Physical and Mechanical Characterization of Jute Fabric Composites

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ABSTRACT: As-received and washed jute fabrics were used as reinforcement for a thermoset resin. The mild treatments performed on the jute fabrics did not significantly affect their physical and thermal behaviors. The washed fibers absorbed less water than the unmodified (as received) ones, indicating that the coating used to form the fabrics was hygroscopic. Measurements of the fiber mechanical properties showed a high dispersion due to fiber irregularities, although the values obtained were in agreement with data reported in the literature. These results were also analyzed with the Weibull method. To investigate the effect of the jute treatments on the interface properties, impact, compression, and tensile tests were carried out. The composites made from as-received jute had the highest impact energy, which was probably associated with weak interfacial adhesion. Composite samples behaved more ductilely in compression than in tensile situations due to the brittle characteristics of the resin used as matrix. The effect of the orientation of the fibers with respect to the direction of the applied force in the different mechanical tests was also studied. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 98: 639–650, 2005

Key words: composites; fibers; mechanical properties

INTRODUCTION

Most commercially available composites use glass fibers as their reinforcing agent.[1] Other fibers that have been successfully used for composite preparation include carbon, aramidic, and polyethylene, although these are used for high-performance applications. Synthetic fibers are stronger than vegetable ones, but they are also more dense.[2] Nevertheless, when the specific composite properties (i.e., ratio property to density)[3] are taken into account, the differences between both reinforcements become smaller and allow one to use vegetable fiber composites at least in nonstructural applications. Composite materials from natural fibers can be produced with a low investment and low cost and cause relatively little wear on tooling.[4] Textile reinforcements, such as random mats and woven materials, are widely used for composite manufacturing because they allow the fabrication of stiff parts that are easily handled; this explains the success of many processes such as resin transfer molding (RTM) and structural reaction injection molding (SRIM).[5]

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Among all the natural reinforcing materials, jute appears to be a promising fiber because it is relatively inexpensive and commercially available in the required form. It has a higher strength and modulus than synthetic polymers usually used as matrices[6] and is a good substitute for conventional fibers in some situations, when mechanical properties are not a priority. The jute fiber has a multicellular structure composed of microfibrils, and the cross-section is highly nonuniform. Unfortunately, the mechanical and physical properties are highly inconsistent[6] because the properties of all natural fibers are influenced by their growing conditions, fiber extraction technique and processing, and like other fiber types, the fiber dimensions and sample test length.[7]

Jute fiber has inherent advantages, including its renewable nature, biodegradability, moderate moisture regain, good thermal and acoustic insulation properties, and low price.[4] On the other hand, the major disadvantages of jute fabric are its coarseness, low extensibility, moderate wash shrinkage, poor abrasion resistance, high fiber shedding, photo yellowing, limited maximum processing temperature, ready susceptibility to microbial attack, and poor crease recovery.

The structural aspects of jute fiber have been investigated, and several disadvantages have been improved. Bismarck et al.[8] characterized several modified jute fibers with ζ-potential measurements and analyzed the relationship between the modification of the jute fibers and the water uptake. Mannan and Munir[9] modified jute fibers with soap-glycerol mi-

celles to improve their mechanical properties and to reduce natural weathering.

The performance and properties of fiber-filled polymer composites are governed by the properties of the components and by the nature of the interface between the matrix and the fiber. The strength of the interfacial bond between the matrix and the fiber plays an important role in determining the strength of the composite. There are many reports on the use of jute as a reinforcing filler for polymers; these include the chemical modification of the filler or the use of additives or adhesion promoters. Rana et al.,[10] who studied the performance of polypropylene–jute composites, found that the mechanical properties increased and the water sorption decreased with the addition of a compatibilizer (maleated polypropylene). Gassan and Bledzki[7] reported the improvement of the mechanical properties of jute–epoxy composites by alkali treatment of fibers. They attributed this improvement to the enhancement of interfacial bonding, which gave rise to additional sites of mechanical interlocking and thus promoted more resin–fiber interpenetration at the interface. Saha et al.[11] showed that a significant improvement in the tensile and flexural properties of jute–polyester composites in dry and wet conditions was achieved due to the use of cyanothylated fibers. Important for good adhesion between the fibers and the matrix was the degree of wetting during the production process.

The aim of this study was to investigate the effects of two simple and inexpensive fiber treatments on the performance of the resulting composites. As-received and washed jute fabrics were used as reinforcement for a low-viscosity thermoset resin. The jute fabric was physically and mechanically characterized. The effect of the jute fiber treatments on the interface properties was inferred from the mechanical properties of the resulting composites.

EXPERIMENTAL

Materials

Commercial jute bidirectional fabrics, plain weave 0/90 (that means with same rovings in the weft and warp directions), were used as reinforcement. The approximate chemical composition of jute fiber was given as 12–14% lignin, 58–63% cellulose, and 21–24% hemicellulose.[6,12] In addition to these three principal constituents, the jute contained minor constituents such as 0.4–0.8% fats and waxes, 0.6–1.2% inorganic matter, 0.8–1.5% nitrogenous matter, and traces of pigments. All percentages refer to the weight of the dry fiber. It is known that jute fibers have a semicrystalline structure, and α-cellulose predominantly forms the crystalline region, whereas lignin and hemicellulose exists in an amorphous region. Jute fabrics commercially available have a surface coating that is added to the fibers to facilitate the woven–weaving procedure. To study the influence of the interface between the fiber and the resin on the composite properties, the jute fabrics were used in three different ways: (1) as received, (2) washed with acetone, and (3) washed with detergent (a 2 wt % aqueous solution of the dodecylbenzenesulfonic acid sodium salt usually used in textile fabric processing).

The washing steps performed onto the fibers were made in very mild conditions (room temperature for 24 h with mild stirring) to ensure that only the coating was removed from the fiber surface. The fabrics were then dried, in a vacuum oven, at 70°C for 24 h.

