Visual Abstract

Mechanical properties and statistical analysis of the Charpy impact test using the Weibull distribution in jute-polyester and glass-polyester composites

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ABSTRACT. In recent years, the use of natural fiber composites to provide a possible replacement for synthetic fiber composites for practical applications has been the subject of several studies. This study deals with the fabrication and investigation of jute-polyester composites and the comparison of it with glass-polyester composites. The static mechanical properties of the composites is obtained by testing the composite lamina for tensile and flexural strength. The dynamic mechanical properties of the composites is determined by using the Charpy impact test. By the Williams method based on the principle of linear elastic fracture mechanics, the impact toughness of the composites is deduced. The experimental results were statistically analyzed by using the Weibull theory to better understand the impact behavior of the composites. It is found that the glass-polyester composite has better properties than the jute-polyester composite.

KEYWORDS. Jute; Glass; Polyester; Statistically analyzed; Impact strength.

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INTRODUCTION

Natural fibers are increasingly replacing conventional inorganic fibers as a reinforcement in composite materials [1-6]. They are low cost, renewable, lightweight and less abrasive. Jute is among the best vegetable fibers in terms of strength and mechanical properties. In addition, jute fibers are flexible and can be combined with different polymer resins such as phenolics, polyesters, and epoxies [7]. Jute fiber reinforced composites can be used as an alternative to glass fiber reinforced composites [8].

Many works have been published in recent years concerning the impact characterization of natural fiber composite materials. Amanda et al. [9] presented observations by scanning electron microscopy on test specimens made of composites with a polyethylene matrix reinforced with jute fiber fabric under impact stress with a difference in the percentage of reinforcement jute. The results showed that the incorporation of the jute fabric in the polyethylene resin increases the strength of the material. The addition of jute fabric in the polyethylene matrix completely changes the fracture characteristics of these composite materials. Muhammad Haris, et al. [10], using unnotched specimens subjected to an impact test, showed that there is an increase in impact energy with the increase in the percentage of jute fibers; however, when the fiber rate exceeds 30%, the value of impact strength decreases.

Wambua et al. [11] carried out studies on composite materials with a polypropylene matrix reinforced with natural fibers (sisal, kenaf, hemp, and coconut fiber). The mechanical properties of different natural fiber composites were examined and compared. A further comparison was made with the corresponding properties of glass mat reinforced polypropylene matrix composites. The natural fiber composites showed a low impact resistance. Hemp and sisal composites show a strength comparable to that of glass fiber composites. The specific properties of natural fiber composites are sometimes better than those of fiber glass composites. This suggests that natural fiber composites can be an alternative to replace fiber glass composites in many applications that do not require very high loading. Many authors [12-16] have reported the mechanical properties of natural fiber reinforced composites. The results obtained show that the mechanical properties in bending and static tension undergo a significant improvement by adding different percentages of natural fibers.

Glass fibers reinforcing is a widely market-accepted technology benefitting by the easy processability and the high strength of the fibers [17]. Impact tests carried out by Khalid et al. [18] on composites containing 45%, 55%, and 65% by volume of glass fibers have shown that the fracture energy decreases with the increase in the volume fraction of the glass fibers. Takahashi et al. [19] carried out Charpy impact tests on glass/epoxy composite materials. The results showed that the difference in the impact strength for the composite due to the duration of water immersion was not significant. Leonard et al. [20] investigated the Fracture toughness and critical energy release rate of polyester-reinforced glass fibers. The results showed a dramatic increase in the values of fracture toughness and critical energy release rate with increasing fiber content. The anisotropic microstructure of composite materials has a negative effect on the strength and causes very complex damage and failure mechanisms under impact loading. As a result, the results of the characterization tests, whether static or dynamic, show important dispersions, especially for impact tests on notched specimens. Therefore, there is a strong need to use statistical methods to interpret the experimental data of the Charpy impact test based on failure probabilities to achieve a better design of composite materials and to ensure the stability of the loaded elements [21]. Reliability analysis using Weibull probability was done to represent distributions of random variables. This law assumes that the failure of composite materials is linked to the presence of microstructural defects in the reinforcements and that it begins precisely at the level of the weakest defect [22,23].

