Polish Society of Composite Materials
Polskie Towarzystwo Materiałów Kompozytowych

21: 3 (2021) 102-106

COMPOSITES THEORY AND PRACTICE
ISSN: 2084-6096
ISSN (online): 2299-128X

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Received (Otrzymano) 6.06.2021

EFFECT OF THERMAL TREATMENT ON MECHANICAL PROPERTIES OF SUSTAINABLE COMPOSITE: EXPERIMENTAL AND SIMULATION STUDY

The aim of this work is to accurately characterize the thermomechanical behavior of jute-polyester composites. The thermal characteristics and the mechanical properties are determined over a temperature range from ambient to 100°C. The effect of temperature on the tensile breakage of specimens was investigated in order to determine the ability of this composite to maintain its mechanical resistance. It was observed that Young's modulus and the tensile strength undergo an increase of about 80% when the temperature rises from ambient temperature to 60°C and a decrease for a temperature range from 60°C to 100°C. Numerical simulations, based on FEM analysis, provided results in good agreement with the experimental data in terms of the stress-strain curves. These simulations were achieved using Abaqus explicit finite element code. The increase and decrease in the mechanical properties were attributed to modification of the adhesion forces at the fiber/matrix interface.

Keywords: **jute fibers, composites, tensile modulus, Young's modulus, X-ray computed tomography, MEB, finite element analysis (FEA)**

INTRODUCTION

High-performance thermoplastic resins represent a promising alternative to thermosetting resins in advanced composite applications [1-3]. Moreover, natural fiber reinforced polymer composites can exhibit very different mechanical performances and environmental aging resistances depending on their interphase properties [4]. In fact, only a few studies have been conducted on the mechanical characterization of jute-based composite laminates [5-7]. Roe and Marin investigated the effects of jute fiber treatment on the performance of the resulting composite [8]. They assume that the properties of jute and glass fiber are comparable, and on a weight and cost basis jute fiber is seen in many respects to be superior to glass fiber as a composite reinforcement. Ahmed and Vijayarangan studied the experimental mechanical performance of isothalic polyester-based untreated woven jute-fabric composites subjected to various types of loading [9]. They found that the tensile strength and Young's modulus of the jute-fabric composite are 83.96 and 118.97% greater than the tensile strength and modulus of unreinforced resin, respectively. Recently, Deb et al. published a study on the mechanical behaviors of jute-polyester composites compared to hybrid jute-steel composites [7]. They discovered that the hybrid jute composites exhibit higher Young's modulus and flexural stiffness as well as consistent compressive strength as compared to plain jute-polyester composite laminates. The thermomechanical behavior of jute-polyester composites has been reported in several studies [10-13]. The thermomechanical properties of the composite were evaluated.

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MATERIALS AND EXPERIMENTAL CHARACTERIZATIONS

Materials

Natural fiber-reinforced composites are of particular interest for industry such as automotive and packaging manufacturers are looking to integrate new ecological and biodegradable materials due to their interesting mechanical properties, recycling possibilities and low production cost.

The experimental approach was limited to the preparation of jute-polyester composite materials. In this context, threes specimens of laminated composites consisting of 8 plies of jute fiber and polyester resin were studied. The characteristics of the jute fibers are listed in Table 1.

TABLE 1. **Characteristics of jute fibers**

Fiber length	Shape	Diameter
120 mm	Cylindrical	4 mm

Figure 1 presents the tensile curves of jute dry yarn specimens treated at different temperature (25, 60 and 100°C). The results show a large dispersion of the mechanical properties of the jute exposed to different temperature cycles. Young's modulus of jute yarns decreases with an increase in the temperature of the thermal cycles. However, the yield strength remains stable for all the treated yarns. In addition, the jute yarns are anisotropic (a high dispersion of results), confirming the work performed by Sanjay et al. in the case of natural yarns [14]. Ben Smail et al. studied the effects of temperature on the mechanical properties of natural yarns. They attributed the dispersion observed in our study to the quality of the fibers as well as to their properties and to the number of the continuous fibers in each specimen [15].