The matrix was an unsaturated polyester (UPE) based on bisphenol A–fumarate (RQ 426 Perlinac S.A., Buenos Aires, Argentina), crosslinked with styrene in a 60 : 40 weight proportion and with no additives. The initiator was benzoyl peroxide (Lucidol 0.75, Akzo Chemical S.A., Buenos Aires, Argentina), 1.5 wt % with respect to the total reaction mixture.

Composite preparation

Neat resin samples were obtained by pouring the reactive mixture inside a two-glass-plate mold. The mold was left at room temperature for a day to facilitate the elimination of trapped air bubbles. Then, the samples were cured by heating at 80°C for 1.5 h and finally postcured at 150°C for 2 h.

A simple hand lay-up technique was used for laminate preparation. First, the jute fabrics were dried in a vacuum oven at 70°C for 24 h. Each layer of fabric was impregnated with the uncured resin and placed one over the other in the mold, with care taken to maintain practically achievable tolerances on fabric alignment. All fabric layers were placed with the same orientation. Eight layers were used for each plaque. The metal mold was left open for 2 h at 50°C for degassing (elimination of air trapped during the hand lay-up process).[13,14] Compression molding was used to obtain the final composites; thus, the mold was closed, and the temperature was increased to 80°C. The reaction was carried out under pressure (4 MPa) for 1.5 h; after that time, the sample was postcured in an oven for 2 h at 150°C. After curing, the final weight of the composites was measured, and the resin content in the composite was calculated as the difference between that value and the weight of the jute fabrics. The final plaques contained 46–54% jute fabric treated in different ways. The samples were dried in a vacuum oven until a constant weight was achieved (ca. 24 h) at 70°C before testing.

Fiber characterization

The volumetric density of jute technical fibers was measured by picnometry at room temperature with distilled degassed water. At least 30 specimens were

measured. The fabric superficial density was determined with square jute samples cut from the fabrics and dried in a vacuum oven until a constant weight was reached. The length of each side of the sample was measured with a caliper (up to 0.01 mm), and the surface area was then calculated. The superficial density was calculated as the ratio of the measured weight (up to ± 0.01 g.) to the calculated area. The linear density was determined with jute yarns approximately 10 cm in length, which were taken from the fabrics and dried in a vacuum oven at 70°C until a constant weight was reached. The length of each sample was measured with a caliper (up to 0.01 mm). The linear density was calculated as the ratio of the weight (up to ± 0.01 g.) to the measured length.

Scanning electron and optical micrographs from the fiber and yarn surfaces were taken with a scanning electron microscope (Philips, model SEM 505, Eindhoven, the Netherlands) and an Olimpus SZH-ILLB optical microscope equipped with a Sony camera adaptor (CMA-D2) (Tokyo, Japan), respectively.

The water absorption of the raw and modified jute yarns was measured. They were cut to a length of 4 cm and dried in a vacuum oven at 70°C until a constant weight was attained. The weight of the dry specimens (w_1) was measured carefully (up to 0.01 g). Then, the samples were immersed in distilled water for 24 h at room temperature (ASTM D 570). After that, the specimens were taken out and wiped with filter paper. The sample wet weight (w_2) was again measured, and the water absorption was calculated with the following equation:

$$\text{Absorbed water (\%)} = [(w_2 - w_1)/w_1] \times 100$$

Single filament tensile tests were performed according to ASTM D 3379-75 with an Instron 8501 universal testing machine (Buckinghamshire, England). Single filaments (technical fibers) were mounted along the centerline of a slotted tap and dried in a vacuum oven at 70°C until a constant weight was achieved. The tests were carried out with a 20-mm gauge length and a crosshead speed of 5 mm/min. From the stress–strain curve, the tensile strength (measured as the breaking load per unit area) and the modulus of the single fibers were obtained. The cross-sectional area of the jute fiber was assumed to be circular, although the filaments had very irregular transverse sections. To minimize the error, the diameter was measured in five points along the fiber using optical microscopy, and the average diameter was used to calculate the properties of each fiber.

Composite testing

The water absorption of the composites was determined from specimens 40 × 12 × 3 mm in size according to the technique described previously (water absorption of the jute yarns). Tensile tests were performed according to ASTM D 638 with an Instron 8501 universal testing machine at a crosshead speed of 1 mm/min. Compression tests were carried out at room temperature at a crosshead speed of 0.5 mm/min, according to ASTM 695-85, with an Instron 8501 universal testing machine. Impact tests were carried out on dry and wet composites in accordance to ASTM D 229 (unnotched Izod). The wet samples were immersed in distilled water for 24 h at room temperature before testing. A Fractovis Ceast impact machine was used in this study. The speed of the test was set as 1 m/s, and the striker minimum mass (3.6 kg) was used. In all cases, the composite samples were oriented at 0, 30, and 45° with respect to the applied force.

At least five specimens of each composite were tested to obtain the average mechanical properties.

Scanning electron micrographs from the fracture surfaces of the dry and wet composites were taken with a scanning electron microscope (Philips, model SEM 505). The samples were previously coated with gold.

RESULTS AND DISCUSSION

Fiber characterization

The volumetric density of the as-received sample was 0.464 ± 0.05 g/cm^3. The average superficial density of the raw jute fabric was 0.027 ± 0. 002 g/cm^2, and the washed jute fabrics had a superficial density of 0.029 ± 0.004 g/cm^2 and 0.028 ± 0.001 g/cm^2 for the acetone- and detergent-washed fabrics, respectively. The superficial density results show that there was no significant difference for the three types of fabrics. Finally, the linear density of the as-received sample was 0.0031 ± 0.0006 g/cm. The fiber linear density is a measure of the average number of fibers in the cross-section of a given yarn, and this controls the yarn's irregularity: the more fibers there are in the cross section, the more uniform the yarn thickness will be from point to point.[12]

Figure 1 shows the representative micrographs of a technical fiber and a yarn taken from as-received fabrics. The cross-section of the yarn [Fig. 1(B)] was not homogeneous along the sample length. The fiber also exhibited also a very irregular cross-section [Fig. (A)].

