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Original Article

Charpy impact tenacity of epoxy matrix composites reinforced with aligned jute fibers☆

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ABSTRACT

Natural fiber reinforced polymer matrix composites are gaining attention as engineering materials for advanced applications, including components of high performance ballistic armors. This requires superior mechanical properties, such as tenacity. Composites reinforced with jute fiber are currently being investigated as possible advanced engineering materials. Therefore, the objective of the present work was to evaluate the impact resistance of epoxy matrix composites reinforced with up to 30 vol% of continuous and aligned jute fibers. This evaluation was performed by measuring the Charpy absorbed impact energy of standard ASTM notched specimens. The results indicated a significant increase in the absorbed impact energy with the volume fraction of jute fibers. The microstructural mechanism related to this performance was revealed by scanning electron microscopy analysis.

1. Introduction

Polymer composites reinforced with glass and carbon fibers have replaced several conventional materials since mid-last century [1]. In the present century, however, these synthetic fiber composites are being questioned due to problem related to environmental and energy issues [2,3]. Indeed, the substitution of natural fibers for the traditional synthetic ones is gaining a growing attention since the past decade, as indicated by review articles [4–12]. The automotive industry, in particular, is already applying natural fiber composites mainly in interior parts [13,14]. In addition to lower cost and environmental benefits, technical advantages also favor natural lignocellulosic fibers extracted from plants. The impact resistance of the flexible fibers is an important advantage over the brittle glass fiber in an automobile crash event. This is the case of composites parts such as the head-rest and front panel.

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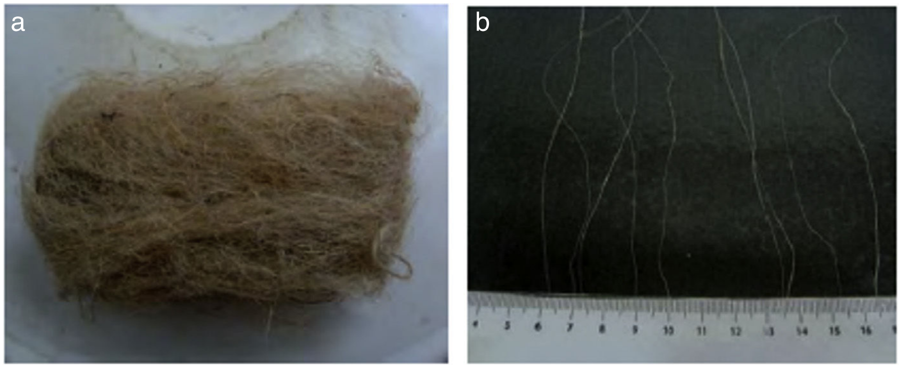

Fig. 1 – A bundle of as-received (a) and individually separated jute fibers (b).

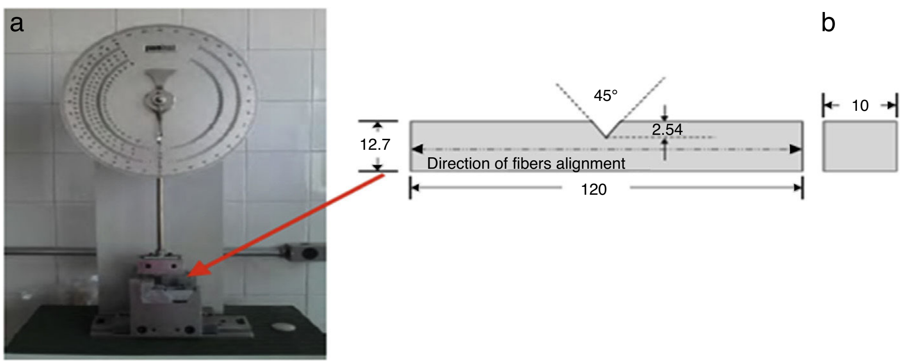

Fig. 2 – Charpy equipment and standard specimen schematic.

They should be soft and able to absorb the impact energy, associated with sharp pieces to avoid injuring the passengers [13].