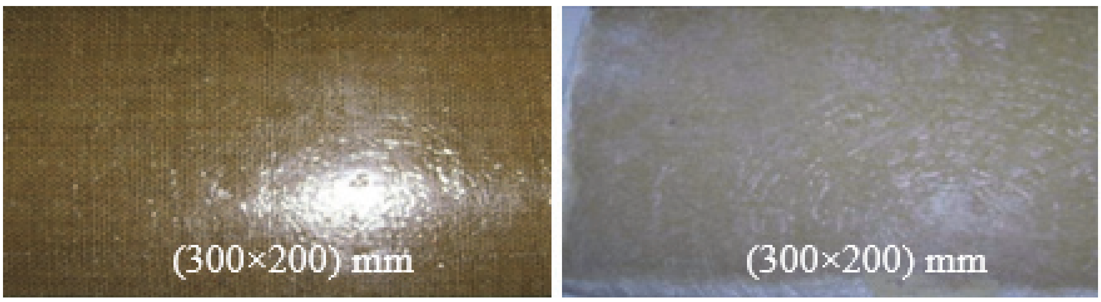
The major objective of this study is to predict the Charpy impact behavior and dynamic resilience of jute-polyester composites and to compare them with glass-polyester composites by analyzing them statistically using the Weibull theory.

MATERIALS AND EXPERIMENTAL METHODS

Materials

Two types of composite materials were used in this study were fabricated using contact molding technique:

- Rectangular jute - polyester plates composite 300 mm long and 200 mm wide, with three (03) layers of bidirectional jute fibers and a reinforcement rate of 40 %, shown in Fig 1 (a).
- Glass - polyester plates composite in the form of rectangular 300 mm long and 200 mm wide, with rate of 30 % of fibers randomly oriented and four layers of short multidirectional glass fibers, shown in Fig 1 (b).



(a) (b)

Figure 1: Rectangular composites plates of (a) jute – polyester (b) Glass – polyester

Tensile and flexural testing

Tensile and flexural strength tests were conducted in Zwick Roel universal-testing test machine with a ± 20 KN capacity and controlled by the computer software "test expert" at room temperature. Both the fabricated composites type is cut using a saw cutter to get the dimension of the specimen for tensile testing as per ASTM D638 standards, the length, width and thickness of the specimen were 165, 13 and 4 mm, respectively. Three point bend tests were performed in accordance with ASTM D 790 to measure flexural properties. The samples were 100 mm long by 15 mm wide by 4 mm thick. In three point bend test, the outer rollers are 80 mm apart. Test machine along with "test expert" software make calculating Young's Modulus.

The impact Charpy tests were carried out on a Charpy Zwick 5113 Pendulum impact testers in 3-point bending in accordance with ASTM D6110. The release angle of the machine is 160° and the impact speed is 3.85 m/s. The pendulum used in the case of the study materials has an energy of 7.5 J. Fig. 2 shows the experimental device used as well as the data acquisition and processing device by a microcomputer equipped "with an expert test software". The specimens used in the impact test are prismatic in shape, 80 mm long, 10 mm wide and 4 mm thick, with a single edge notch. The distance between supports of the impact apparatus is 64 mm. The notch lengths are all in the ratio $0.2 < a/D < 0.6$. Where a is the notch length and D is the notch width of the specimen, respectively.

Figure 2: Zwick/Roell type Charpy impact machine used.

Application of linear fracture mechanics to impact tests

The experimental resilience R of notched specimens is calculated in accordance with EN-ISO-179-1 using the following equation:

$$R = \frac{U}{B.(D-a)} \tag{1}$$

The Williams method based on the principles of linear elastic fracture mechanics has been used to interpret the results of impact tests on notched specimens [23-24]. This method makes it possible to obtain an estimate of the energy or toughness G_{IC} intrinsic parameter of the material from the total energy dissipated U during the impact according to the equation:

$$U = \left[G_{IC} BD\phi\right] + U_C \tag{2}$$

B and D represent the thickness and width of the specimen, respectively, and $\varnothing$ is a calibration factor which depends on the geometry of the specimen and which was tabulated by Williams for various lengths of notches (Eqn. 3). Thus, the recording of the energy lost by the hammer at the moment of impact for each notch plotted on a diagram U a function of (BD $\varnothing$) gives a straight line whose slope measures G_{IC} and the kinetic energy U_C.

$$\phi = \frac{1}{2}\left(\frac{a}{D}\right) + \frac{1}{36\pi}\left(\frac{L}{D}\right)\frac{1}{\left(\frac{a}{D}\right)} \tag{3}$$

where a and L represent the notch length and the distance between supports, respectively.