The degradation of natural fibers is a crucial aspect to the development of natural fiber composites and thus has an effect on the curing temperature in the case of thermoset composites;[15] however, in this study, we found that all the jute fabrics began to degrade at about the same temperature (ca. 240°C), independently of the treatment performed on them. The degradation pattern was the expected one for lignocellulosic fibers and has been described extensively in literature;[1,11,12,16,17] therefore, thermogravimetric analysis curves are not included in this article.

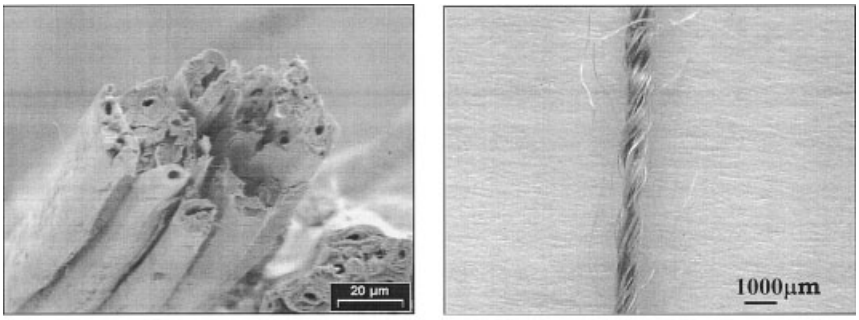

Figure 1 Micrographs from as-received jute: (A) single jute fiber scanning electron micrograph and (B) jute yarn optical micrograph.

Because of their hydrophilic nature, jute fibers take up moisture from the surroundings during humid conditions or when they are in direct contact with water. The cell wall constituents of the fibers contain hydroxyls and other oxygen-containing groups that attract moisture through hydrogen bonding. The hemicelluloses are mainly responsible for moisture sorption, but the accessible cellulose, noncrystalline cellulose, lignin, and surface of the crystalline cellulose also play major roles. Moisture swells the cell wall, and the fiber expands until the cell wall is saturated with water.[12] The water absorption of raw and treated fabrics is shown in Table I. The increment in weight in all cases was very high because yarns were formed by many fibers. Also, the as-received jute absorbed about 20% more water than the washed samples. This behavior indicated that the coating onto the as-received fibers made them more hygroscopic. Although Fourier transform infrared analysis (not shown) did not show any distinctions in the corresponding spectra, some changes were introduced as the water absorption capacity changed.

Jute is a strong fiber, but it exhibits brittle fracture and has only a small extension at break. It has a high initial modulus but shows very little recoverable elasticity. Tenacity measurements recorded in the literature vary widely, and although some of this variation is due to differences in the methods of measurement, a major part is due to the intrinsic variability of properties that characterize natural fibers[2] and to variations in the linear densities of the fibers themselves.[12] This inverse dependence of tenacity on linear density is common to most fibers. The mechanical parameters of the as-received fibers were obtained from the tensile tests performed on the technical fibers (no test were performed on the yarns). To calculate these parameters, an average fiber diameter of 66 ± 16 μm (calculated as the average measured diameter of 300 specimens) was used. The average ultimate strength of the untreated jute was 407.42 ± 148.68 MPa, and the average tangent modulus of elasticity was 19.26 ± 4.61 GPa. These results are in agreement with the values reported in literature, 400–800 MPa and 10–30 GPa, for ultimate strength and tangent modulus, respectively.[3,4,7,15] On the other hand, we noticed that the error in both measurements was quite high. This important variation could be due to (1) the assumption that the cross-sectional area of each filament was circular and (2) the irregular transverse section along the jute filament. Moreover, a broad distribution in the tensile strength of fibers is usually attributed to flaws or defects that are either present in the material intrinsically or are introduced during the handling or processing. It is widely accepted that these defects are the main cause of premature failure of the fiber under tensile load.[2]

To confirm the values of ultimate strength, the results were analyzed further. The brittle behavior of jute filaments and the occurrence of flaws, which is random in nature, allowed the fiber strength to be analyzed in terms of Weibull's statistical approach.[18,19] In this study, the Weibull method was used to calculate the Weibull modulus (m; a parameter that is determined by the scatter of the strength data) and the scaling parameter (σ_0). The values obtained are m = 1.3 and σ_0 = 693.52 MPa. The value of m indicates that the measurements had a very high dispersion.

TABLE I
Water Absorption of Jute (24 h at Room Temperature)

Jute	Absorbed water (%)
As received	112.20 ± 8.48
Detergent-washed	89.84 ± 1.22
Acetone-washed	83.95 ± 7.53

Composite mechanical performance

Drying the fibers before composite preparation is an important step because water on the fiber acts like a separating agent in the fiber–matrix interface.[20] Addi-

TABLE II
Composite Density and Void Content

Sample	Fiber content (wt %)	Theoretical density (g/cm^3)	Experimental density (g/cm^3)	Void content (vol %)
As received	56	1.3608	1.343 ± 0.015	0.97
Acetone-washed	54	1.3541	1.351 ± 0.044	0.17
Detergent-washed	48	1.3340	1.335 ± 0.036	0

tionally, because of the evaporation of water during the reaction process, voids will appear in the matrix. The composites tested in this study were prepared from dried fabrics and did not show any naked-eye visible voids. Moreover, the void content of the samples was calculated as the ratio of the difference between the composite theoretical and experimental densities to the theoretical one. A simple rule of mixtures was used to estimate the theoretical density of the composites (ρ_{matrix} = 1.19 ± 0.05 g/cm^3, experimental value, and $\rho_{cell\ wall}$ = 1.53 g/cm^3).[21] Both the densities and void content are reported in Table II. The void content was very low or negligible, which confirmed the high quality of the composite. The low viscosity of the uncured matrix used in this study and the applied pressure during composite manufacturing allowed the resin to penetrate into the fiber capillaries, leading to a material with practically no pores or voids.

