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Impact of biaxial square woven jute fabric reinforcement on mechanical performance of polyester-based composites

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In this study, 4, 6 and 8 plied biaxial square woven jute fabric reinforced polyester composites have been fabricated by the compression molding technique. The physical properties (void fraction, fibre/volume and fibre/weight ratios) and mechanical properties (tensile, flexural and impact strength) of the composites are investigated. According to the physical evaluation test results, the highest void content is calculated for 8 plied composites (11%), where the fibre volume ratio (41.7%) and weight ratio (46.4%) are also maximum. The mechanical test results show that with the increase in jute fabric plies from four to eight, tensile strength, flexural stress and impact resistance improve by 25%, 100% and 340% respectively.

Keywords: Biaxial woven fabric, Composite, Compression molding, Jute fibre, Mechanical testing, Polyester, woven fabric

Bio-composites are the composites in which plant-based natural fibres such as jute, hemp, flax, kenaf and sisal are used as reinforcement materials in a matrix of either biodegradable or non-biodegradable resins[1]. Natural fibre-reinforced composites are demanding materials due to their low-cost production, low specific weight, renewable nature, lack of a health hazard, availability in huge quantities, low fossil-fuel energy requirements and reasonably good mechanical properties[1–3]. These bio-composites are preferred in the applications where moderate mechanical performance is required with light weight and reduced manufacturing cost, such as sport equipment, wall panels, indoor parts in the automobile industry, etc[4–7].

Jute, which constitutes the second-highest global production level of cellulosic fibres[1], is one of the most preferred natural reinforcement materials that has good physical and mechanical properties compared to other natural fibres[2]. Among all other natural fibres, jute contains the highest amounts (75%) of stiff natural cellulose[8].

In most studies, instead of biaxial woven jute fabrics, jute fibres were preferred as the reinforcement material. To the best of our knowledge, there are not many studies about biaxial woven jute fabric reinforced composites. In one such study, Gowda *et al.*[9] investigated the mechanical properties of untreated jute woven fabric-reinforced polyester composites. The hand lay-up method was used to produce the composite laminates. The average values of tensile strength and impact strength of these composites were 60 MPa and 29 kJ/m^2 respectively. They stated that although the mechanical properties of jute reinforced composites are not as high as conventional composites, they have better strength than wood composites and some plastics. Carvalho *et al.*[10] investigated the effect of fabric type (plain woven fabric and weft knitted fabric), fibre weight fraction and direction of applied load on the impact and tensile strength of jute reinforced polyester composites. Their results showed that the impact strength of the knitted fabric reinforced composite was higher than that of the plain woven reinforced composite and it was almost independent of the test direction. Higher tensile strength was achieved with plain woven reinforced composites. While the tensile strength of knitted fabric reinforced composites was independent of the test direction and fibre content; however, that of plain weave reinforced composites was dependent on those factors[10]. Ahmed *et al.*[11] investigated the mechanical properties of woven jute fabric reinforced polyester composites under tension, compression, flexural, interlaminar shear, in-plane shear and impact loading. The hand lay-up method was used for fabrication of 10 plied composite laminates. They stated that this product can be a convenient material for use in medium load-bearing applications[11]. As mentioned above, jute is one of the most preferred reinforcement materials among natural

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fibres. However, in the literature, jute is mostly used in fibre form in composite structures. Here, biaxial square woven jute fabric was preferred instead of jute fibre to obtain similar mechanical properties in each direction of the composite sample. The aim of this study is to fabricate biaxial square woven jute fabric reinforced polyester composites and to investigate the effect of fabric ply increment (4, 6, and 8 ply) on the physical and mechanical properties (tensile strength, flexural stress and impact resistance) of the composite. The composites are reinforced with 4, 6, and 8 plied jute fabrics in which the number of plies is determined in light of earlier findings[12–22].

Experimental

Biaxial square woven jute fabric (plain woven) having a basis weight of 300 g/m^2 was used as the reinforcement material. Polyester (POLRES PRE-62), cobalt and methyl ethyl ketone peroxide were chosen as resin, accelerator and hardener respectively, and they were mixed in the ratio of 1:0.00175:0.002 (by weight).

