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Original Article

Mechanical behavior of mallow fabric reinforced polyester matrix composites☆

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ABSTRACT

Woven fabrics made of a natural lignocellulosic mallow fiber have been used for a long time in common clothes. Recently, these fabrics are being considered as reinforcement for engineering composites. This work investigates the basic mechanical behavior of polyester composites reinforced with up to 40 vol% of mallow fabric. Room temperature tensile tests allow the evaluation of properties, such as the ultimate strength, elastic modulus, resilience and total strain. An improvement in these properties was found with increasing amount of mallow fabric in the composite. Indeed, a significant increase in strength, modulus and resilience occurred up to 40 vol% of fabric reinforcement. A slight increase was also observed in the total strain. Fracture analysis by scanning electron microscopy revealed that this improved performance of the reinforced composites might directly be associated with arrest of cracks propagation in the brittle polyester matrix by the mallow fibers in the fabric.

1. Introduction

In past decades, engineering applications of natural fibers extracted from cellulose-containing vegetables, also known as lignocellulosic fibers, are raising attention as sustainable alternatives to replace more expensive, non-recyclable and energy intensive synthetic fibers [1]. Among these applications, reinforcement of polymer matrix composites is being extensively investigated [2–9] and already used in industrial sectors, mainly the automotive [10–12]. Not only environmental but also societal, economical and technical reasons support a promising future for natural fiber composites, especially in comparison with the commonly used fiberglass [13]. Numerous natural fibers are currently being studied and applied in polymer composites [8,9,14]. In addition, some relatively unknown fibers, such as *Saccharum ciliare* [15] and *Hibiscus sabdariffa* [16], have only recently been investigated for their

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Fig. 1 – The mallow plant (a) and fabric (b).

potential as reinforcement. This is also the case of the fiber extracted from the stem of the bush plan *Urena lobata*, known as mallow, malva or mauve fiber, illustrated in Fig. 1(a). The mallow fibers have, for a long time, been used to produce fabrics for clothes and carpets as well as sackcloth to store and transport grains or nuts. In recent years, the possibility of using mallow fibers as composite reinforcement is being investigated [17–22]. To our knowledge, as for the low cost commercially available mallow fabric, investigations on possible polyester composite reinforcement are yet to be performed.

Therefore, the objective of the present work was to investigate for the first time the basic mechanical properties, obtained by tensile tests of polyester matrix composites reinforced with mallow fabric

2. Experimental procedure

The mallow fabric was supplied as continuous roll by the "Companhia Castanhal do Pará", Brazil. Fig. 1(b) illustrates the bidirectional woven aspect of the mallow fabric. The polymer matrix is an unsaturated orthophtalic polyester resin mixed with 0.5 wt% of methyl-ethyl-ketone as catalytic hardener.

The as-received fabric was cleaned in running water and dried at 60 °C in a stove for 24 h. Both the volume and surface densities of the fabric were evaluated by simple measurements of weight in an automatic scale and dimensions with a precision caliper.

The evaluation of the heat resistance of mallow fabric was carried out by thermal gravimetric analysis, TG, and its derivative, DTG, in a model 2910 TA Instruments operating at a heating rate of 10 °C/min, from 25 to 700 °C under air.

Composites were prepared by lying 120 × 150 mm^2 pieces of fabric in a steel mold. Still fluid polyester resin mixed with hardener was poured into the mold to produce distinct composite plates with volume fractions of 10, 20, 30 and 40% mallow fabric. Plain polyester (0% fabric) plates were also produced as control. During this process, particular care was taken to avoid formation of air bubbles. A pressure of approximately 3 MPa was applied to the mold throughout the cure for 2 h at room temperature (RT). Standard prismatic dogbone-shaped tensile specimens were machined with 30 mm of gage length and 5 × 4 mm^2 of reduced gage area; six specimens from each distinct composite plates. These specimens were RT tensile tested up to rupture in a model 5582 Instron machine, at a constant strain rate of 10^{-4} s^{-1}.

The fracture surface of tested specimens was analyzed by scanning electron microscopy (SEM) in a model Quanta FEG 250 Fei microscope with secondary electrons operating at 15 kV.

