Mechanical Properties of Jute Fibers and Interface Strength with an Epoxy Resin

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ABSTRACT: Four different forms of jute fibers, namely untreated jute filament (UJF), sliver jute filament (SJF), bleached jute filament (BJF), and mercerized jute filament (MJF), have been subjected to tensile strength analysis following Weibull's theory. The MJF and BJF were obtained by the chemical modification of the UJF. A minimum of 50 fibers of each type, at three different gauge lengths, i.e., 15, 30, and 50 mm, were used to study the strength distribution and the effect of gauge length. The mean fiber strength was found to be the maximum for UJF followed, in the order, by BJF, MJF, and SJF ($\sim$ 700, $\sim$ 660, $\sim$ 580, and $\sim$ 540 MPa, respectively, at 50-mm gauge length). The strength was also found to decrease with an increase in gauge length. In all cases, good agreement was found with Weibull's statistical model. Single fiber composite tests, with an epoxy resin as the matrix, were carried out determine the critical fragment lengths and interfacial strength, following the Kelly–Tyson approach. The BJF was found to have the maximum interfacial adhesion ($\tau \approx 140$ MPa) followed by UJF, SJF, and MJF having τ values of $\sim$ 83, $\sim$ 57, and $\sim$ 47 MPa, respectively. Scanning electron microscope pictures showed the fiber surface was physically modified by the various treatments. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 75: 1585–1596, 2000

Key words: jute fibers; surface modification; jute/epoxy adhesion; Weibull Strength Analysis; S.F.C. tests

INTRODUCTION

Extensive research has been undertaken during the last few decades to evaluate the possibility of using natural fibers, such as hemp, kenaf, coir, jute, sisal, broom, and ramie, as an alternative to the synthetic counterparts with both thermosetting and thermoplastic matrices.[1–15] Merits and faults of the composites prepared from natural ligno-cellulosic fibers have been recognized and well documented in these papers, only a few of which are listed. Recognized handicaps with these composites are the poor interfacial adhesion with nonpolar matrices and ageing phenomena; in several cases, in fact, it has been found that the adhesion in these materials is not good enough, particularly on a long-term basis, for their commercial exploitation in engineering areas. Several surface modifications have been suggested to improve the adhesion between various polymer matrices and reinforcements. However, it seems to us that the methods suggested to modify the fiber surface have little economic viability because of the inexpensive nature of the fibers, which is one of their basic and attractive features. We felt that

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thorough, systematic, and grass-roots level research on the adhesion of the natural fibers with various matrices is needed now in order to feed the results to the composite manufacturers. Literature is replete with the research work on interfacial adhesion between synthetic fibers, such as glass or carbon, and plastic matrices, with the help of various techniques, the most elegant and widely used of which is the single fiber composite (SFC) test, which involves measuring the strength distributions of the fibers with the help of the Weibull's statistical analysis.[16–22] It is surprising that there is no report on the Weibull analysis and SFC tests on natural fibers and composites with plastic matrices.

Jute is one of the most promising natural fibers because it has good specific strength and a high strength-to-cost ratio. Although it is a fiber of southeast Asian origin, it can be grown elsewhere and/or can be imported from the jute-producing countries at a very cheap price. A considerable amount of work[23–40] has also been done on jute–plastic composites around the world. Gassan et al.[27] used epoxy functional γ-glycidoxypropyltrimethoxy silane as a coupling agent with jute fibers to improve the dynamic mechanical properties of jute–epoxy composites. In another paper, Bledzki et al.[7] suggested the use of modified silanols as coupling agents to improve the performance of natural fiber-thermosetting systems. Mukherjea et al.[31] used the polyesteramide–polyol (PEAP) as the interfacial agents to improve the mechanical strength of jute–epoxy and jute–polyester composites. Ali et al.[39] found an improvement of mechanical strength of jute fibers by exposing them to UV light in the presence of methyl methacrylate. Ghosh et al.[40] studied the effect of graft copolymerization with a mixture of acrylonitrile and methyl methacrylate on mechanical properties of jute fibers of different lignin and hemicellulose contents. They showed that the tenacity and other mechanical properties increased drastically at certain optimum composition of jute and grafting percentage. Little importance, however, has been paid to surface modifications with inexpensive reagents, such as alkali or bleaching agents, or to evaluate the effects of fiber treatments, either mechanical or chemical, routinely carried out to facilitate processing or just for aesthetic purposes. In this work we investigated the effects of several inexpensive treatments on the mechanical properties of jute filaments according to the Weibull's statistical approach. The effect of surface treatments on the interfacial strength with an epoxy resin also was investigated by means of the SFC technique.

EXPERIMENTAL: MATERIALS AND METHODS

Four different varieties of jute fibers were used: (1) untreated jute filament (UJF), (2) sliver jute filament (SJF), (3) bleached jute filament (BJF), and (4) mercerized jute filament (MJF).

Untreated Jute Filament (UJF)

The untreated jute fibers were obtained directly from plants without further processing or chemical treatment. The remaining three types were derived from this variety by means of mechanical or chemical modification, the details of which will be discussed later. The used jute was the white variety (*Corchorus capsularis*). The UJF samples were obtained from the Indian Jute Research Associations (IJRA), Calcutta, India.