Among the several natural fibers being used as polymer composite reinforcement, that of the jute extracted from the *Corchorus capsularis* plant is one of the most investigated, which is composed of 60% of cellulose, 22% of hemi-cellulose and 16% of lignin [15]. The jute fiber displays relevant properties for composite reinforcement, such as 393–773 MPa of tensile strength, 10–30 GPa of elastic modulus and density of 1.44 g/cm^3 [16]. However, some properties of specific composites reinforced with jute fibers still need evaluation. In particular, the tenacity is a relevant property for applications that might be associated with impact conditions such as the aforementioned automobile crash [13]. Additionally, impact resistance is a basic requirement for the ballistic performance of armor using natural fiber composites [17–24].

In view of these considerations, the present work evaluates the Charpy notch impact tenacity of epoxy matrix composites reinforced with up to 30 vol% of continuous and aligned jute fibers. The impact tenacity of plain epoxy used as matrix was also evaluated as control specimen.

2. Materials and methods

The jute fibers used in this work were supplied as a 5 kg lot by the Brazilian firm Sisalsul. Fig. 1 illustrates a bundle of the as-received lot of jute fibers as well as isolated fibers extracted from the bundle.

As composite matrix, a type diglycidyl ether of the bisphenol A (DGEBA) epoxy resin hardened with 13 parts per hundred of triethylene tetramine (TETA) in stoichiometric proportions was used. The as-received fibers were water cleaned and dried in a stove at 60 °C for 24 h.

Composites with 10, 20 and 30 vol% of jute fibers as well as neat epoxy (0% fiber) were manufactured by accommodation of continuous and aligned fibers in a rectangular 152 × 122 × 10 mm mold and embedded with the epoxy matrix until the desired fraction of weight was obtained.

Plates of each composite were then cut, according to the direction of alignment of the fibers, into bars measuring 120 × 12 × 10 mm, which were the basis for making Charpy specimens for impact test as per ASTM D256 standard, according to the scheme shown in Fig. 2.

The notch was prepared with a depth of 2.54 mm and angle of 45° required by the standard (Fig. 2b). For this purpose, a manual carver style brand CEAST Notchvas was used. The specimens were tested in an instrumented Pantec pendulum (Fig. 2a) in Charpy configuration.

The impact fracture surface of the specimens was analyzed by scanning electron microscopy, SEM, in a model SSX-500 Shimadzu microscope. Gold sputtered SEM samples were observed with secondary electrons imaging at an accelerating voltage of 15 kV.

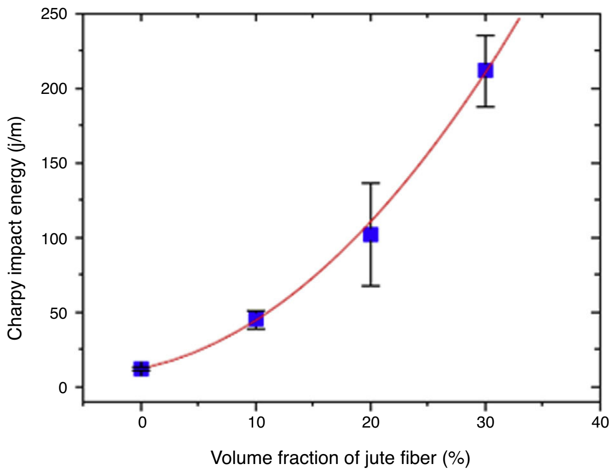

Fig. 3 – Charpy impact energy as a function of the amount of jute fiber.

3. Results and discussion

The results of Charpy impact tests of the epoxy matrix composites reinforced with different volume fractions of aligned jute fibers are shown in Fig. 3. This figure reveals a marked increase in Charpy impact energy with the volume fraction of jute fibers. It is also important to note that the points in Fig. 3 display error bars, corresponding to relative large standard deviation. This is due to the heterogeneous nature of natural fibers, which results in substantial dispersion properties of their reinforced composites [3].

Even considering the error bars, it is possible to interpret the increase of absorbed impact energy, i.e., the tenacity of the composites in Fig. 3, as varying exponentially with the volume fraction of jute fibers. A line passing through the points within the error bars demonstrates this exponential increase. The mathematical adjustment for this line corresponds to the equation:

$$E_e = \exp(0.10F + 2.4) \quad (1)$$

where E_e is the energy absorbed by the epoxy matrix composite Charpy impact and F the percentage of volume fraction of jute fibers.