Tensile properties

Table III illustrates the effect of the jute modification and the orientation of the fabric with respect to the applied force on the tensile properties of the composites. Both the jute treatments and the fiber orientation influenced the tensile modulus and strength. The modulus at 45° was about 70% of the modulus in the principal direction (0°), as was found for similar systems.[22] The modulus in the principal direction of these bidirectional composites was lower than the corresponding one for unidirectional samples because only about one half of the fiber ran in each direction. Also, the packing was less efficient because the crimping of the warp and weft yarns at the crosslinking points in the fabric must also have certainly brought about some further reduction in the modulus. As a result of these various factors, the modulus of a bidirectional composite is typically only about a third of that of a unidirectional one with the same reinforcing material.[23]

When one tests an orthotropic material, it is interesting to know what percentage of properties is lost in each direction with respect to the property in the main direction. Moreover, the interface effects can be revealed more clearly by testing the material at different angles from the fiber direction. Figure 2 summarizes the variation of the tensile strength with the angle for the different composites. Except for the as-received samples, where the strength of the samples tested at 30 and 45° was almost the same (considering the experimental error), for the other composites, the strength decreased monolithically as the angle increased. Composite samples with fibers oriented at 0° showed the highest values because half of the fibers were aligned with the direction of the applied force.

The 30° tensile strengths of the composites made with washed jute were higher than that of the as-received samples, but no clear tendency (with the error bars taken into account) was observed for the 45° samples. On the other hand, the tensile strength of the as-received samples was higher than those of the washed composites when fibers were oriented at 0°.

TABLE III
Tensile Properties of Jute Composites

Sample	Fiber orientation (°)	Fiber content (wt %)	Modulus (GPa)	Maximum stress (MPa)	Maximum strain (mm/mm)
Matrix[a]	—	0	3.0	55.00	
As received	0	56	7.8 ± 0.9	59.5 ± 5.2	0.0096 ± 0.0017
	30	53	4.3 ± 0.2	29.5 ± 0.8	0.0081 ± 0.0017
	45	56	4.9 ± 0.1	31.9 ± 3.9	0.0096 ± 0.0014
Acetone-washed	0	54	7.0 ± 1.1	47.5 ± 2.1	0.0100 ± 0.0017
	30	53	5.1 ± 0.2	38.4 ± 1.4	0.0109 ± 0.0024
	45	55	5.1 ± 0.1	30.4 ± 3.1	0.0068 ± 0.0011
Detergent-washed	0	48	6.7 ± 0.5	52.0 ± 2.8	0.0120 ± 0.016
	30	51	2.9 ± 0.1	46.2 ± 0.6	0.0137 ± 0.002
	45	46	4.9 ± 0.1	38.2 ± 2.6	0.0107 ± 0.002

[a] Taken from ref.[23].

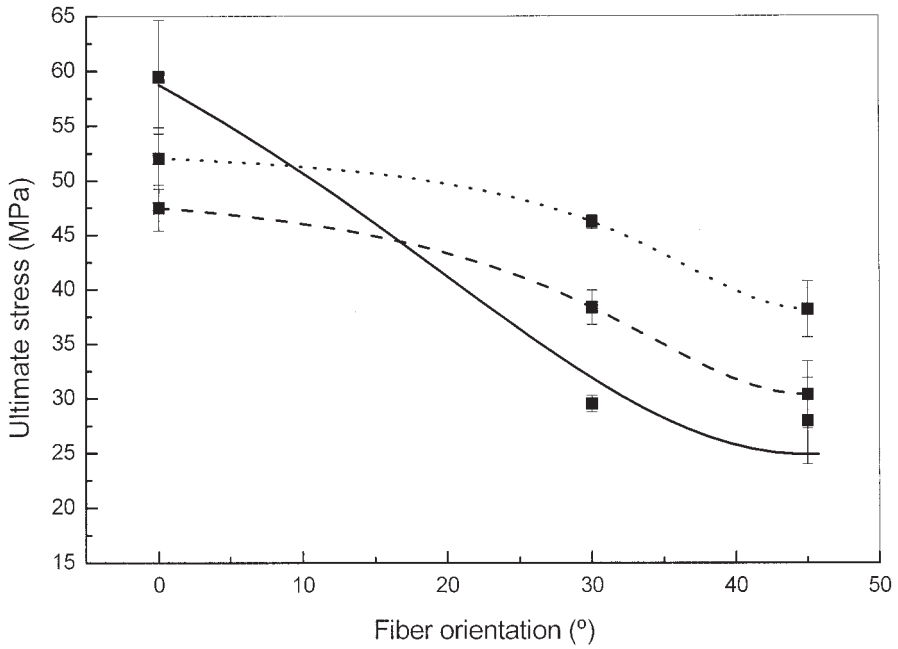

Figure 2 Tensile strength as a function of the angle of testing for the different composites: (—) as received, (- - -) acetone-washed, and (· · ·) detergent-washed.

The tensile strength of a composite material is more sensitive to the matrix interfacial properties, whereas the modulus is dependent on the fiber properties. To improve the tensile strength, a strong interface, low stress concentration, and fiber orientation are required, whereas fiber concentration, fiber wetting in the matrix phase, and a high fiber aspect ratio determine tensile modulus.[15] However, the reasons for the different tensile strengths of the as-received and washed composites were not completely understood. There are many factors that can influence adhesion at the interface: coupling agents, coatings, finishing agents, and so on, in some way, can produce a deformable layer between the resin and the filler to help relieve the stress built up as the resin cools (after curing)[24] or to migrate from the interface, changing the activity of certain components of the uncured resin; thus, the final polymer in the interphase region is likely different from the polymer in the bulk. Moreover, superficial failures or irregularities in the fibers (more important in the washed jute than in the as-received fibers) can act as the initiating flaws, weakening the composite material.[25] The different behavior of the composites could also have been attributed to the changes in surface area, rugosity, and surface functional groups and the removal of weak outer layers of the fibers due to the washing steps. Nevertheless, there was no simple relationship of the interfacial bond strength with these factors. The increase in the fiber surface area by the formation of pits or the enhancement of longitudinal striations certainly improved the mechanical anchoring of the matrix and the interpenetration between the fibers and the matrix. However, because the rugosity developed mainly in the fiber axial direction, the improvement of the interfacial bonding was realized only in the same direction.