Composite Fabrication

Composite panels were produced by the compression molding technique. A hydraulic press (Yurtmak, TR.) with 8000 kg capacity was used, consisting of female bottom and male top molds with 250 × 500 mm dimensions. In the manufacturing steps, releasing agent was applied both to the female and male molds to prevent sticking of the composite panels. After the releasing agent had dried, the resin system was prepared by adding the accelerator and hardener into the polyester just before the fabrication period; then it was poured into the female mold, and one layer of jute fabric was laid on it. Again, the resin was applied to the fabric, and this process continued until the required fabric layers were achieved in the composite. Finally, the male mold was put onto the female mold and placed under a hydraulic press. Three thousand kilograms pressure was applied to the composite panels and left for 24 h for curing. The cured panels were moved from the molds, and their edges were trimmed by guillotine scissors for further specimen cutting.

Physical and Mechanical Testing of Jute Fabrics

The linear yarn densities of the jute yarns obtained from woven fabric were measured according to the TS 244 EN ISO 2060 standard. The basis weight (g/m^2) (TS EN 12127) and thickness (mm) of the fabrics were measured by precision balance and R&B Cloth Thickness Tester. Fabric counts were calculated according to the TS 250 EN 1049-2 standard.

Physical Testing of Composites

The fibre volume ratio was calculated using the following equation:

$$V_f = \frac{\frac{W_j}{\rho_j}}{\frac{W_j}{\rho_j}+\frac{W_p}{\rho_p}} \qquad \text{...(1)}$$

where W_j & W_p represent the weight ratios of the jute and polyester; and ρ_j & ρ_p, the densities of jute and polyester respectively. According to the literature and datasheets of supplier companies, the densities of jute and polyester used were 1.45 g/cm^3 and 1.2 g/cm^3 respectively[23].

To calculate the weight ratios of the samples, they were first weighed by a precision balance, and their dimensions were measured with a ruler. According to the known dimensions and basis weight of fabrics, the amount of fabric used in the sample was calculated. By dividing the weight of the fabric by that of the sample, the weight ratio of the sample was obtained. The void fraction was calculated using the following equation, according to the ASTM D2734-94 standard:

$$\Delta v = \frac{\rho_{ct} - \rho_{ex}}{\rho_{ct}} \qquad \text{... (2)}$$

where ρ_{ex} and ρ_{ct} are the experimental density and theoretical density of the composite laminate respectively. Experimental densities of composite laminates were measured by dividing the measured weight (g) by the measured volume (cm^3). A micrometer and precision balance were used to measure the dimensions and weight of the samples respectively. Following equation was used to calculate the theoretical density of the composites:

$$\rho_{ct} = \frac{1}{(W_f/\rho_f)+(W_m/\rho_m)} \qquad \text{... (3)}$$

where W_f & W_m represent the weight fractions of the fabric and matrix; and ρ_f & ρ_m are the densities of fabric and matrix respectively.

Specimen Preparation

An Autocad® software program was used for drawing the form of the test specimens according to related standards. Drawings were arranged and sent to the CNC cutting machine by Isycam® and Remote® software programs. For all tests, three specimens were cut from each of the two different panels belonging to the 4, 6, and 8 plied groups.

Mechanical Testing

Tensile and three-point bending tests were performed using the Shimadzu AG-IS test machine, according to the ASTM D638-10 and ASTM D790-10 standards, while the impact test was carried out using a Devotrans Charpy test machine, according to the EN ISO 179: 1997 standard. Tensile strength, three-point bending and impact resistance tests were performed on the composite panels cut both in the warp and weft directions. The flexural stress of the samples was calculated according to the following equation:

$$\sigma_f = \frac{3.P.L}{2.b.d^2} \quad ...(4)$$

where σ_f, P, L, b, d represent stress in the outer fibres at the midpoint (MPa), load at a given point on the load-deflection curve (N), support span (mm), width of the beam tested (mm) and depth of the beam tested (mm) respectively. The charpy impact strength of the samples was calculated according to following equation:

$$a_{cN} = W.\frac{10^3}{h.b_n} \quad ... (5)$$

where a_{cN}, W, h and b_n represent the charpy impact strength of the notched specimen (J), corrected energy absorbed by breaking the test specimen (J), thickness of the test specimen (mm) and the remaining width at the notch base of the test specimen (mm) respectively.