The results in Fig. 3 reveal a significant increase in the tenacity of epoxy matrix with incorporation of continuous and aligned jute fibers. This is not surprising since similar Charpy tests on the same DGEBA/TETA epoxy matrix reinforced with other continuous and aligned natural fibers also show exponentially increasing absorbed impact energy up to 30 vol% of fiber incorporation [25–28]. Table 1 presents average values of Charpy impact tenacity of epoxy composites reinforced with distinct natural fibers.

In this table, one should notice that, as compared to the absorbed impact Charpy impact energy of the plain DGEBA/TETA epoxy specimen (~10 J/m), an increase in the amount of fiber for those composites in Table 1 significantly raises the composite tenacity. As shown in Table 1, the jute fiber offers a superior composite reinforcement if compared to other natural fibers, with the exception of banana fiber.

Table 1 – Charpy impact tenacity of epoxy composites reinforced with 30 vol% of continuous and aligned natural fibers.

30 vol% natural fiber composite	Absorbed impact energy (J/m)	Reference
Jute/epoxy	214	Present work
Banana/epoxy	543	[25]
Ramie/epoxy	211	[26]
Coir/epoxy	174	[27]
Curaua/epoxy	109	[28]

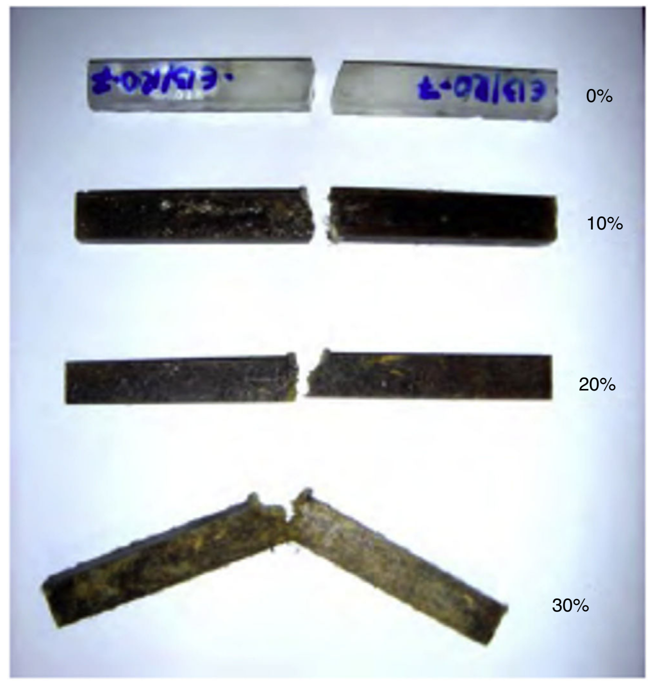

Fig. 4 – Typical ruptured specimens by Charpy impact tests.

Another important aspect to be discussed is the characteristic macroscopic rupture of the specimens after the test. Fig. 4 illustrates typical views of broken specimens of epoxy composites with different volume fractions of jute fibers. In this figure it is shown that the specimen with 30 vol% jute fibers, i.e., one with greater tenacity was not separated into two parts after the impact.

In this figure, up to 20 vol% of jute fibers, the initial crack nucleated at the notch proceeds into the matrix causing complete rupture of the specimen. However, with 30 vol% of jute fiber, the crack is blocked by the fibers and rupture occurs along the interface fiber/matrix. The specimen then bends around the head of the hammer, but does not separate due to the flexibility of the fibers that were not broken. Because total rupture in Fig. 4, does not occur for the specimen with 30 vol% fiber, the tenacity of the composite is underestimated. If all fibers were broken, causing the specimen to separate into two parts, the energy absorbed would be even greater. The reason for having a crack nucleated at the notch, changing its trajectory to reach the jute fibers and to propagate through

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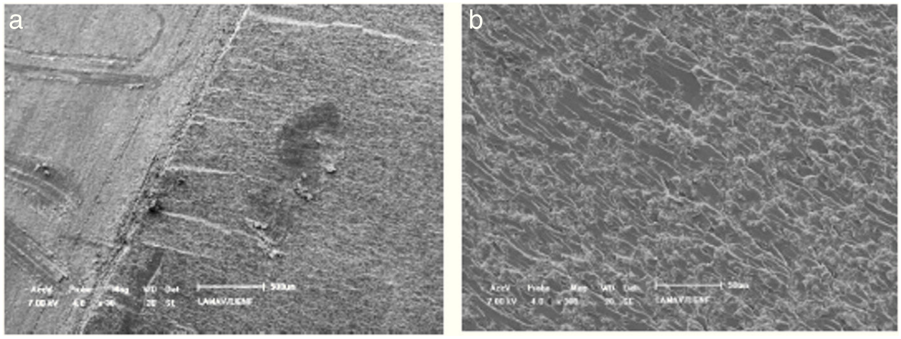

Fig. 5 – Charpy impact fracture surface of neat epoxy specimen (0 vol% of fiber): (a) general view; (b) detail of the epoxy transversal fracture.