The fibers were first removed from the plant by the process called "retting," in which the plant is immersed in water for the purpose. The coarse aggregates of fibers just obtained from plants are called "reeds." When the dried reeds are spread and the fibers are segregated, one gets thinner fiber structures called "strands." A strand looks like an individual fiber while, in reality, it is composed of a number of true individual fibers, called filaments or fibrils, that strongly adhere longitudinally to one another by means of the natural binder lignin. It is a tough and tedious task to separate true filaments from the strand because filaments are very thin and tenaciously stick to one another. One has to use the finger and nails to separate the individual filaments from the bundle; in the process, the filaments are not only unevenly separated but also weakened because they are easily damaged. Debris is observed on the surface in the form of lignin particles, and this contributes to making the diameter of the filament rather nonuniform. However, it is relatively easy to select filaments of reasonable integrity for the mechanical tests.

Sliver Jute Filament (SJF)

Jute slivers also were obtained from IJRA. These are the compact form of jute fibers, which is specially made for making prepeg plies for the preparation of laminates. These are prepared from

untreated jute fibers by a special mechanical processing technique called "carding." Carding opens the mesh structure of the untreated fibers and makes the strands parallel and compresses them to a compact form with minimum free volume between fibers. A vegetable oil, called jute batch oil (JBO), is used during the carding process. The resultant product, of approximately 15-cm width and of continuous lengths (cut at the desired length), is almost a unidirectional fleece having 90–95% uniaxial orientation. During laminate production, the sliver is directly impregnated with the resin, and such slivers, 3 to 5 one above the other, are pressed to form a laminate of desired thickness. We selected filaments from this sliver with a view to study their mechanical strength and adhesion properties with an epoxy resin. We noticed that it is relatively easy to separate the filaments from the strand of sliver. This might be due to the effect of mechanical action onto the fibers in presence of the JBO, which somehow smoothes the surfaces of the strands and opens the mesh structure.

Bleached Jute Filament (BJF)

The untreated jute fibers were subjected to the process of bleaching or delignification by the following process.[32] First, the jute fibers were washed with a mild detergent, rinsed with distilled water, and air dried. Then the fibers were refluxed with a mixture of alcohol and benzene (1 : 2) for 72 h, thoroughly washed with distilled water, and finally air dried. This process removes the small fat contents of jute fiber. The defatted fiber samples were treated with $NaClO_2$ solution (0.7%), whose pH was adjusted to 4 with acetic acid and sodium acetate buffer, for 1 h at 90°C. Delignification occurred, resulting in the color change of the fiber from brown to silver white. Then the samples were washed with water, followed by an antichlor solution containing 2% $NaHSO_3$ for 15 min at room temperature, using a liquor ratio of 20 : 1. The bleached samples were subsequently washed with distilled water and air dried. This process removes nearly 70% of lignin from the untreated jute fiber.[32] After bleaching we noticed that the meshy structure of the strands opened up to a great extent because of removal of the binder lignin, and for that reason, the filaments could be separated to a greater extent compared to sliver and untreated jute filaments.

Mercerized Jute Filament (MJF)

The untreated jute fibers were subjected to the process of mercerization as follows. First, the fibers were defatted according to the procedure already described in the bleaching process. The defatted samples were treated with 2% NaOH solution for 1 h at room temperature. Then the samples were kept under running water for 2 days until they were completely free of alkali. Finally, the samples were air dried. It was noticed that in this variety of jute, it was most difficult to separate the filaments from the strands because the fibers not only became more brittle, but also became more meshy.

Fiber Strength

The tensile properties of these jute filaments/strands were determined with an Instron 1185 (load cell 10 N) at the cross-head speed of 2 mm/min at room temperature (20 ± 2°C) and 70 ± 5% relative humidity. In general, the diameter of the filament/strand was not uniform across the length of the fiber. Filaments/strands of more or less uniform diameters were selected with the help of a low-magnification microscope; the diameter for each was taken at five different places across its length, with the help of a precision gauge meter, and the average value was used. The diameter measured by the gauge meter was also verified by the calibrated microscope eyepiece. Occasionally the filaments/strands diameters were also measured by SEM photographs and were found to vary within 20 to 60 μm. To measure the strength of each variety of fiber three different gauge lengths were used, i.e., 15 mm, 30 mm and 50 mm, and a minimum of 50 filaments were taken for each gauge length. Moduli and elongations at break were obtained by the load-displacement diagrams. The following are the factors that mostly influence the distribution of tensile properties:

1. Jute type: the kind of jute used according to its origin, such as white jute, grey jute, etc. We used the white jute.
2. Handling and mechanical processing of the fiber: starting from removal of fibers from the plants to separation of filaments, the fibers were subjected to a lot of manual handling, wear and tear, and sometimes mechanical processing (as in slivers). All this may increase the original content of