Results and Discussion

Design of Composite Structure

In this study, 4, 6, and 8 plied jute fabric reinforced composite panels have been manufactured with various thicknesses, such as 3.2 mm, 3.6 mm and 4.5 mm respectively, having 250 × 500 mm dimensions.

In the literature, jute fabrics that are used as reinforcement material mostly have higher warp densities (yarns/cm) than weft densities (yarns/cm) such as 8.6 × 5[21], 7.8 × 4.7[9], and 8.6 × 5[11,24], which result in an anisotropic structure, leading to anisotropy in mechanical properties. However, in this study, a plain square woven fabric, which has balanced yarn densities and yarn linear densities in the biaxial direction, has been selected as the reinforcement material to obtain an isotropic composite structure. An analysis of the woven fabric is conducted according to the related standards. Fabric count, yarn linear density, basis weight and the thickness of the jute fabric are tested as 5 × 5 yarns/cm, Ne 2 (warp and weft yarn), 300 g/m^2 and 1.12 mm respectively. Titan universal strength tester has been also used to carry out the fabric tensile test (according to EN ISO 13934 -1) as 8.6 MPa (SD 1.05 MPa) in the biaxial direction. On the other hand, the basis weight of our jute fabric (i.e. 300 g/m^2) is also found in the range of literature values of jute fabrics used as reinforcement materials (300–340 g/m^2) for similar purposes[10, 21, 25].

Physical Testing of Composites

The fibre weight and volume ratios of samples together with the composite thicknesses are given in Table 1. Clearly, both fibre weight and volume ratios increase with increasing number of fabric plies. The results are consistent with literature outcomes.[10, 26]

Table 2 shows the void content and experimental & theoretical densities of the composite samples. In the literature, it is stated that the void content of plant fibre reinforced composites is mostly up to 5% for composites with fibre volume fractions below 40%; but it can reach 25% when the fibre volume fraction surpasses 40% (ref. 27). As it is seen from Table 2, the void content of the 8 plied sample (11%) is about 3–4 times greater than that of other samples. When the fibre volume ratios of samples are taken into consideration, it turns out that this result makes sense.

Table 1 — Fibre weight and volume ratios of samples

Samples	Thickness mm	Fibre weight ratio, %	Fibre volume ratio, %
4 Plied	3.2	31.2	27.2
6 Plied	3.6	40.0	35.5
8 Plied	4.5	46.4	41.7

Table 2 — Experimental densities, theoretical densities and void contents of samples

Samples	Experimental density, g/cm^3	Theoretical density, g/cm^3	Void content, %
4 Plied	1.2	1.27	4.5
6 Plied	1.25	1.29	3.1
8 Plied	1.15	1.30	11