RESULTS AND DISCUSSION

Tensile and flexural behavior

The stress-strain curves and average modulus of elasticity obtained in static tension for the jute-polyester and glass-polyester composite materials are represented in Figs. 3 and 4, respectively.

The glass-polyester composites clearly had a better performance among the two types of composites. They could withstand up to 172 MPa tensile stress with 5% strain compared to jute-polyester composites with an average of 43 MPa tensile stress and 2.2% strain. The average tensile modulus is also high for the glass-polyester. It is about 1.8 times that of the jute-polyester.

On the other hand, it was observed from each stress-strain curve that specimens of the two types of composites follow the same trend of the stress-strain behavior. All stress-strain diagrams are linear until the rupture, reflecting a fragile and elastic character of the composites tested. Note that the break always occurs in the central part of all samples tested. The factors that lead to breakage are complex: matrix breakage, fiber breakage, interface breakage [24]. All of these factors can take place simultaneously. It is very difficult to assess which is more dominant in the samples tested for both composites studied. From the results of the tensile test, it can be concluded that the glass-polyester composite is performing well compared with the jute-polyester composite. This is mainly due to the nature of the fibers and their architecture [8]. The glass fibers are stronger and stiffer than the jute fibers.

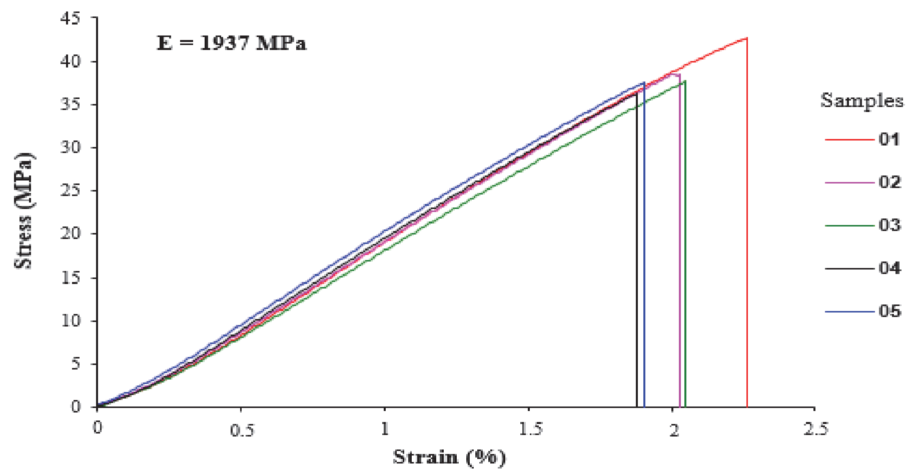


Figure 3: Stress – strain (σ - ε) of the bidirectional jute – polyester composite in tension tests

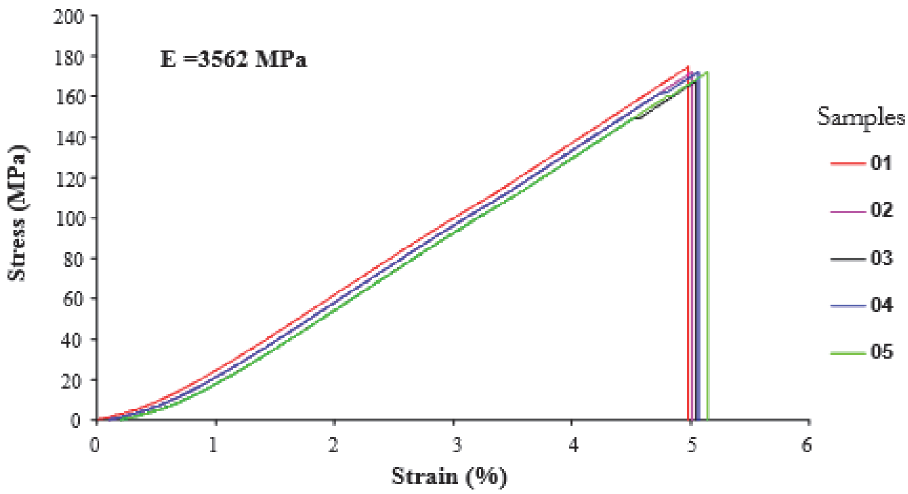


Figure 4: Stress – strain (σ - ε) of the multidirectional glass – polyester composite in tension tests

The flexural properties represent the flexibility of the materials, and a good flexural strength indicates that the materials have brittle properties and high hardness [2]. Figs. 5 and 6 show the stress-strain curves and average modulus of elasticity obtained in the flexural strength test for the jute-polyester and glass-polyester composites. The flexural property behaviour, of the glass-polyester composites generate higher values of the flexural properties (flexural stress, strain, and flexural modulus) than the jute-polyester composites. Also, the results of the flexural properties exhibits higher values compared to the tensile properties.