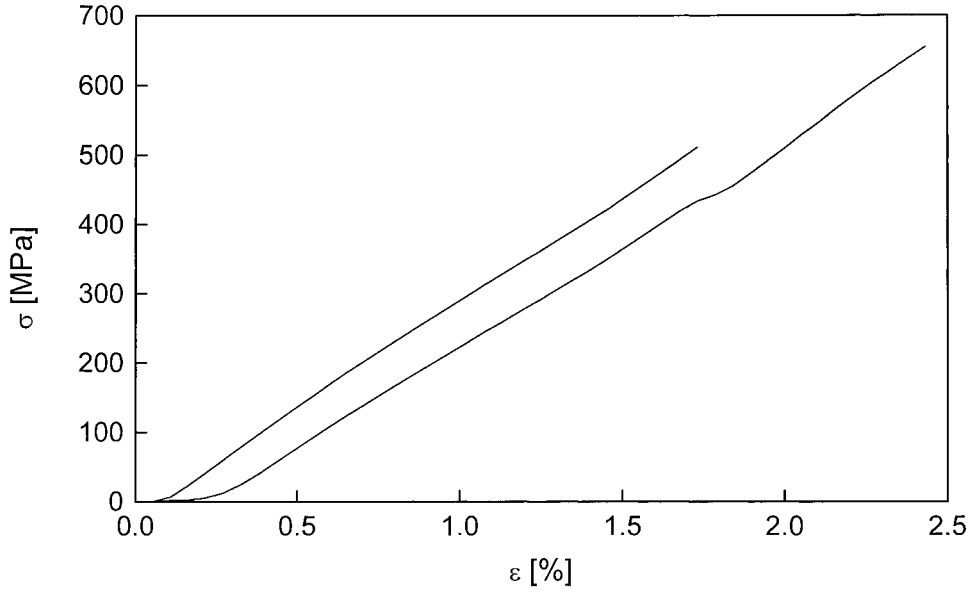


Figure 1 Typical stress–strain diagrams for jute filaments (in this case mercerized fibers at 50-mm gauge length).

defects in the fiber so that, in general, the less the mishandling, the greater the strength. We have taken maximum care to keep mishandling to minimum.

3. Type of chemical modification: the strength of the fiber varies significantly when subjected to chemical treatment. This topic is of special importance in this work, because we did two types of chemical modifications of the fibers.

S.F.C. Tests

A silicon rubber mold was used to make six at a time dog-bone shaped, single-fiber coupons (length 60 mm, side width 10 mm, neck width 2.6 mm, thickness 1 mm, and length of the neck 20 mm). Filaments were selected as to assure that their diameters were similar (40–50 μm). The epoxy resin was a bifunctional bisphenol-A type with an epoxy equivalent of $\sim$ 195 (Epikote 828, Shell Co.). The hardener was *p*-amine-dicycloexyl-methane, used at the content of 25% by weight. Resin and hardener were intimately mixed at room temperature and freed from air bubbles by degassing at 50°C for 10 min in a vacuum oven. The mold containing the filaments was also equilibrated at 50°C prior to resin pouring. The casts were cured at 70°C for 2 h and postcured at 100°C for 3 h.

The coupons were slowly strained under an optical microscope (Wild Heerbrugg Make) with a hand operated screw-type straining apparatus. The fragmentation of the fiber was observed with microscope at $\times$40 magnification. The fragment lengths were measured by the help of a calibrated eyepiece. This test was repeated with identical coupons to get 100 to 110 fragments for having a reasonable distribution of fragment lengths. The coupons were finally fractured and the fracture surfaces were subjected to SEM analysis. SEM pictures of gold coated samples were taken with a JEOL T 300 machine.

RESULTS AND DISCUSSION

Fiber Strength

Jute filaments are very rigid when loaded in tension. The load-elongation diagrams were almost linear up to fracture (Figure 1). Occasionally, irregularities were observed in the curves, likely originated by the failure of individual fibrils prior to sample rupture. The mean elastic modulus was about 30 GPa; this value was found to be substantially independent of fiber treatments. The strength and the elongation at break were much more variable, in the range 500–1000 MPa and 1.5–2.5%, respectively. These values place jute

among the strongest vegetable fibers, for example, cotton, ramie, pineapple, and sisal.

The brittle behavior of jute filaments allowed their strength to be analyzed in terms of Weibull's statistical approach. Because of the intrinsic variability of properties that characterizes natural products, the tensile data of jute fiber, even those obtained under carefully controlled laboratory conditions, exhibit a large amount of scatter. On the other hand, the strength of brittle synthetic fibers also has to be assessed on a statistical ground.

Broad distributions in tensile strength of fibers is usually attributed to flaws or defects that are either present in the material intrinsically or are introduced during handling or processing. It is widely accepted that these defects are the main cause of premature failure of the fiber under tensile load.[21] Since the occurrence of flaws is random in nature, the tensile strength is to be characterized by a statistical model, the most widely used being the Weibull's distribution function.[16] In this model the cumulative probability of failure $P_n(\sigma)$, i.e., the fraction of filaments having tensile strength not exceeding σ, is given by

$$P_n(\sigma) = 1 - \exp[-l(\sigma/\gamma)^{\alpha}] \quad (1)$$

where α and γ are the Weibull's parameter characteristics of the fiber, σ is the stress at break, and l is the gauge length. Equation (1) can be manipulated to give

$$f(P_n, l) = \ln\left(\ln\frac{1}{1 - P_n(\sigma)}\right) - \ln l = \alpha \ln \sigma - \alpha \ln \gamma \quad (2)$$

A plot of $f(P_n(\sigma), l)$ versus $\ln(\sigma)$ is expected to give a linear graph whose slope gives the value of α, and from the intercept, γ can be calculated.

Once the Weibull's parameters are obtained, the mean fiber strength σ_m, at a given gauge length, can be calculated by the following equation:

$$\log \sigma_m(l) = -\frac{1}{\alpha}\log l + \log \gamma + \log\left(\Gamma\frac{\alpha + 1}{\alpha}\right) \quad (3)$$

where Γ is the complete Gamma function obtained from the literature.

A plot of $\log \sigma_m(l)$ versus $\log l$ therefore should be linear. From the above equation one can get the mean tensile strength at a particular gauge length, since all the other quantities are known. The mean tensile strength at gauge lengths experimentally inaccessible is obtained by linear regression analysis of $\log(\sigma)$ versus $\log l$ data.