3. Results and discussion

The volume density of the mallow fabric was calculated as 996 kg/m^3, while the surface density was found as 0.329 kg/m^2. Fig. 2 shows TG/DTG curves of the mallow fabric. A peak of the adsorbed water loss of 6% occurred around 40 °C. Thermal decomposition being at about 200 °C with a peak at 346 °C and total degradation, 99% weight loss, at 600 °C. Thus, by drying at 60 °C only moisture was eliminated without thermal damage to the mallow fabric.

Typical tensile load versus elongation curves for the distinct mallow fabric reinforced polyester composites are shown in Fig. 3.

From load vs. elongation graphs such the ones in Fig. 3, the basic tensile properties were evaluated. Fig. 4 depicts the variation of ultimate tensile strength (σ_u) with the volume fraction (V) of mallow fabric. In this figure, one notes the significant increase in strength caused by the mallow fabric

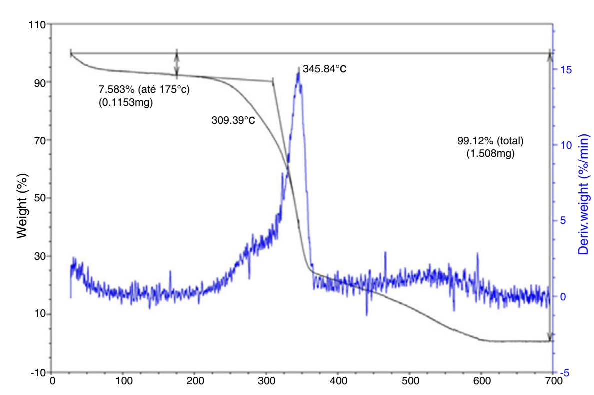

Fig. 2 – TG/DTG curves for the investigated mallow fabric.

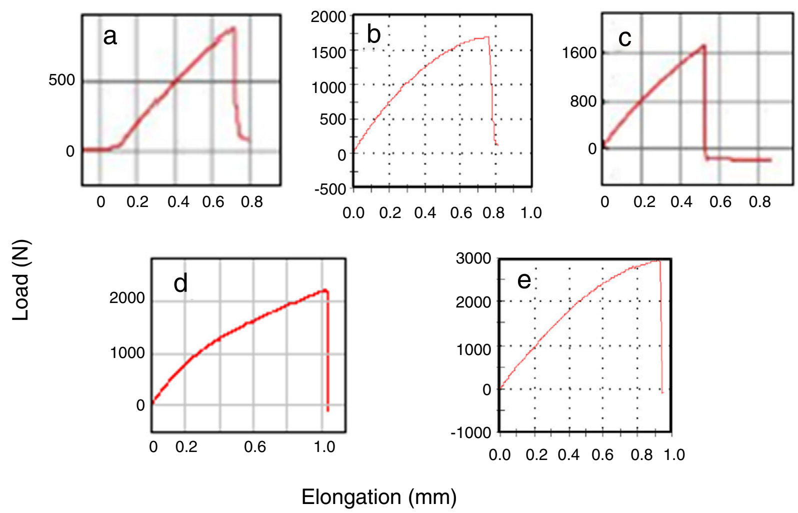

Fig. 3 – Typical load vs. elongation curves of tensile specimens with (a) zero (0%), (b) 10, (c) 20, (d) 30 and (e) 40 vol% of mallow fabric.

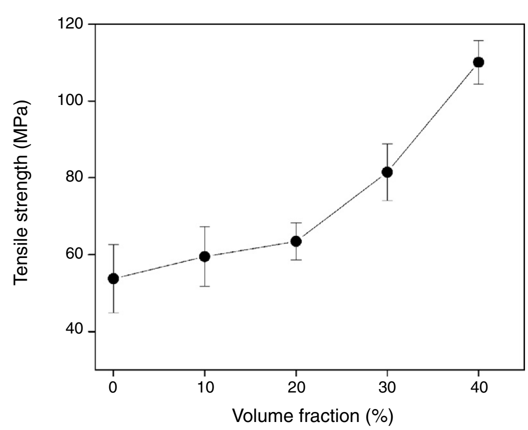

Fig. 4 – Variation of tensile strength of polymer composites as a function of volume fraction of mallow fabric.