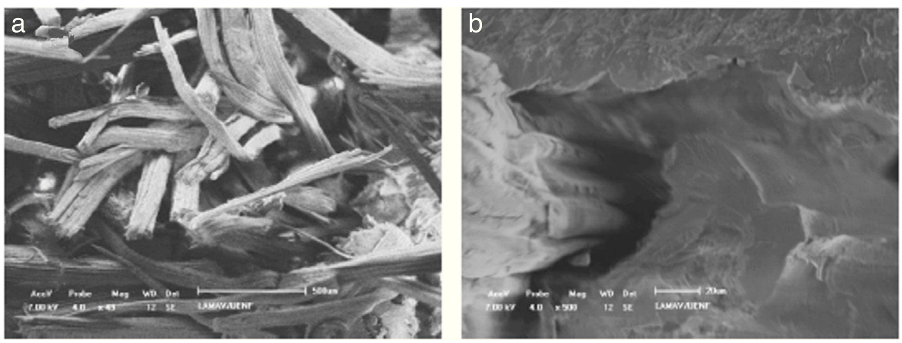

Fig. 6 – Impact Charpy fracture surface of an epoxy composite reinforced with 30 vol% jute fibers: (a) 30× and (b) 500×.

the interface with the matrix is due to the low interfacial resistance [29]. Similar behavior was also found for Charpy specimens of other natural fiber epoxy composites [25–28].

The SEM analysis of the Charpy impact fracture allows a better comprehension of the mechanism responsible for the higher tenacity of epoxy composites reinforced with continuous and aligned jute fibers. Fig. 5 shows the aspect of the fracture surface of a neat epoxy (0% fiber) specimen. With lower magnification, the lighter layer in the left side of Fig. 5a corresponds to the specimen notch, revealing the machining parallel marks. The smoother and gray layer on the right side corresponds to the transversal fracture surface. The fracture in Fig. 5 suggests that a single crack was responsible for the rupture with the roughness in Fig. 5b being associated with voids and imperfections acquired during the processing.

Fig. 6 presents details of the impact fracture surface of an epoxy composite specimen with 30 vol% of jute fiber. This fractograph shows a low adhesion between the fibers and the epoxy matrix, where cracks preferentially propagated. Some of the fibers were pulled out from the matrix and others were broken during the impact. The region of the specimen, in which the rupture preferentially occurred longitudinally through the fiber/matrix interface, reveals that most of the fracture area is associated with the fiber surface. This behavior corroborates the rupture mechanism of cracks that propagate preferentially in between the jute fiber surface and the epoxy matrix due to the low interfacial strength [25]. The greater fracture area (Fig. 6), associated with the aligned jute fibers acting as reinforcement for the composite, justifies the higher absorbed impact energy (Fig. 3), with increasing amount of jute fibers. The fracture surface of other Charpy impact-tested natural fiber epoxy composites [25–28] display the same characteristics, which indicates a common rupture mechanism. The significant higher amount of absorbed energy, Table 1, contributes to the ballistic performance of armors using natural fiber polymer composites [17–24].

4. Conclusions

- Composites with continuous and aligned jute fibers reinforcing an epoxy matrix display a significant increase in the tenacity, measured by the Charpy impact test, as a function of the amount of the fiber. The values of the absorbed energy are among the highest thus far obtained for lignocellulosic fiber composites.
- Most of this increase in tenacity is apparently due to the low jute fiber/epoxy matrix interfacial shear stress. This results in a higher absorbed energy as a consequence of a longitudinal propagation of the cracks throughout the interface, which generates larger rupture areas, as compared to a transversal fracture.
- Amounts of jute fibers above 20 vol% are associated with incomplete rupture of the specimen owing to the bend flexibility, i.e., flexural compliance, of the jute fibers.

Conflicts of interest

The authors declare no conflicts of interest.

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