Figure 2 give the plots of $f(P_n, l)$ versus ln (stress at break), at 50-mm gauge lengths, for all types of jute filaments. Similar plots for 30- and 15-mm gauge lengths were also drawn. Table I gives only the final results of the mean fiber strengths (σ_m), at the three different gauge lengths, for the four types of fibers used.

Figure 3 gives the plot of log(mean stress) versus log(gauge length) for all fibers mentioned. The solid line in each graph represents the regression line. In all the cases studied it is observed that the fiber strength increases with decrease of gauge length. Although the experimental points are somehow spread, the departure from linearity is acceptable. It is observed that UJF has the highest mean strength at all gauge lengths, and BJF has strength values very close to UJF. It is to be noted that chemical modification of UJF with sodium chlorite did not appreciably degrade the strength of the fiber, contrary to the belief that this treatment at pH 4 might degrade cellulose chains during the delignification process. In our case the fiber retained nearly 90% of the strength compared to the control (UJF). The mercerized jute filament exhibited very low strength, close to the sliver jute; this proves that treatment of jute with mild alkali significantly reduces its strength.

The sliver jute filaments exhibited the least strength at each gauge length. This appreciable strength reduction is likely due to the damage the fibers undergo during the production of sliver from UJF. Precautions should therefore be taken during sliver production to limit the mechanical damage induced during the process and keep loss of strength, compared to UJF, to a minimum.

It is interesting to compare the properties of jute with those of the two most important synthetic fibers (Fig. 4). As expected, the artificial fibers are stronger than the vegetable counterparts whose strength, however, approaches the gigaPascal range. It has to be noted that a comparison made on the basis of specific properties would appreciably reduce the distance between glass and jute, the latter being lighter than the former (specific gravities are 2.56 and 1.45 g/mL, respectively). This confirms that jute, and vegetable fibers in general, can stand beside artificial reinforcements, at least in nonstructural applications.

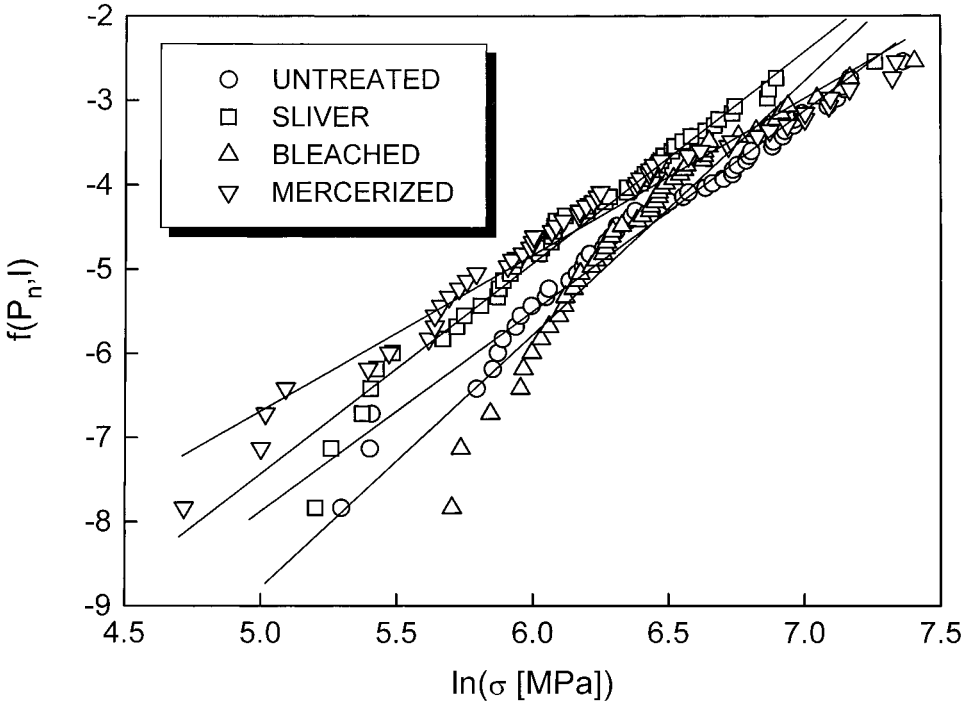


Figure 2 Distribution of fiber strength [according to eq. (2)].

However, the fact is that glass fibers are isotropic in nature, whereas the jute filaments, because of the alignment of cellulose microfibrils along the axis, are not. Moreover, vegetable filaments may be split if high transverse stress is applied. All this would adversely affect the properties of unidirectional composites but might have positive effects on the impact behavior.

It is also interesting to note that the slopes of line in Figure 4 are substantially the same for all fibers. This was somehow surprising since one would expect natural fibers to possess a much wider variability and a more pronounced effect of filament length on fracture stress. Instead, jute, carbon, and glass fibers appeared to be very similar in this respect.

Table I Effect of Gauge Length on Strength of Jute Fibers

Gauge Length (mm)	Mean Stress at Break (MPa)			
	UJF	SJF	BJF	MJF
15	990	700	1030	710
30	880	650	700	640
50	700	540	665	580

Interface Strength

The chief function of the interface is to transmit stresses from the weak polymer to the high-strength fibers. The stress transfer efficiency depends on the mechanical properties of the matrix, the load-bearing capacity of the fiber and the strength of the fiber–matrix interface. A good adhesion is also desirable to prevent, or inhibit, environmental agents from invading and destroying the interface. In case of lignocellulosic fibers, the degradation caused by water at the interface is of primary concern because the fibers are highly hygroscopic. Chemical modification of fibers is done with an intention to improve the adhesion. In order to develop high-performance composite materials, a strong and chemically stable interface is necessary. Of the several methods devised for characterizing the stress transmission capability across the interface, the most elegant is accepted to be the single-fiber composite (SFC) test. The Single Filament Test, first proposed by Kelly and Tyson,[17] has been widely used to study the interfacial adhesion of synthetic fibers[18–22] but has so far not been extended to the natural fibers.