Moreover, the stress-strain curves, unlike those obtained in tension, show three zones for the two types of composites tested. A linear phase reflecting the elastic behavior of the composite. A second linear phase of weaker slope translating the damage, which occurs gradually within the composite during the loading. This damage starts to take place at a stress intensity lower than that of the breaking stress. A decrease in the stress beyond the maximum load announces the unstable failure of the specimen. The most dominant mechanism of failure observed in the flexural strength of samples tested, the accumulation of deformations on the stretched part leads to generalized damage, which spreads to the core of the specimen and causes delamination.

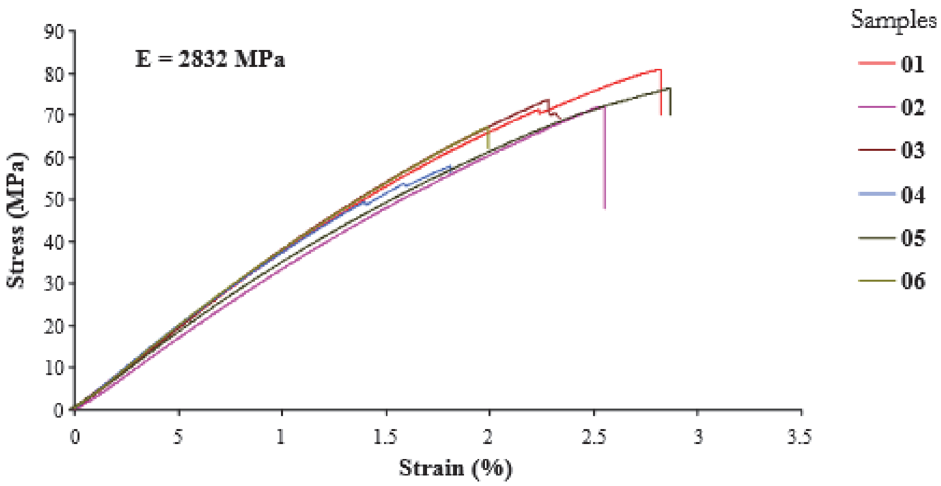


Figure 5: Stress – strain (σ - ε) of the bidirectional jute – polyester composite in flexural tests

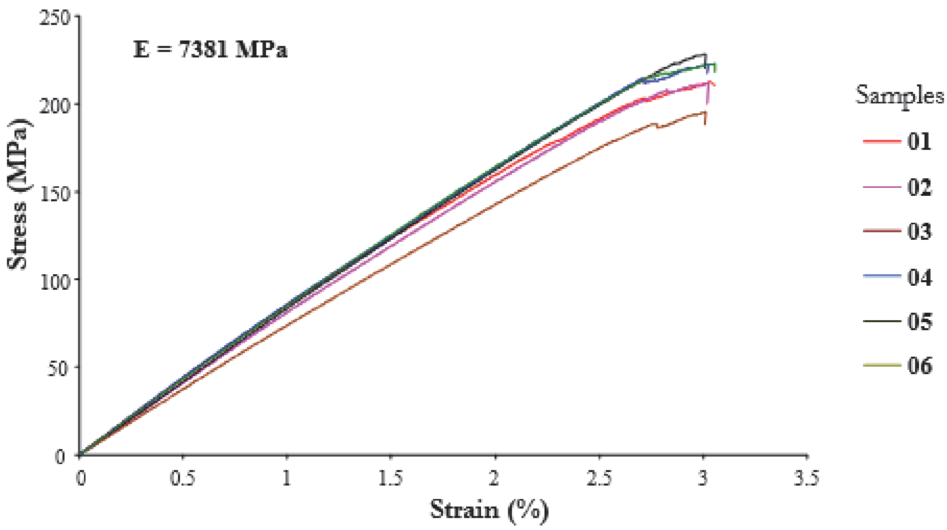


Figure 6: Stress – strain (σ - ε) of the multidirectional glass – polyester composite in flexural tests