The ultimate strain of the composites made with washed jute, in particular that of the detergent-washed samples, was quite higher than that of the as-received samples, which indicated that the fibers became more ductile after the removal of the coating.

Figure 3 shows the tensile stress–strain curves for the detergent-washed composites. After the maximum stress was reached, indications of progressive failure of the fibers as the applied load increased were noticed. This behavior could be attributed to fiber fracture and pull-out, and it was noticed in composites tested at 45°.

Compressive properties

Table IV summarizes the dependence of the compressive modulus, yield stress, and ultimate deformation with orientation of the jute fabric and the type of treatment. The compressive moduli were lower than the tensile ones, whereas the yield stresses exhibited the opposite behavior. The composite samples behaved more ductilely in compression testing than in tensile testing; that is, the maximum strain was higher for the compressive test. This was the expected behavior because the UPE resin used as the matrix was brittle in tensile testing but exhibited yielding in compression testing. Figure 4 shows the stress–strain curves for the acetone-washed composites tested with the jute fabric oriented in different directions, where the features discussed previously can be found.

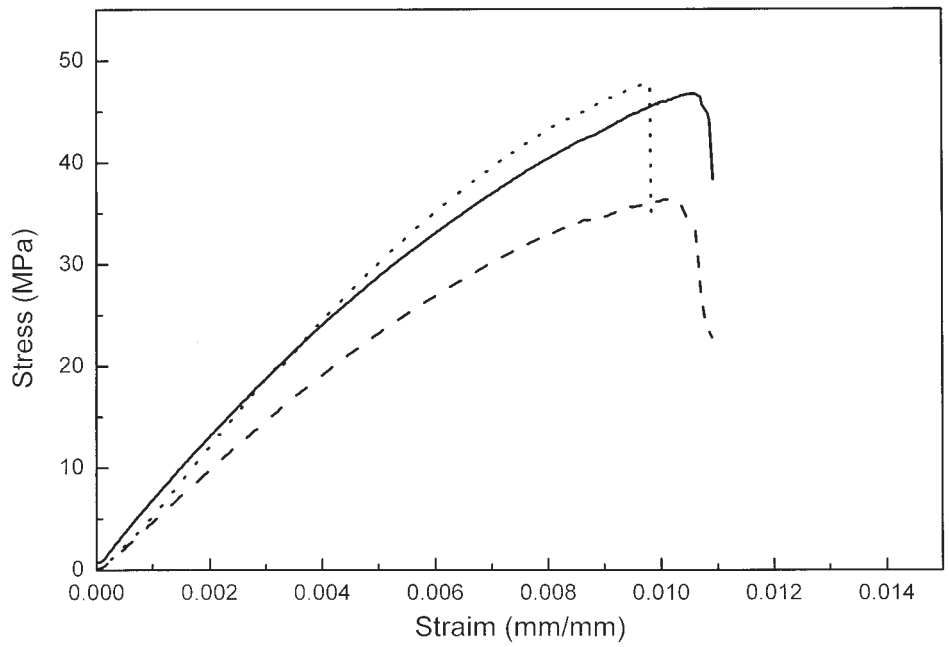

Figure 3 Tensile stress–strain curves for the detergent-washed composites: (· · ·) 0, (—) 30, and (- - -) 45°.

When a sample of a unidirectional composite is loaded in compression testing parallel to the fibers (0°), the mode of fracture depends on the strength of the fiber–resin bond. If the bond is weak, fibers debond from the matrix at low loads, and the compression strength never reaches the same level as the tensile strength.[25] However, with bidirectional fabrics as reinforcement, as in this case, the expected fiber buckling during the test is decreased because the fibers are interconnected, and the compressive yield stress is higher than the tensile one. Besides, the good behavior of the polyester matrix in compression contributes to these results. As shown in Table IV, the compressive stress was slightly affected by fiber orientation, but the slightly high interfacial adhesion between acetone-washed jute and the polyester resin allowed higher compression stresses for those samples. In general, an increase in interfacial bond strength enhances the composite compressive strength by increasing the load required to cause the interface to fail in transverse tension due to the fiber Poisson effect. Delamination is reduced in favor of the microbuckling of the surface-treated fibers.[26] However, all of these beneficial effects of improved stress properties are inevitably accompanied by a loss in the impact fracture toughness of the fibers.

Impact properties

Figure 5 shows the force versus time curves obtained from the impact testing for the composites prepared with the as-received and washed fibers. Force was applied on the edge of the plaque and parallel to one of the directions of the bidirectional fabric. Although the overall response was qualitatively the same in all cases, the energy absorbed (measured as the area un-

TABLE IV
Compressive Properties of Jute Composites

Sample	Fiber orientation (°)	Fiber content (wt %)	Modulus (GPa)	Maximum stress (MPa)	Maximum strain (mm/mm)
Matrix	—	0	2.5 ± 0.04	111.4 ± 4.05	0.305 ± 0.07
As received	0	56	2.3 ± 0.3	52.4 ± 1.0	0.041 ± 0.008
	30	53	1.8 ± 0.3	53.8 ± 6.1	0.045 ± 0.007
	45	56	1.3 ± 0.1	57.4 ± 2.4	0.056 ± 0.005
Acetone-washed	0	54	1.8 ± 0.3	66.8 ± 13.2	0.040 ± 0.010
	30	53	1.7 ± 0.5	70.9 ± 7.6	0.050 ± 0.010
	45	55	2.1 ± 0.5	84.1 ± 1.7	0.060 ± 0.010
Detergent-washed	0	48	1.7 ± 0.4	60.5 ± 4.2	0.050 ± 0.005
	30	51	1.8 ± 0.4	64.8 ± 5.3	0.052 ± 0.016
	45	46	1.6 ± 0.5	63.0 ± 7.1	0.045 ± 0.005