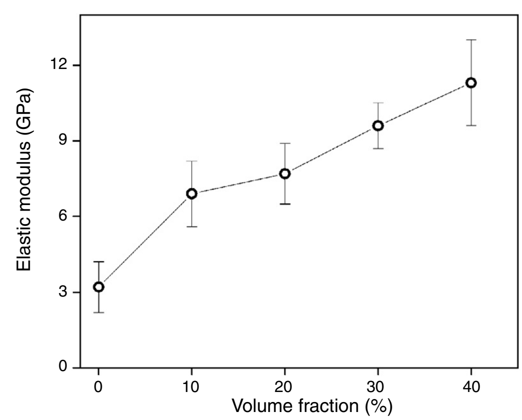

Fig. 5 – Variation of elastic modulus of polyester composites as a function of the volume fraction of mallow fabric.

reinforcement. Indeed, an exponential increase is found between σ_u and V:

$$\sigma_u = \exp(7.5V + 1) + 54 \quad (1)$$

The strength values (>100 MPa) reached by these mallow fiber reinforced composites with higher volume fractions is similar to those obtained with other natural fibers reinforced polyester matrix [6]. Moreover, polymer matrices reinforced with flax and jute fabric [9] also display results comparable to those in Fig. 3.

Fig. 5 shows the variation of the elastic modulus E of polyester composites as a function of the volume fraction (V) of mallow fabric. An almost linear increase of E is observed in Fig. 4 with the volume fraction of mallow fabric:

$$E = 0.2V + 3.7 \quad (2)$$

Comparable values of elastic modulus were also reported [9] for high amount of flax and jute fabric reinforced composites.

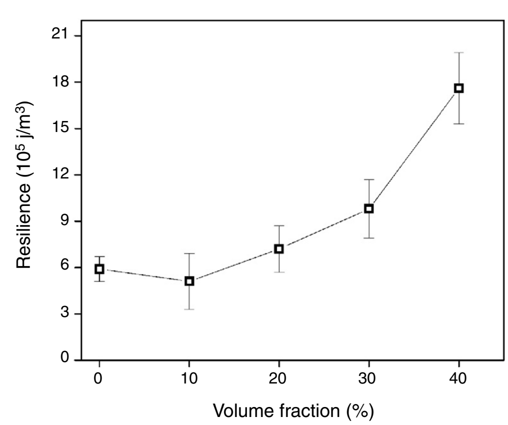

Fig. 6 – Variation of the polyester composite resilience with the volume fraction of mallow fabric.

It is worth mentioning that both Figs. 4 and 5 indicate, respectively, that strength and stiffness of composites reinforced with mallow fibers are not only higher than the polyester matrix but also have a favorable potential for

Table 1 – Total strain of polyester composites.

Volume fraction of mallow fabric (%)	0	10	20	30	40
Total strain (%)	2.2 ± 0.3	1.7 ± 0.5	2.3 ± 0.4	2.4 ± 0.6	3.2 ± 0.5

engineering application, which is comparable to other woven natural fabric composites [9].

The absorbed mechanical energy is also a relevant property for eventual engineering applications. Fig. 6 exhibits the variation of tensile resilience (U_R) of polyester composites as a function of the volume fraction (V) of mallow fibers. The resilience undergoes a marked increase with incorporation of mallow fabric in the polyester composite. In this case, a power equation fits more precisely the graph in Fig. 6:

$$E = (5.4V + 1)^{3.2} + 5.9 \quad (3)$$

In principle, Eqs. (1)–(3) are just experimental curve-fitting expressions, without theoretical basis, that indicate the strong increase in tensile properties of a polyester composite reinforced with mallow fiber.

A distinct behavior is obtained for the composite ductility. Table 1 presents the total strain for the different investigated composites. The results in this table show that, within the standard deviation, the total strain has a slight tendency to increase above 10 vol% of mallow fabric. However, all composites display a brittle behavior with very small plastic deformation, Fig. 2, after the elastic regimen.