Impact Behavior

The graphical presentation of the impact energy U as a function of the ruptured areas BDϕ for the jute-polyester and glass-polyester composites (Figs. 7 and 8) shows that the total fracture energy increases with increasing ruptured areas, which indicates that fracture is an energy-consuming phenomenon; thus, increasing ruptured areas require more fracture energy. On the other hand, despite a dispersed orientation of the glass fibers, a short length, and a lower rate (30% compared to 40% in the case of jute), the Charpy impact strength and dynamic toughness values of the glass/polyester composite (R = 103 kJ/m² and G_{IC} = 234 kJ/m²) are very high compared to that of the jute/polyester composite (R = 6 kJ/m² and G_{IC} = 5.3 kJ/m²). In addition, the glass-polyester specimens did not break completely. They are characterized by the development of a damaged zone before the rupture. However, the jute/polyester specimens were completely broken, showing a rather fragile nature. This difference is mainly due to many factors including the nature of the fiber, fiber/matrix interface, and the construction and geometry of the composite [25].

The linear regression line of the curves in Figs. 7 and 8 gave a positive intersection with the U ordinate line, which is due to the effects of the kinetic energy transmitted to the specimens during the impact test. The jute/polyester composite presents a value of kinetic energy of about 0.098 J, which is less important than the value of the glass/polyester composite, which about 0.252 J. It is important to note that any kinetic energy transferred to the specimens first enters as strain energy, as momentum is transmitted to the outer ends (supports) by shear waves passing outward along the beam [26].

The calculated impact toughness results of the Charpy impact test on all the tested specimens show correlation coefficient values of 0.81 and 0.84 for the jute/polyester and glass/polyester composite, respectively, reflecting the dispersion of the results of the impact energy of the cracked specimens around the linear regression line. This is essentially due to the presence of defects during the manufacture of the specimens, can be attributed to presents of fibers in the polyester matrix causes often tortuous paths of rupture which do not necessarily follow the direction of the initial notch and which are different from one specimen to another.

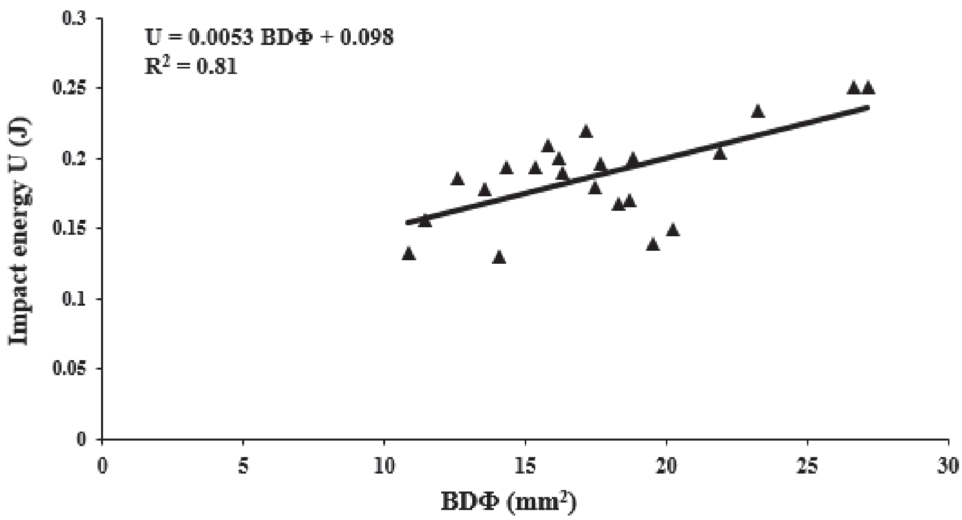


Figure 7: Total fracture energy as a function of broken areas of jute – polyester composite