When a single-fiber coupon is loaded in tension, fragmentation of the fiber occurs (Fig. 5),

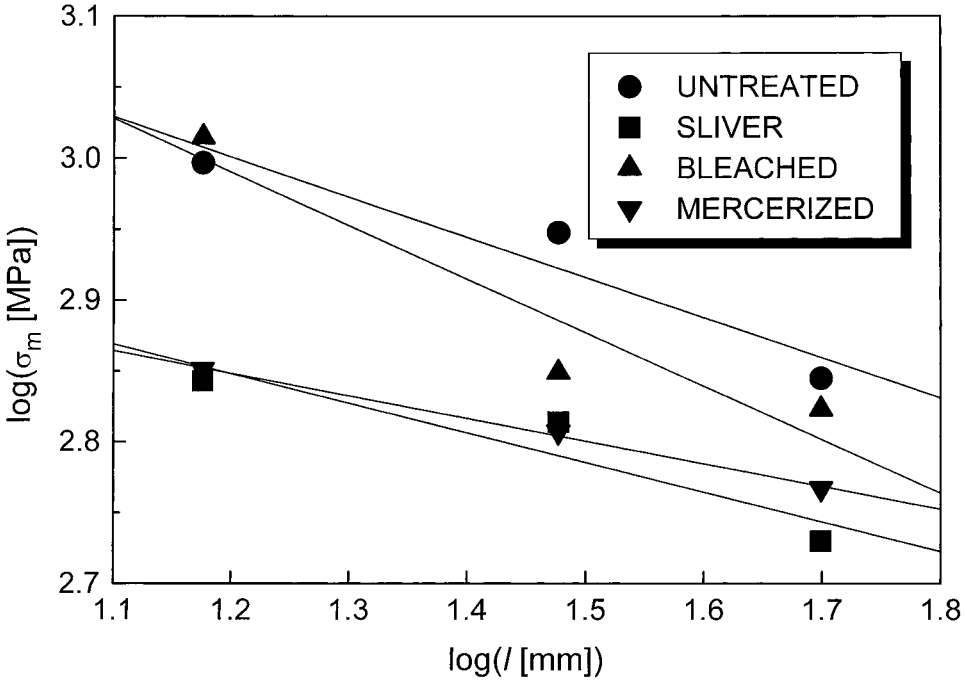


Figure 3 Influence of gauge length on strength of fibers [according eq. (3)].

provided the ultimate elongation of the matrix is higher than that of the fiber. Fragmentation continues until all the segments are shorter than a critical length l_c. Beyond this point, the stress transfer is no longer high enough to cause fiber breakage. The maximum shear stress the inter-

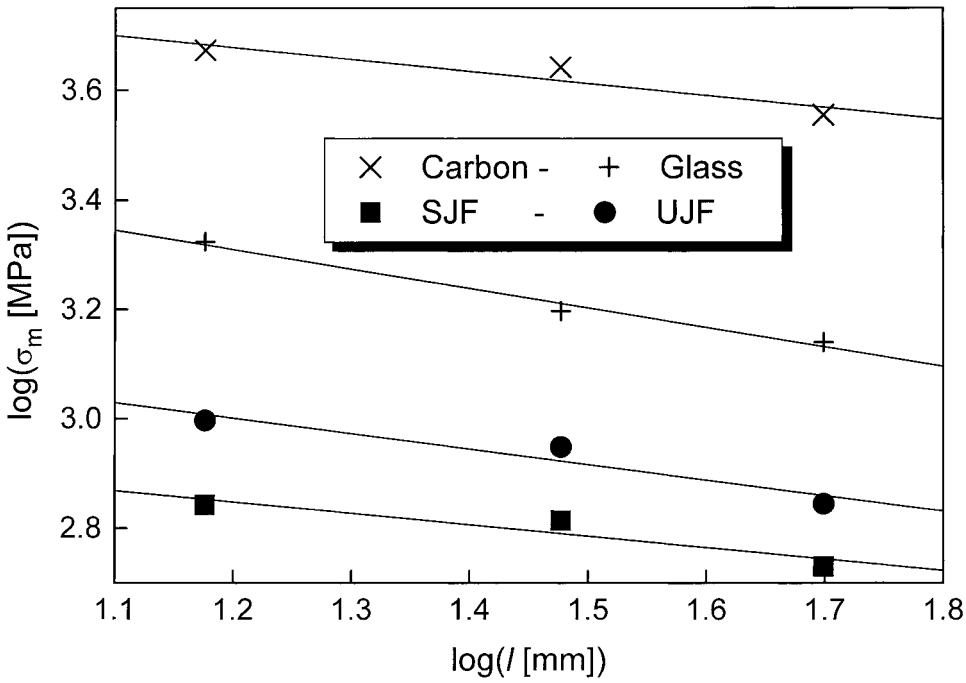


Figure 4 Comparison of the influence of gauge length on strength of jute, carbon, and glass fibers.

