bundle shown in Fig. 1. The fibers were individually separated and cleaned in running water before drying at 60°C in a stove. A preliminary statistic of the fiber diameter distribution was performed in 100 fibers by measurements in a profile projector at fiber distinct location, with 90° rotation at each point, for a total of ten measurements per fiber.

Fig. 2 shows the histogram of PALF diameter distribution associated with 6 selected 0.03 mm intervals from 0.10 to 0.28 mm. An average diameter of 0.20 mm corresponds to the PALF used in this work.

A plate of neat epoxy was prepared for control specimens. Composite plates with 10, 20 and 30 vol% of PALF incorporated epoxy composites were prepared by hand-lay continuous and aligned fibers in a 152 × 122 × 10 steel mold. Still fluid diglycidyl ether of the bisphenol A (DGEBA) epoxy resin mixed with stoichiometric (13 parts per hundred) triethylene tetramine (TETA) hardener was poured onto the mold. Each plate was cured under 3 MPa of pressure at room temperature (RT) for 24 h. After cure each plate was cut into 7 specimens with 122 mm × 25 mm × 10 mm that were three points bend tested, as per ASTM D 790, in a model 5582 Instron machine. Tests were carried out at RT with span-to-depth ratio of 9 and constant speed of 10^{-4} m/s. Ruptured specimens were analyzed by scanning electron microscopy (SEM) in a model SSX-550 Shimadzu microscope operating with secondary electron at 20 kV.

3. Results and discussion

The typical flexural force vs. deflection curves, directly obtained from the machine acquisition data system, are shown in Fig. 3. In this figure it should be noticed that flexural curves for the PALF reinforced composite specimens display limited plastic deformation after the linear elastic stage. A sudden drop then occurs in association with the beginning of rupture.

The neat epoxy specimen, Fig. 3(a), and specimen with lower 10 vol% PALF, Fig. 3(b) suffer total rupture just after the sudden drop. On the contrary, specimens with higher amounts of PALF, Fig. 3(c) and (d), present after the drop and additional deflection, which could be attributed to fibers still resisting the applied force after the total rupture of epoxy matrix. This indicates that PALF composites with more than 10 vol% fibers should put an extra resistance until being gradually broken or pulled out from the completely ruptured matrix.

From curves such as the ones shown in Fig. 3, the flexural strength $\sigma_f$ (maximum bend stress) was calculated for each test specimen as:

$$\sigma_f = \frac{3F_m L}{2hd^2}$$

(1)

where $F_m$ is the applied flexural force, $L$ the distance between support points, $h$ specimen width (25 mm) and $d$ the specimen thickness (10 mm). The Weibull statistical method was used to
analyze the flexural strength. By means of the Weibull Analysis computer program probability plots of reliability vs. location parameter, shown in Fig. 4, were obtained for each composite with distinct PALF volume fraction.

### 3.1. Amount of fibers in the composites

Table 1 presents these values for composites with different volume fraction of PALF fibers. It is important to mention that in this table the flexural strength increases with the amount of PALF fibers incorporated.

The Weibull plots in Fig. 4 might be considered unimodal and associated with one straight line, which allows the determination of Weibull parameters: characteristic strength ($\theta$), modulus ($\beta$) and precision adjustment ($R^2$). These parameters are listed in Table 1 for each different composite as well as the neat epoxy.

From results in Table 1, the variation of average flexural strength with volume fraction of PALF in epoxy composites is shown in Fig. 5. In this figure it should be noted that a significant increase occurred in the flexural strength with PALF content in the epoxy composite. Above 10 vol% PALF, within the statistical deviation, this increase is practically linear following the equation:

$$\sigma_f = 2.3V_p\% + 50$$

(2)

where $\sigma_f$ in the flexural strength and $V_p\%$ is the percentage of PALF volume fraction.

A possible mechanism for this marked reinforcement of PALF on the flexural strength of epoxy composites is shown in the SEM fractographs in Fig. 6.

For the neat epoxy rupture, Fig. 6(a) only brittle surface with evidence of easy crack propagation (river patterns) are observed. Composite with 10 vol% PALF, Fig. 6(b), displays mostly epoxy brittle surface with signs of fiber pullout. With 20 vol% PALF, Fig. 6(c), fibers are intact and same sticking out of the surface. These are evidence of cracks in the brittle epoxy being arrested by PALF. With 30 vol% PALF, Fig. 6(d) fibers are dominant and relatively small brittle epoxy surface are observed. From this SEM results it is suggested that PALFs, with reasonable adhesion to epoxy matrix, act as an effective barrier to crack propagation above 10 vol% incorporation.

### 4. Conclusions

- The incorporation of pineapple leaf fibers (PALFs) into DGEBA/TETA epoxy matrix composites caused a significant reinforcement effect.
- As revealed by Weibull statistics, this reinforcement, above 10 vol% up to 30 vol%, follow a linear increase to a value of flexural strength around 120 MPa.
- Fractographs analysis by SEM disclosed an effective barrier of PALFs, with reasonable adhesion to the epoxy matrix, to crack propagation at 20 and 30 vol% incorporation.
Fig. 4 – Weibull plots for the: (a) neat epoxy, (b) 10, (c) 20, (d) 30 vol% PALF incorporated epoxy composites.

Table 1 – Weibull parameters for the flexural strength of neat epoxy and PALF incorporated polyester matrix composites.

<table>
<thead>
<tr>
<th>Volume fraction (%)</th>
<th>Weibull modulus, $\beta$</th>
<th>Characteristic flexural strength, $\nu$ (MPa)</th>
<th>Precision adjustment $R^2$</th>
<th>Average flexural strength (MPa)</th>
<th>Statistical deviation (MPa)</th>
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</thead>
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<tr>
<td>0</td>
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<td>0.9344</td>
<td>75.61</td>
<td>11.02</td>
</tr>
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<td>101.52</td>
<td>0.9430</td>
<td>103.25</td>
<td>13.31</td>
</tr>
</tbody>
</table>
Fig. 5 – Variation of the flexural strength with volume fractions of PALF reinforcing epoxy matrix composites.

Fig. 6 – SEM fractographs for the: (a) neat epoxy, (b) 10, (c) 20, (d) 30 vol% PALF incorporated epoxy composites.

Conflicts of interest

The authors declare no conflicts of interest.

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References