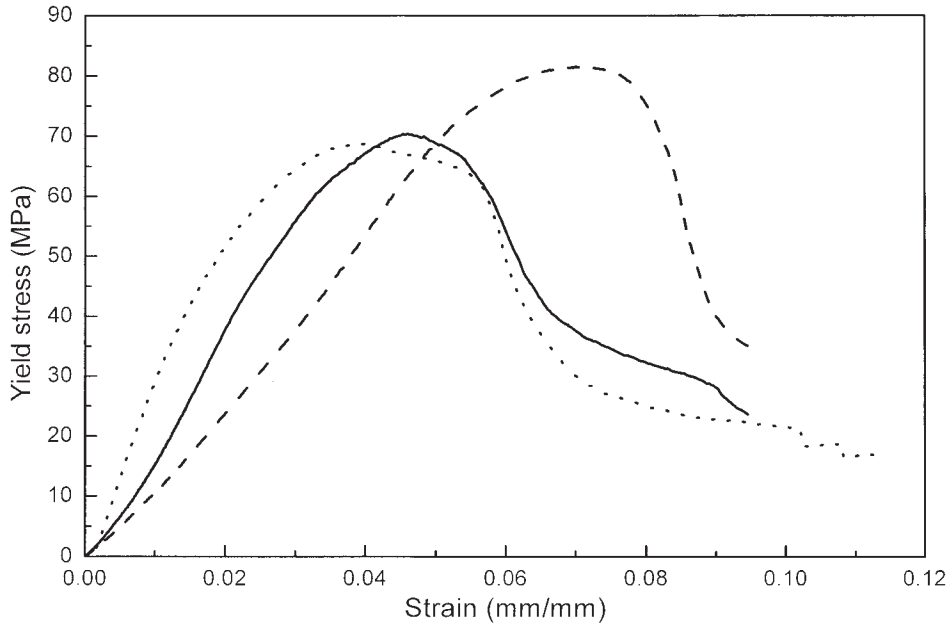

Figure 4 Compressive stress–strain curves for the acetone-washed composites: (· · ·) 0, (—) 30, and (- - -) 45°.

der force versus time curve) was higher for the as-received composites and decreased when the reinforcement was washed.

Figure 6 summarizes the results of the impact tests of all the samples. The energy absorbed by all the composites was more than three times the energy absorbed by the matrix. An increase in the impact energy when the fibers were added to the brittle matrix UPE was expected. Also, the degree of enhancement in the mechanical properties depends on a number of parameters, where the volume fraction of filler and the surface treatment are among the most important ones.[27]

When jute brittle fibers are very strongly bonded to a brittle matrix (e.g., UPE), cracks can propagate easily through both the fibers and the matrix, and thus, the fracture energy of the composite will be higher than that of the matrix itself, but the energy absorbed by these composites with high bond strengths [Fig. 6(c)] will be lower than that expected when a weaker inter-

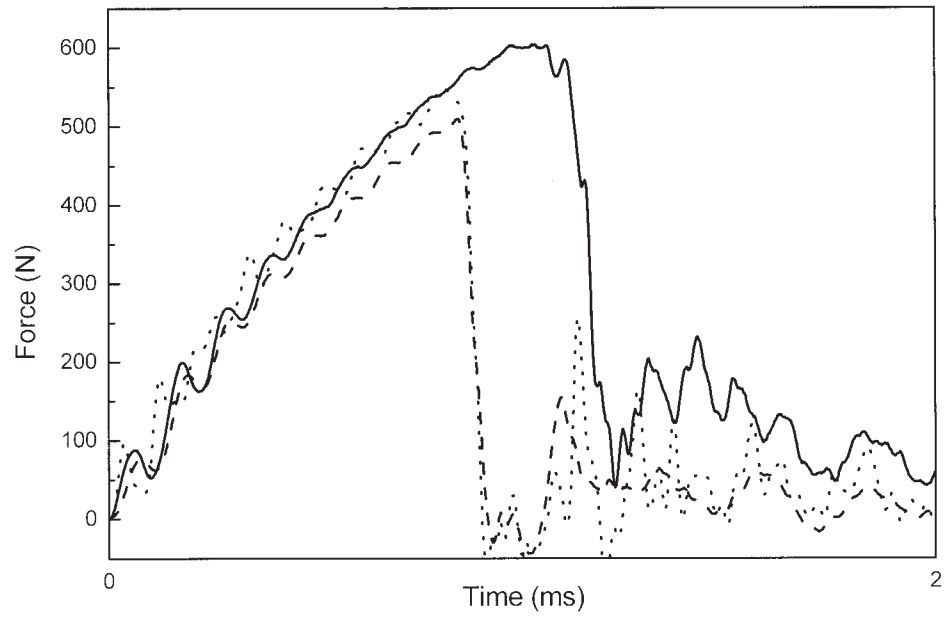

Figure 5 Impact curves (force vs time) obtained from the dry composites: (—) as received, (- - -) acetone-washed, and (· · ·) detergent-washed.

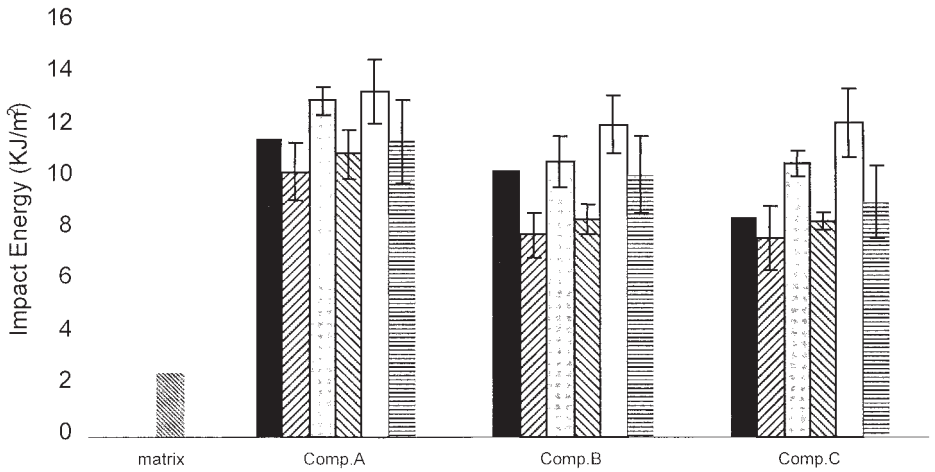

Figure 6 Impact behavior of dry and wet samples: (matrix) neat polyester resin and (Comp.A) as-received, (Comp.B) detergent-washed, and (Comp.C) acetone-washed samples. (■) 0° and dry, (▧) 0° and wet, (▦) 45° and dry, (▨) 45° and wet, (□) 30° and dry, and (▤) 30°, wet.

face is formed [Fig. 6(a,b)]. In the first case, the fracture advances with little change in the cracking plane, breaking the fibers instead of pulling them out. On the other hand, when the interface is weak, interface debonding and fiber pull-out, which are the major sources of fracture toughness in composites, can take place.