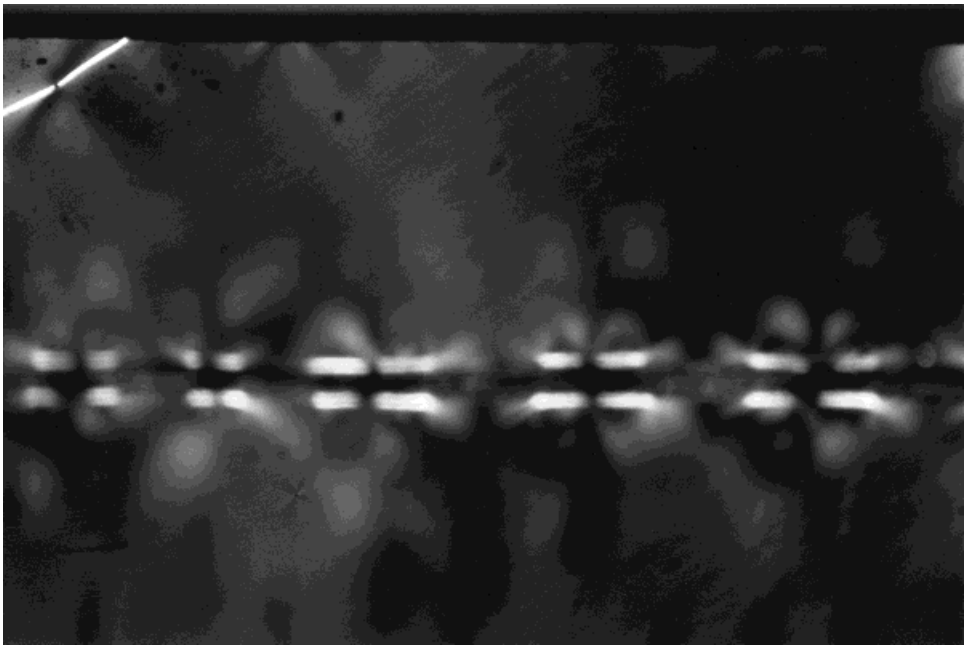


Figure 5 Multiple fragmentation in a single-fiber jute coupon loaded in tension (view in polarized light).

face can bear (τ) is given by the following equations:

$$\tau = \frac{\sigma_c d}{2l_c} = \frac{3\sigma_c d}{8l_m} \quad (4)$$

where σ_c is the strength of the fiber at the critical length (l_c), l_m is the mean fragment length and d is the fiber diameter.

It has to be pointed out that the model is based on the assumptions of brittle behavior of the fibers (requirement fully fulfilled by jute filaments) and that the probability to find defects along the filaments depends only on the gauge length. The latter assumption is satisfied in artificial fibers whose diameter is fairly constant. In the case of natural fibers, there can be differences in diameter among filaments. A difference in diameter brings about a change in surface extension (even at constant gauge length) that scales with the square of diameter. When comparing strength data pertaining to different gauge lengths, one has either to limit the diameter variability or to assure that diameters are evenly distributed. The method usually adopted in the Weibull's analysis for determining σ_c at the critical length is the extrapolation of the $\log\sigma_m$ versus $\log l$ plots to the l_m value (or to l_c). The fragment length distribution, i.e., plots of cumulative probability versus fragment length, are obtained from the SFC tests (Fig. 6). From such plots, l_m at $P(l) = 0.5$ were obtained, and from eq. (4) the τ values were calculated (Table II).

A point of weakness of this approach is the fact that the strength of fibers is determined at gauge lengths in the 10^1 mm order of magnitude and estimated in the 10^{-1} mm order of magnitude. It is doubtful such a long extrapolation would accurately estimate σ_c. Although doubts can be cast on the real meaning of τ values, particularly when, as in the present case, they exceed the yield strength of the matrix, they can be safely used to compare the interfacial properties of similar components.[19,20,22] High τ values are generally taken as indicative of good adhesion between resin and fiber.

One of the reasons for the efficiency of epoxy resins as adhesives is the formation of polar groups (—OH) that strongly interact with high surface energy solids. A high concentration of —OH groups, on the other hand, characterizes the surface of cellulosic materials so that a strong interface can readily develop. Besides chemistry, other effects that may contribute to the stress transfer mechanism are (1) the irregularity of the surface and (2) the variation of fiber diameter. The simple stress analysis embodied in eq. (4) assumes the fibers to be circular. As shown in

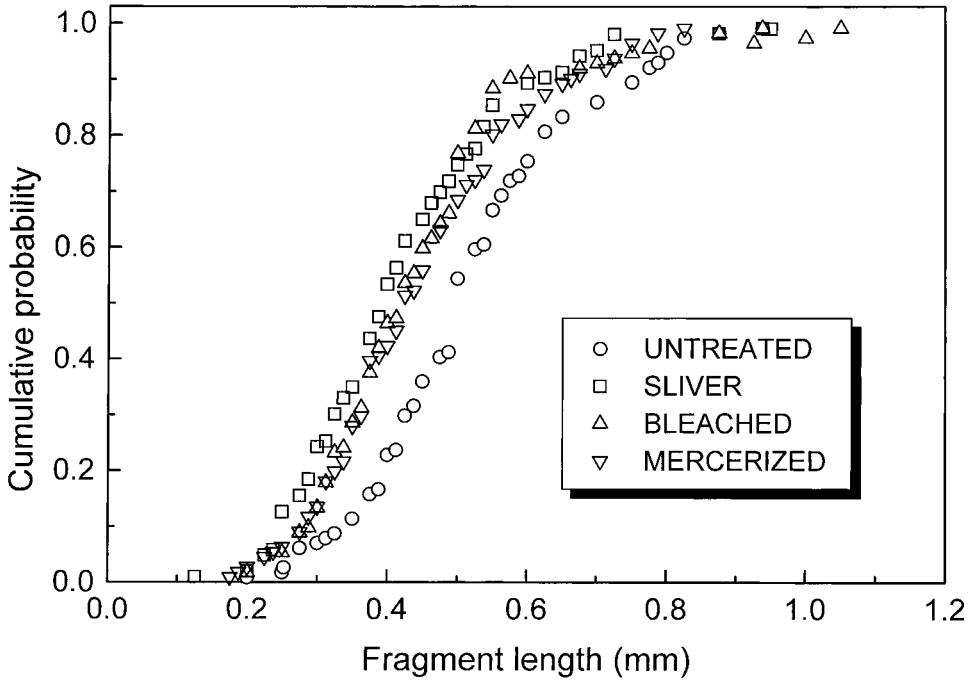


Figure 6 Fragment length distribution in a single-fiber coupon loaded in tension.