The jute-polyester composite specimens for tensile testing were prepared by contact molding. The first layer was arranged on a mold coated with a release agent; this is the gelcoat. Then the impregnated jute fibers and catalyzed accelerated resins were alternatively layered once the gelcoat was set. The jute-polyester composite composition is shown in Table 2.

TABLE 2. **Jute-polyester composite composition**

Component	Content [wt.%]
Polyester resin	60%
Jute fiber	40%

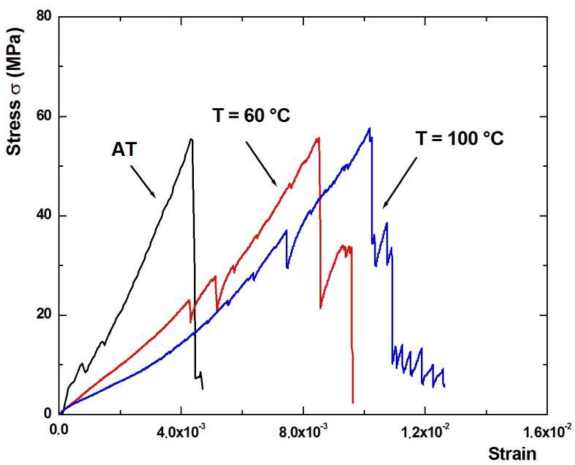

Fig. 1. Stress-strain curve of yarn specimens treated at different temperature (25 (AT), 60 and 100°C)

The first stage of preparation of the composite materials consisted informulation of the resin and its catalyst, to allow casting of the fibers. The second step was drying. It was carried out by several processes according to the elaboration process chosen. After drying, cutting of the composite plates was necessary in order to obtain specimens with the desired dimensions.

Characterization

The tensile tests of the prepared composites were carried out using an RP 25 ATF 3R electromechanical machine with a load cell capacity of 25 kN (Fig. 2b). The crosshead speed was 0.1 kN/s to determine the tensile strength. For the mechanical tests, three test pieces were used. Standard test specimens corresponding to ASTM D 3039 [16] were used. For the thermal treatment, we chose three temperature values: AT = 25°C, T = 60°C and T = 100°C. The time was about 1 hour for each treatment. Three tests were performed on three different specimens of 120 x 20 x 4 mm (Fig. 2a).

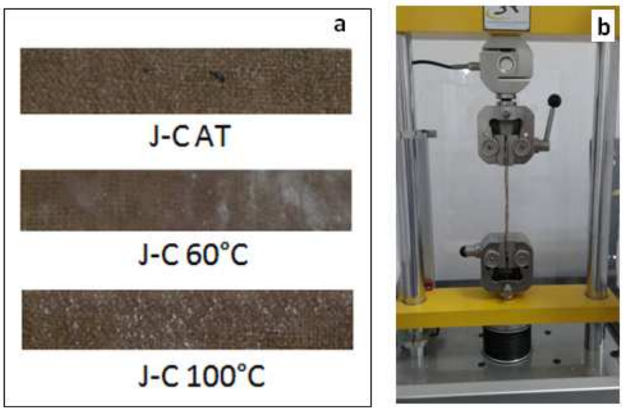

Fig. 2. a) Specimens of jute polyester composite treated at different temperatures (AT 25°C), b) setup used for tensile test

X-ray computed tomography (CT) was employed for visualization of the interior features of the jute-polyester composite. This is a frequently used non-destructive technique [17, 18]. CT consists in directing X-rays at an object from multiple orientations and measuring the decrease in intensity along a series of linear paths. This decrease is characterized by Beer's Law, which describes the intensity reduction as a function of the X-ray energy, path length, and the material linear attenuation coefficient. A specialized algorithm is then used to reconstruct the distribution of X-ray attenuation in the volume being imaged. In our specific case, tomographic analyses were performed on X-ray microtomography (Easy Tom Nano, Rx SOLUTIONS) acquisitions with a maximum X-ray beam power of 160 kW, which enables a spatial resolution of 0.5 µm. Prismatic specimens with dimensions 25 mm x 25 mm x 2 mm were inspected under 80 kV. The analysis takes more than 5 hours. The tomograms were reconstructed using commercial software programs (AVIZO and X-Act 2.0).