It is known that the cracks in composites can propagate preferentially along the fiber–matrix interfaces or transversely right through the fiber and matrix, depending on the properties of the interface with respect to those of the fiber and matrix. In this case, where the results of the unnotched tests are considered, energy absorption is through a combination of crack initiation and propagation. Cracks are initiated at places of high stress concentrations, such as the fiber ends (due to defects, Comp.C in Fig. 6), or at the interface region where the adhesion between the two phases is very poor (Comp.A. in Fig. 6). Thus, the described behavior confirmed that the adhesion between the fibers and the matrix was improved by the washes performed on the jute fabrics, probably because exposing the roughness of the fiber surface allowed improved mechanical interlocking between the fibers and the matrix.

Water sorption

Because of the absorption of moisture, swelling took place and altered the dimensions of the hygroscopic fibers, resulting in changes in the mechanical performance and in the dimensions of the ultimate composite. The water uptake of the different composites is shown in Table V. No important differences were noticed between the amount of water absorbed by the composites made with the as-received jute fibers or the acetone-washed ones, although composites made from the detergent-washed fibers were slightly more hydrophobic than the other samples. Figure 7 shows the impact behavior of the dry and wet composites prepared from the as-received jute oriented at 0°. The energy absorbed by the wet composites was lower than that absorbed for the dry samples.

When wet samples (oriented at 0°) were considered (Fig. 6), all of the composites showed a decrease in their impact energies compared to the dry samples (12 and 23% for the as-received and detergent-washed samples, respectively), but this reduction was less important for the acetone-washed samples (9.9%). The moisture absorbed by the composite produced mainly the swell of the reinforcement but also the plasticization of both the polyester resin and the natural reinforcement, as it was reported for similar systems.[28] However, because the adhesion between the acetone-washed jute and the polyester resin was better than in the other composites, the empty space between the fiber and the matrix was limited, and the fiber could not swell very much; thus, the decrease in impact energy due to the absorbed moisture was the lowest. In the case of the untreated and detergent-washed composites, the fibers could swell more than the acetone-washed ones; the empty space between the reinforcement and the resin disappeared, and the fibers exerted pressure on the matrix. In other words, the

TABLE V
Water Absorption (%) of Composites (24 h at Room Temperature)

Orientation (°)	As received jute	Detergent-washed jute	Acetone-washed jute
0	10.1 ± 1.3	8.9 ± 0.3	10.0 ± 0.7
30	9.1 ± 0.4	8.6 ± 0.4	10.5 ± 1
45	9.2 ± 1.1	8.7 ± 0.4	9.2 ± 0.6

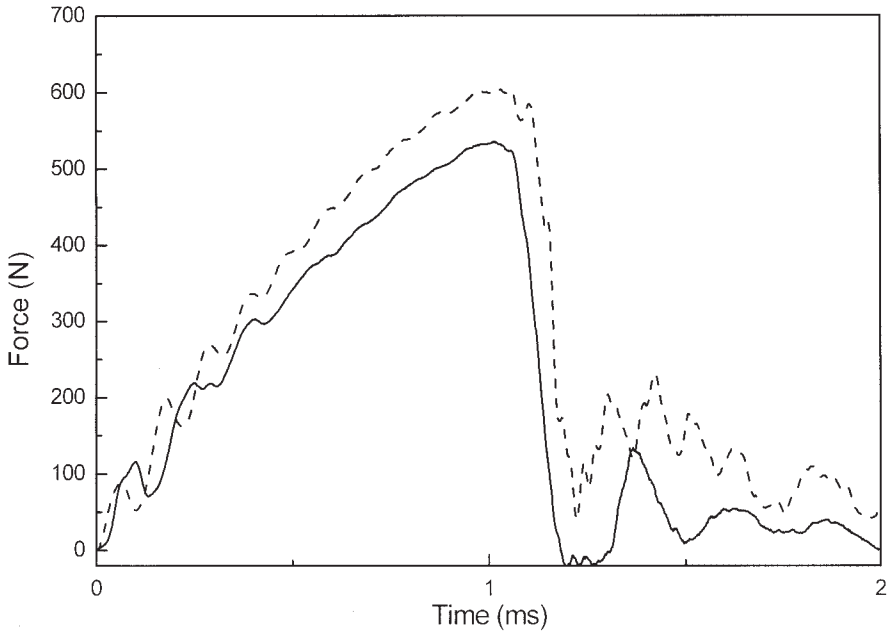

Figure 7 Impact curves of (- - -) dry and (—) wet composites prepared from as-received jute oriented at 0°.

composites behaved as ideal materials, with perfect adhesion between the phases, and consequently, the impact energy of the wet samples was much lower than that of the dried samples. In summary, the impact energy values also confirmed that the adhesion between the acetone-washed fibers and the matrix was higher than that in the other cases.

Scanning electron microscopy (SEM)

The surface topology of the jute fibers was also studied by SEM, and the micrographs are shown in Figure 8. The uneven surface of the as-received samples is shown in Figure 8(a). Certain globular protrusions were present on the surface of the as-received fibers. When the fibers were washed with acetone [Fig. 8(b)] or detergent [Fig. 8(c)], these protrusions practically disappeared, which led to rather rough surfaces on the jute itself. The removal of the coating led to a very different fiber surface, which promoted mechanical anchorage; thus, the enhancement of adhesion between the polymer matrix and the fibers was obtained.