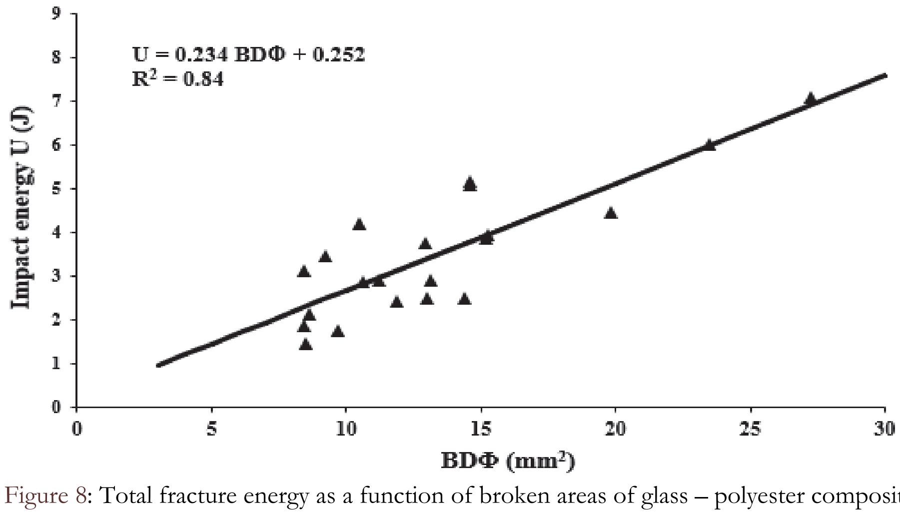


Figure 8: Total fracture energy as a function of broken areas of glass – polyester composite

Probabilistic analysis by the Weibull theory

Weibull's analysis [22] is based on two essential hypothesis:

- The material is statistically homogeneous and isotropic. The probability of finding a defect of a given severity in an "arbitrarily small" volume of material is the same everywhere;
- The rupture of the most critical defect leads to the complete rupture of the sample, a perfect brittle fracture.

The first assumption is that the number of defects N is proportional to the volume V, we can present the relationship in the form:

$$P_f = 1 - \exp\left[-V\varphi(\sigma)\right] \tag{4}$$

where, $\boldsymbol{P_f}$: presents the probability of the considered system, and $V\varphi(\sigma) = NF_1(\sigma)$

$\varphi(\sigma)$ is a function of unknown shape. Weibull [17] proposed the following empirical relation in view of the experimental results:

$$\varphi(\sigma) = \left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m \qquad \text{for } \sigma > \sigma_u \tag{5}$$

$$\varphi(\sigma) = 0 \qquad \text{for } \sigma < \sigma_u$$

where, σ_u stress threshold for zero failure probability. σ_0 normalization factor and m: characteristic parameter of the material, modulus of heterogeneity.

He comes then:

$$P_f = 1 - \exp\left[-V\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^m\right] \qquad \text{for } \sigma > \sigma_u \tag{6}$$

$$P_f = 0 \qquad \text{for } \sigma < \sigma_u$$

A statistical analysis by the Weibull theory [19] applied to impact tests becomes interesting in order to better understand the behavior of these materials at high stress speed. For this, it is necessary to graphically represent the distribution of the rates of energy restitutions. The calculation of the failure probability P_f was made using the following expression of the median rank:

$$P_f = \frac{i}{n+1} \tag{7}$$

i and n are the rank and the number of samples respectively.

The determination of the Weibull modulus requires the graphic representation of the curve corresponding to LnLn (1/(1-P_f)): as a function of the logarithms of the energy restitution rates and which has the equation:

$$\mathrm{LnLn}\,(1/(1-P_f)) = m.\mathrm{Ln}(G_{IC} - G_S) - m.\mathrm{Ln}(G_0 - G_S) \tag{8}$$

The slope of this line represents the Weibull modulus (m) and the dispersion parameter G_0 can be obtained by the second term in Eqn. 8.

Figs. 9 and 10 show the two-parameter Weibull curve fitting of the Charpy impact test results of the jute-polyester and glass-polyester composites, respectively. It should be noted that the correlation coefficient R^2 presents a value of 0.97, reflecting the good correlation of the experimental data as well as the reasonable fit of the tow parameter Weibull distribution. In addition, all predictions generally follow the trends of the experimental data.