Figure 7(a–d), the actual fibers have rather rough surfaces, so that the real extension of the interface is higher than computed assuming a circular cross-section. The values of τ should accordingly be lowered.

A further contribution to the shear strength of the interface comes from the longitudinal fluctuation of diameter because in the region in which the diameter changes, the shear component of the stress acting on the interface decreases, and normal components develop. This provides an effective locking mechanism since the fiber would be held in place even in the absence of adhesion.

Among the four fibers studied, the adhesion was found to be greatest for BJF and minimum in for MJF with epoxy matrix. The high adhesion in case of BJF might be due to a greater mechanical anchorage of the epoxy resin on the more regular, clean surface with high microporosity. The possibility of chemisorption of the epoxy resin with hydroxy groups of the cellulose in the absence of lignin is another reason for improved adhesion, which cannot be ruled out. The adhesion in UJF is also good ($\tau \approx 83$ MPa) because of its high strength. The SJF and MJF have lower adhesion ($\tau \approx 58$ and ≈ 47 MPa, respectively). Both treatments, which lead to degradation of fiber strength, are probably effective in degrading the fiber surface also so that a weak interface results.

It may be recalled here that while the Weibull's analysis of the fibers strength was done at room temperature, the SFC coupons, and the fibers therein, were treated at 70°C (for 2 h) and 100°C (for 3 h). The effect of temperature on the mean strength of fibers was studied separately and it was found that, at the conditions of curing, the strength remains virtually unchanged.

Table II Mean Fragment Length (l_m), Critical Length (l_c), Fiber Strength (σ_c), and Interface Strength (τ) for Jute, Carbon, and Glass Fibers

Fiber Type	l_m (mm)	l_c (mm)	σ_c (MPa)	τ (MPa)
UJF	0.5	0.67	2455	83
SJF	0.4	0.53	1430	58
BJF	0.42	0.56	3455	140
MJF	0.43	0.57	1200	47
Carbon (7 μm)	0.55	0.73	7430	36
Glass (11 μm)	0.34	0.46	4738	56

SEM Analysis

Figure 7(a–d) gives the surface morphology of the four fibers, UJF, BJF, MJF, and SJF, respectively. Comparison between the surfaces of UJF and BJF reveals that the gaps between the unit

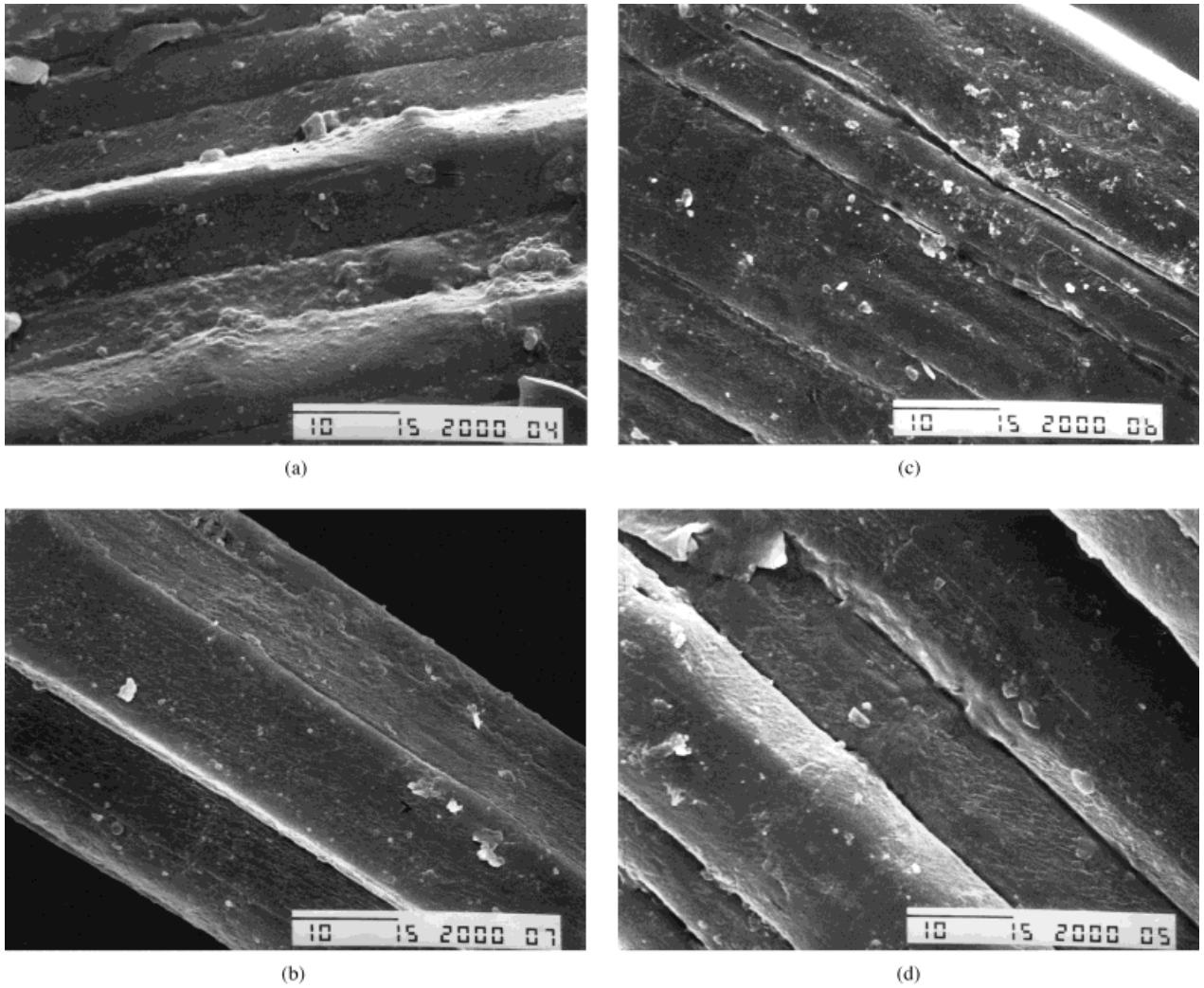
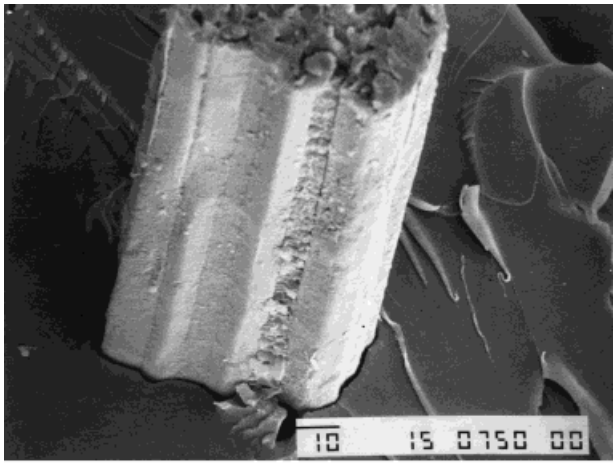