Figure 9 shows the surfaces of fracture of the different composites. Fiber pull-out was observed in all

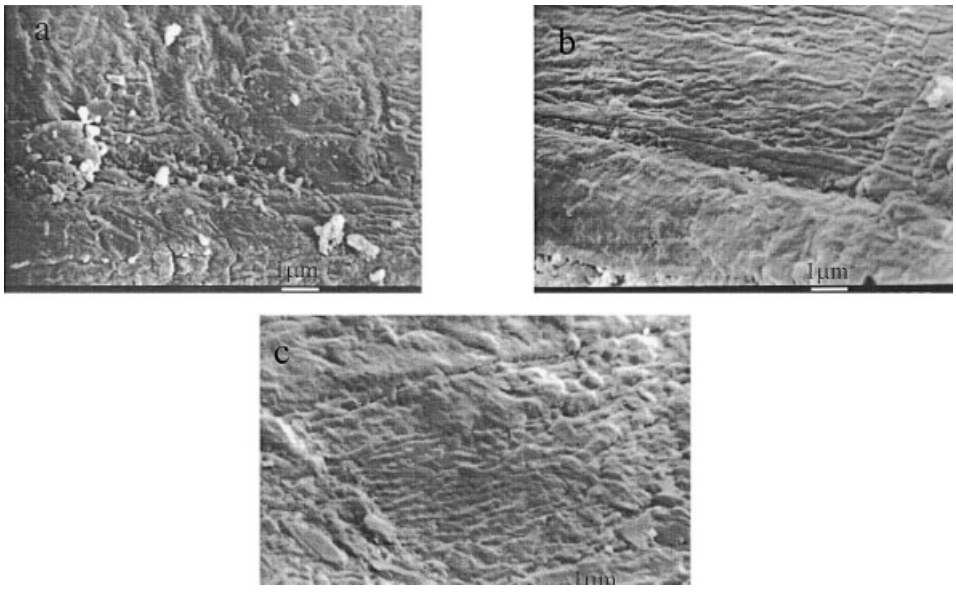

Figure 8 Scanning electron micrographs of the composite fracture surfaces of the (a) as-received, (b) acetone-washed, and (c) detergent-washed fibers.

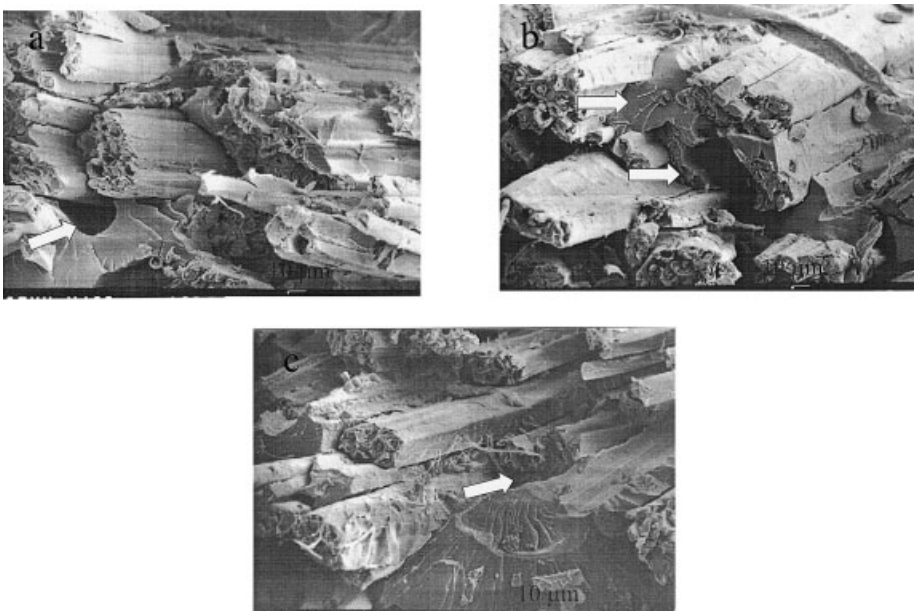

Figure 9 Scanning electron micrographs of the composite fracture surfaces of the (a) as-received, (b) acetone-washed, and (c) detergent-washed composites.

cases, but the fiber length of the pulled fibers was shorter, and the free space between the fibers and the resin was smaller in the acetone-washed composites [Fig. 9(b)] than in the as-received [Fig. 9(a)] and detergent-washed [Fig. 9(c)] composites. Both were indications that there was a stronger adhesion between those fibers and the matrix compared with the other samples. Also, the acetone-washed fibers were more detached, which allowed the matrix to penetrate into the strand and wet the fibers individually, whereas in the untreated jute composites, unaltered roving was easily seen, and thus, the resin was unable to wet all the fibers.

Finally, in all cases, most of the capillaries of the jute fibers were filled completely with the resin, which exhibited fragile fracture. This was due to both the low viscosity of the uncured resin and the use of pressure during the curing steps, which facilitated the filling of the capillaries. No differences between the photographs taken from the wet or dried samples were found, probably because the wet samples lost part of the absorbed moisture during the sample preparation for SEM.

CONCLUSIONS

Jute fabrics were physically and thermally characterized. The mild treatments performed on the jute fabrics did not significantly affect their linear density or thermal behavior. The coating of the as-received fibers increased their water sorption. The tensile strength and Young's modulus of the single filaments showed high variabilities due to fibers irregularities.

The interfacial adhesion between the fibers and the polymeric matrix was improved by the removal of the coating of the reinforcement. This effect was reflected in the mechanical properties of the composites: washed samples reached higher compression stresses and had lower impact energies. Although the adhesion between the matrix and the fibers in the composites made with acetone-washed jute was quite good, the tensile strength of these samples did not reach the highest values because the probability of fiber failure was increased due to the fiber treatment. The composite compressive behaviors, mainly at 30 and 45°, were highly influenced by the polymeric matrix. Also, as the adhesion between the filler and the matrix increased, the buckling of the fiber decreased, leading to a higher compressive strength.

Water sorption produced a reduction in the impact energy of all the composites, but the relative reduction was lower for the acetone-washed composites.

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