Figure 3 presents the tomogram of the jute-polyester laminate composite. Figure 3 areveals the good cohesion between the fiber and matrix. Also, the prepared composite has a low porosity level (Fig. 3b).

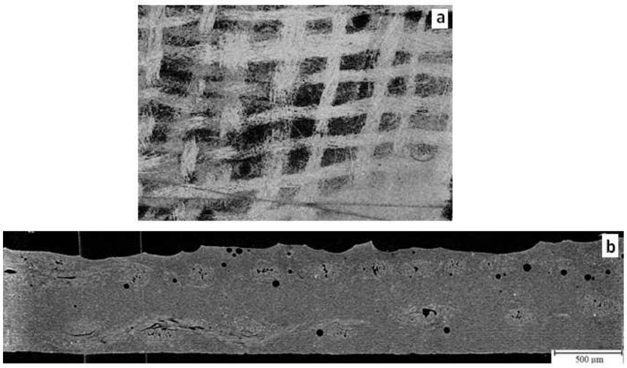

Fig. 3. X-ray tomograms of jute-polyester composite: a) surface of composite and b) impregnated fiber tow in laminates

RESULTS AND DISCUSSIONS

Experimental results

The experimental results giving the stress-strain curves of the jute-polyester laminate composite are presented in Figure 4. The stress-strain curves indicate that all the composites had a linear relationship in their elastic zone, ended by catastrophic brittle failure by complete fiber fracture. This means that the fiber had good adhesion with the matrix, which is lead to a good load transfer. The first observation apparent from Figure 4 is that the jute-polyester composite treated at 60°C has higher mechanical properties, especially in terms of Young's modulus.

The treatment temperature effect on Young's modulus, the tensile strength and elongation at break is summarized in Figure 5. Obviously, the laminate treated at 60°C demonstrates improved mechanical properties when compared to the ones treated at 25 and 100°C. It seems that the treatment at 60°C results in enhancement of the interfacial adhesion between the jute fibers and the polyester matrix. Figure 5 also reveals that the mechanical properties are slightly better for the laminate treated at 25°C compared to the one obtained at 100°C.

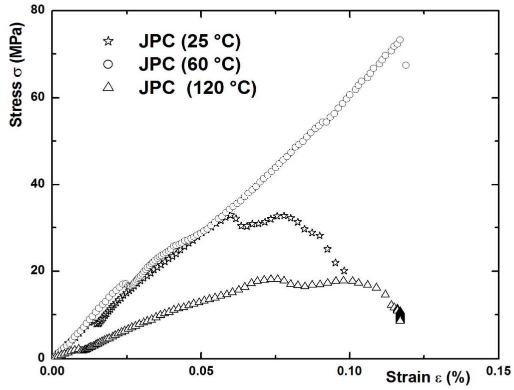

Fig. 4. Stress-strain curve of jute polyester laminate composite treated at different temperatures (25, 60 and 100°C)

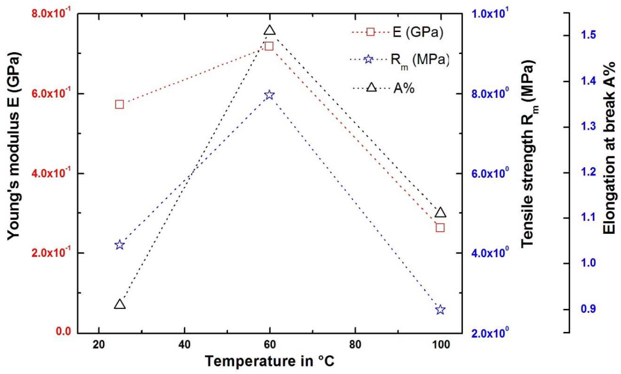

Fig. 5. Mechanical properties of studied jute-polyester composite

The scanning electron micrograph of the jute-polyester laminate composite was used in order to examine the surface adhesion between the fiber and the matrix. At ambient temperature and 100°C the micrograph shows poor adhesion between the jute fiber and the polyester matrix (Fig. 6a and c). It also evident from the SEM micrograph that jute fibers pull out and crack in the polyester matrix, which indicates weak interfacial bonding between the polyester matrix and the jute fibers. This is due to the weak interfacial interaction between the jute and polyester, causing failures of the jute-polyester composite at a lower load as compared to the fibers. The higher values of tensile strength of the jute-polyester composite at the temperature 60°C can be explained by the fracture morphology as shown in Figure 6b.