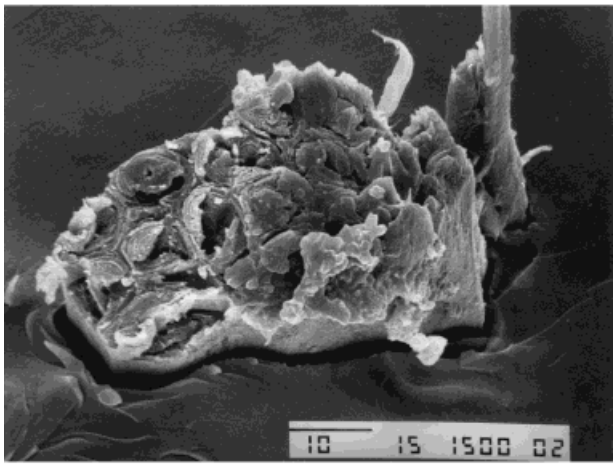
Figure 7 Effect of treatments on the morphology of fiber surface: (a) untreated, (b) sliver, (c) mercerized, (d) bleached.

cells of the filaments are closed in UJF, obviously by the binder lignin, while these gaps are open and quite clear in BJF because of the removal of lignin. Even the surface of the unit cells looks clean, with increased microporosity. This is likely the cause of the greatest adhesion of epoxy matrix with BJF originated by the infiltration of the liquid resin into the surface irregularities. The MJF surface shows a lot of pits and the individual unit cells do not look cylindrical; rather they seem to have parallel grooves or depressions running along the length. Since the MJF is weaker than UJF and BJF, it is logical to believe that the cellulose unit cells have undergone degradation due to the treatment with mild alkali. The results of Chand et al.[15] that the sisal fiber, another lignocellulosic fiber-like jute, becomes 100% stronger when the fibers were soaked in a 5% NaOH solution for 80 to 90 h is really surprising. In our case, with MJF, the results are discouraging. SEM pictures of SJF showed a very compact and clean surface. The fact that sliver filaments are the weakest indicates that the defects affecting the fiber strength are not identified with this technique.

Figure 8(a,b) gives the SEM pictures of the fractured tensile coupons after the fragmentation test. The fiber pull-outs are clearly observed along with the debonding. The debonding at the interface is minimum in BJF and UJF samples and very high in MJF. This confirms that the adhesion is minimum with the MJF, very good with BJF and UJF, and intermediate with SJF.



(a)



(b)

Figure 8 Fiber pull-out after failure of single-fiber coupons: (a) untreated, (b) mercerized. Gap at the interface arises from the radial thinning of the fiber during elongation.

CONCLUSIONS

The jute fibers were brittle, with load-elongation diagrams almost linear up to failure. The chemical treatments did not alter this behavior. The elastic moduli were in the range of 20–40 GPa and the strength varied from 0.5 to 1 GPa, depending on gauge length and treatments. Untreated and bleached filaments were the strongest. The distribution of failure strength obeyed the Weibull's theory. The influence of filament length on strength, related to the defect population, was found to be the same for jute, carbon, and glass fibers.

The interfacial strength with an epoxy resin was good because of the polar nature of both fiber and matrix. Again, untreated and bleached filaments gave the best result.

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