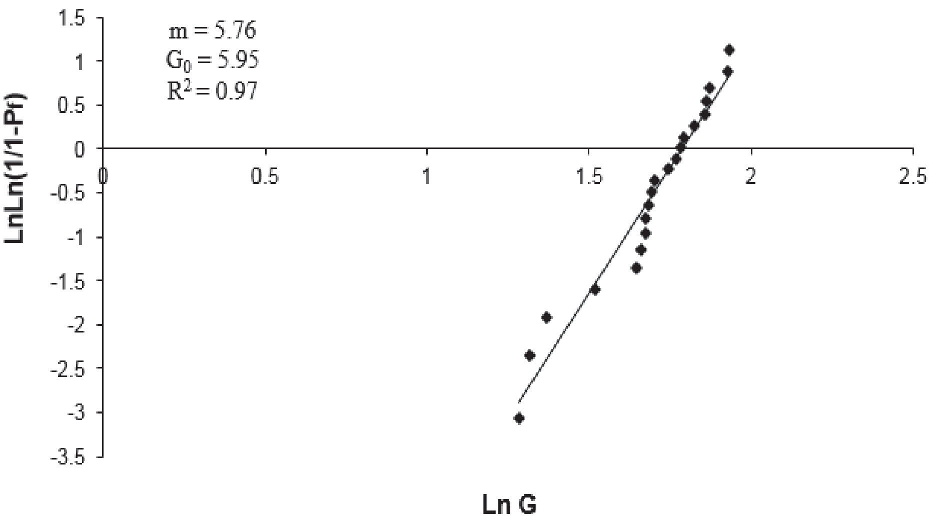


Figure 9: Weibull probability plot of jute – polyester composite

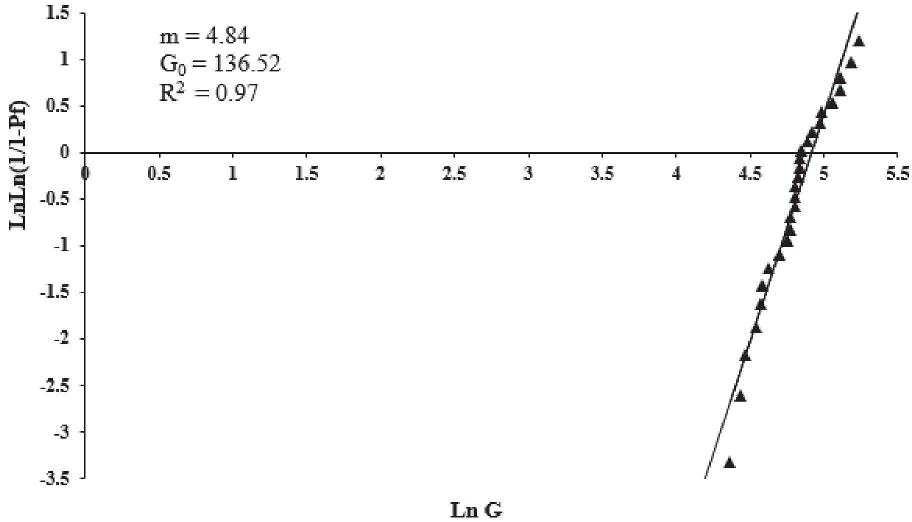


Figure 10: Weibull probability plot of glass – polyester composite

The fracture energy, as well as the impact toughness, follows a distribution characterized by the Weibull modulus m and the scaling parameter G_0. These parameters are a function of the interaction between the pre-existing defect distribution and the stress displacement fields due to the shock loading. However, the large shock pendulum velocity, which is about 3.85 m/s, leads to a variety of phenomena that occur at the time of loading and cracking of the notched specimens. The shape parameter m obtained by the two Weibull analyses shows less significant values of the glass-polyester (8.84) compared to the jute-polyester composite (5.76). It is highly possible that this difference is mainly due to the presence of a non-uniform distribution of glass fibers within the composite material, with the creation of voids and micro pores of different dimensions and shapes. The presence of the short length and dispersed orientation of the glass fibers leads, at the same time, to an increase in the G_{IC} toughness by the absorption of the impact energy and a decrease in the homogeneity of the glass-polyester composite compared to the jute-polyester composite.

CONCLUSION

In order to evaluate the effect of the fiber type on the composite properties, jute and glass were used as the reinforcement. It was clearly observed that the fiber type that was used had a great importance on the strength characteristics of the composites. The short glass fiber with dispersed orientation gave better results. Therefore, the highest tensile and flexural strength were found for the glass-polyester compared to the jute-polyester composites. In addition, the Charpy impact energy and toughness obtained by the Williams theory based on the principles of linear elastic fracture mechanics confirm the brittleness of the jute-polyester composites. Statistical analysis of the results was conducted using the Weibull probabilistic theory. The measured Weibull modulus m shows that the results are scattered for the tow types of materials studied. Despite the excellent mechanical properties of the composite materials based on jute fibers, they remain less efficient than composites based on glass fibers and, above all less, resistant to shocks. These properties preclude their use in situations that involve resistance to heavy loads.

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