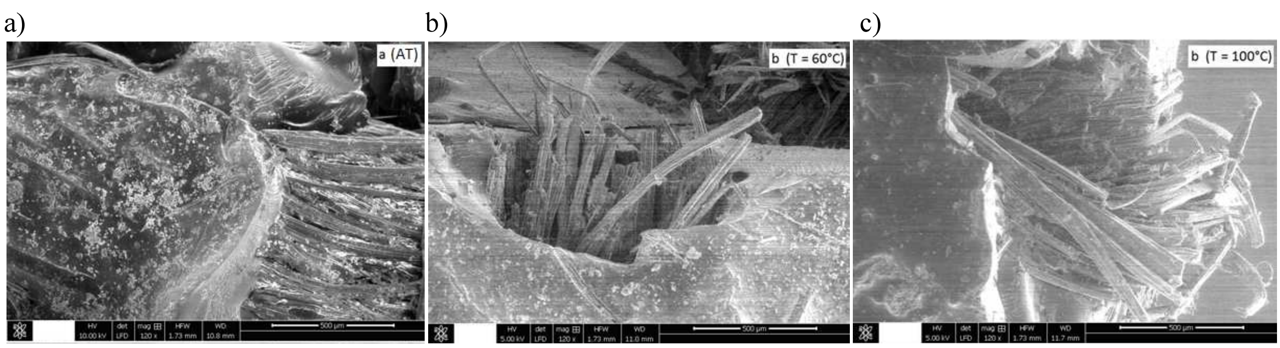

Fig. 6. Typical micrograph of heat-treated jute-polyester composite: a) ambient temperature, b) 60°C, c) 100°C

Simulation

Simplified Johnson-Cook Model

The simplified Johnson-Cook model is widely accepted to describe the coupling factors among stress, strain, and the strain rate [19]. The profile of the stress--strain curves of the jute-polyester composite was similar to those of traditional metals with a well-defined Johnson-Cook model. For the sake of simplicity, only the isotropic hardening and strain-rate hardening effects were considered [19]. Therefore, the main difference in Ref. [19] was that we did not take into account the hardening, otherwise we apply the law on the whole deformation zone, unlike what is done for ductile materials where it takes into account the non-linear part only. The dynamic behavior of the jute-epoxy composite can be expressed as:

$$\sigma = (A + B\varepsilon^n)(1 + C\, ln\dot{\varepsilon}^*) \qquad (1)$$

where σ is the stress, A is the yield stress, B and n represent the effect of strain hardening (in this case $B = 0$), respectively, C is the material constant determined by the specific material, representing the strain rate dependence of the material, ε is the equivalent plastic strain.

$$\sigma = A(1 + C\, ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}) \qquad (2)$$

In the damage model, the effect of the strain-rate on the nonlinear response of composites is modeled by the strain rate dependent function for the strength values as in [20]:

$$\{S_{rt}\} = \{S_0\}\left(1 + C\, ln\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right) \qquad (3)$$

where C is the strain rate constant for the strength properties, $\{S_{rt}\}$ is the rate dependent strength values; $\{S_0\}$ is the strength value of $\{S_{rt}\}$ at reference strain rate $\dot{\varepsilon_0}$, and $\dot{\varepsilon}$are is the longitudinal strain rate $\varepsilon_0 = 0.0004\ s^{-1}$, calculated from the slope of the displacement-time curve on the basis of quasi-static experiments. C can be obtained through the fitting in accordance with Equation (2). The simplified Johnson-Cook model (Equation (3)) was used to describe the dynamic rate-dependent constitutive behavior of the jute epoxy composite. The fitting parameters in the constitutive models in accordance with the experimental data are listed in Table 2 and the constitutive relationships:

$$\frac{\sigma_2(\dot{\varepsilon_1})}{\sigma_0} - 1 = \mathrm{C}\ln\frac{\dot{\varepsilon_1}}{\dot{\varepsilon}_0} \qquad (4)$$