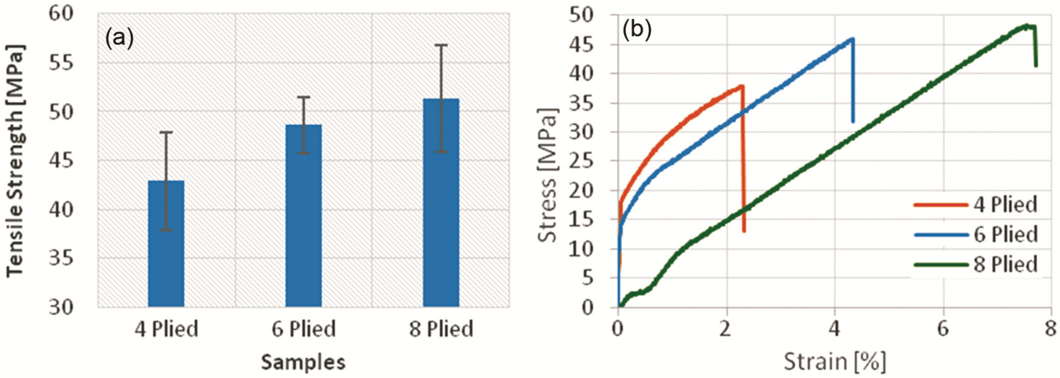

Fig. 1 — Tensile strength (a), and stress-strain curves (b) of composites

Mechanical Testing

Mechanical test results including tensile strength, and stress-strain curves, are shown in Fig. 1; flexural strength and impact resistance are found in Fig. 2. According to the results, the increase in jute fabric reinforcement from four to eight plies improves the tensile strength of the composites by approximately 25% (Fig. 1a). Similarly, the 8 plied jute fabric reinforced composites have almost 2.5 times greater strain values (7.8%) than those of the 4 plied composites (2.2%) (Fig. 1b). The 8 plied composites with 46.4 % wt. fibre ratio has 52 ± 5 MPa tensile strength, which is within the range, as obtained by Acha *et al.*[28] for jute-polyester composites with 56 % wt. fibre ratio (30–60 MPa, based on fibre orientation and test direction). Similarly, the tensile strength of woven jute fabric reinforced composites with 45% fibre volume fraction is measured as 35–60 MPa by Gowda *et al.*[9] based on the variety in the warp and weft yarn counts, densities and test directions. These results are consistent with the results of 8 plied composites produced here with 41.7 % volume fraction[9].

The flexural test results show (Fig. 2a) that the flexural stress of the 8 plied jute fabric reinforced sample (101.36 MPa) is twice to that of the 4 plied jute fabric reinforced sample (50.39 MPa). It is also found that 10 plied jute fabric reinforced polyester composites have a flexural stress of 120 MPa[11,21]. When flexural stress values together with fabric plies are taken into consideration, it can be seen that these values are compatible with the flexural values obtained in the present study.

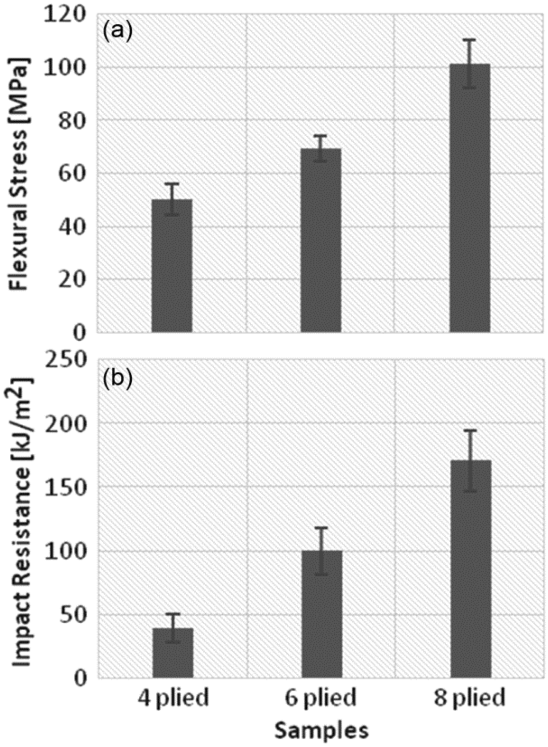

Fig. 2 — Flexural stress (a), and impact resistance (b) of composites

When the impact resistance of jute composite laminates is examined (Fig. 2b), it is clearly seen that the increase in jute fabric plies have the highest influence on the impact properties among the other mechanical properties. While the 4 plied composite has an impact resistance of approximately 40 kJ/m^2, the six- and 8 plied composites have 100 kJ/m^2 and 165 kJ/m^2 respectively. This sharp increase with impact resistance could be due to the higher fibre content in the six and 8 plied composite samples. According to Lai *et al.*[29], both the impact and flexural strength of plant-based fabric reinforced polyester composites increase with the increase in fibre ratio up to a limit of wetting ability of the resin. The reason for expecting increased mechanical properties of the composites with high fibre volume is because more fibres exist and are able to share the force applied to the system[29].

It is inferred that the physical properties, including the thickness of the composite, fibre weight ratio and fibre volume ratio, increase with the increment of jute fabric plies. The void content of the composites calculated both from experimental and theoretical densities reaches 11%, which is within literature values when fibre volume ratio is taken into consideration. On the other hand, higher mechanical analysis test results are achieved with the increase in fibre contents. Tensile strength reaches 51 MPa for 8 plied composites, indicating a 25% improvement as compared to the 4 plied composites. Flexural strength, as well as impact resistance, improve by 100% and 340% with additional jute fabric plies. Since these composites are not able to compete with high-performance materials, they are appropriate for materials such as wall separations, sport equipment and automobile indoor panels, in which moderate mechanical properties and lightness are required. Owing to the high global production rate of jute fibre and its unhazardous properties, these best fibre-reinforced composites are becoming promising candidates as bio-composites for future design.

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