Mechanisms associated with increase in strength (Fig. 4); stiffness (Fig. 5), energy (Fig. 6) as well as brittle behavior (Table 1) were revealed by SEM observation. Fig. 7 shows SEM fractographs of neat polyester as well as 10, 20, 30 and 40 vol% mallow fabric composites. The neat polyester rupture, Fig. 7(a)

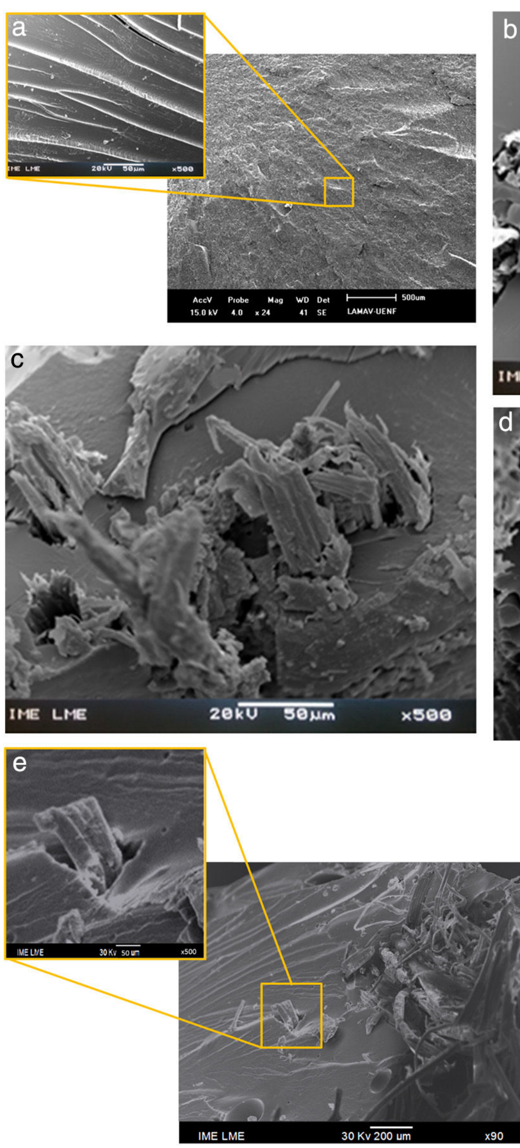

Fig. 7 – SEM tensile fractograph of (a) plain polyester, (b) 10, (c) 20, (d) 30 and (e) 40 vol% mallow fabric polyester matrix composite.

displays a flat and smooth surface, which is typical of brittle fracture [23]. This is caused by cracks that propagate without obstacles, river patterns in the insert, throughout the fragile polyester structure. A predominant smooth fracture surface is also observed for composites with 10 vol%, Fig. 7(b), and 20 vol%, Fig. 7(c), in spite of the incorporated amount of mallow fabric. As for the 30 vol% of mallow fabric composites, evidence of crack interaction with fibers might be noted in Fig. 7(d). By contrast, Fig. 7(e) shows that the existence of 40 vol% of mallow fabric acts as effective obstacles for crack propagation in the polyester matrices. Moreover, decohesion between mallow fiber and polyester matrix, as seen in the insert in Fig. 7(e), nucleates interfacial cracks that contribute to increase the absorbed energy, Fig. 6, without much change in the composite brittleness.

As a final remark, it is important for the reader to realize that the fabric made from mallow fibers has a potential to be used as polymer composite reinforcement, Figs. 2–5, comparable to that of well-known fibers and their fabrics [2–12]. The relatively low density ($\rho < 1$ g/cm^3) of the mallow fabric represents an additional advantage for reinforcement of composites with denser matrices, such as polyester ($\rho > 1$ g/cm^3) to be applied in light engineering components.

4. Conclusions

- Polyester matrix composites reinforced with up to 40 vol% of mallow fabric show exponential increase in tensile strength and linear increase in elastic modulus as well as a marked power law increase in the tensile resilience.
- The ductility of the composites is practically not affected by the mallow fabric and follows the brittle characteristics of the polyester matrix.
- The fractographic analysis reveals, above 30 vol%, an effective obstacle of the mallow fabric to the propagation of cracks throughout the polyester matrix. Decohesion between fibers and polyester indicates that interfacial cracks also play a role in the tensile properties of the composites.

Conflicts of interest

The authors declare no conflicts of interest.

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