Specimen and FEM model

The finite element method (FEM) is applied widely in the evaluation of structures with reliable results [21-23]. FEM makes it possible to solve in a discrete manner a partial differential equation whose approximate solution is sufficiently reliable. Numerical tests were carried out using the well-known commercial finite element software Abaqus (CAE 6.13-1). It offers the possibility of simulating the behavior of composite structures under mechanical constraint. The 3D models were built using parallele piped shapes. The final models were meshed using rectangular elements 0.1 to 1 mm long for the composite. Mesh refinement with the level set to 0.1 (0.1 maximum length of the mesh elements) was performed for the overlaps. A mesh convergence study carried out using displacement measurements indicates that the above mesh is fine enough to obtain a reliable result.

The numerical results of the jute-polyester composite at ambient temperature, 60 and 100°C are presented in Figure 7a-c. Comparison of the flexural FEM results shows that the reinforced beam resists dynamic stresses.

a) b) c)

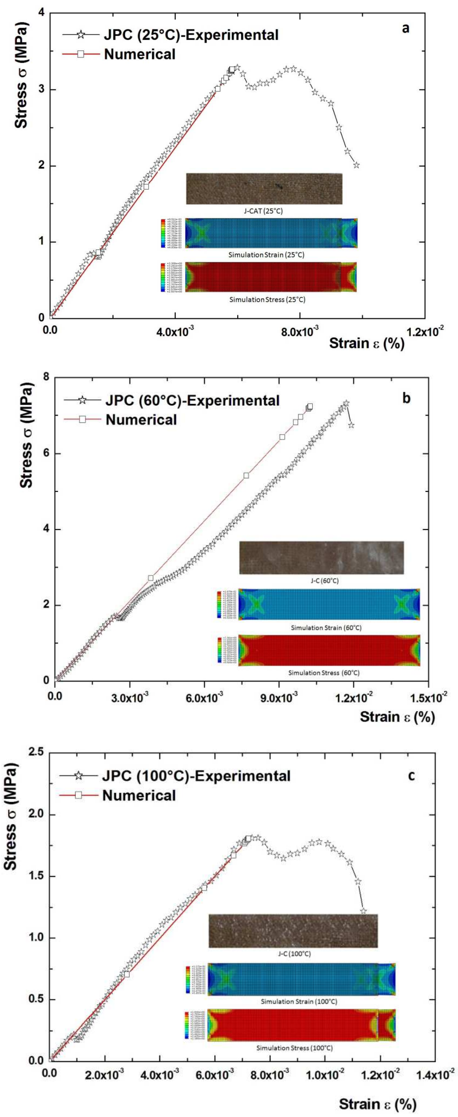

Fig. 7. Numerical results of heat-treated jute-polyester composite: a) ambient temperature, b) 60°C, c) 100°C

The simulations were compared to the experiment. Moreover, the thermal characteristics and mechanical properties were determined over a temperature range extending from ambient to 100°C. The influence of temperature on the specimen tensile breakage was investigated in order to determine the ability of this composite to maintain its mechanical properties. Young's modulus and the tensile strength increased by approximately 80% from ambient temperature to 60°C. These changes were attributed to modification of the adhesion forces at the fiber/matrix interface.

CONCLUSIONS

The study of thermomechanical behavior of jute-polyester composites by the finite element method was conducted using Abaqus code and compared to the experimental tests. Polyester-based jute fiber composite laminates were prepared at three different treatment temperatures. The composite laminate obtained after treatment at the temperature of 60°C exhibits improved mechanical properties when compared to those obtained at both ambient temperature and 100°C. The numerical simulation, based on FEM analysis, provided results in good agreement with the experimental ones for both the stress and strain behavior. These changes were attributed to modification of the adhesion forces at the fiber/matrix interface. By means of this study, we intend to contribute to a better understanding of the mechanical behavior of jute-polyester composites.

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