A Study of the Mechanical Properties of Randomly Oriented Short Banana and Sisal Hybrid Fiber Reinforced Polyester Composites

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ABSTRACT: The mechanical performance of short randomly oriented banana and sisal hybrid fiber reinforced polyester composites was investigated with reference to the relative volume fraction of the two fibers at a constant total fiber loading of 0.40 volume fraction (V_f), keeping banana as the skin material and sisal as the core material. A positive hybrid effect is observed in the flexural strength and flexural modulus of the hybrid composites. The tensile strength of the composites showed a positive hybrid effect when the relative volume fraction of the two fibers was varied, and maximum tensile strength was found to be in the hybrid composite having a ratio of banana and sisal 4 : 1. The impact strength of the composites was increased with increasing volume fraction of sisal. However, a negative hybrid effect is observed when the impact strength of the composites is considered. Keeping the relative volume fraction of the two fibers constant, that is, banana : sisal = 0.32 : 0.08 (i.e., 4 : 1), the fiber loading was optimized and different layering patterns were investigated. The impact strength of the composites was increased with fiber loading. Tensile and flexural properties were found to be better at 0.40 V_f. In the case of different layering patterns, the highest flexural strength was observed for the bilayer composites. Compared to other composites, the tensile properties were slightly higher for the composite having banana as the skin material and sisal as the core material. Scanning electron micrographs of the tensile and impact fracture surfaces of the hybrid composites having volume fraction 0.20 and 0.40 V_f were studied. The experimental tensile strength and tensile modulus of hybrid composites were compared with those of theoretical predictions. J Appl Polym Sci 96: 1699–1709, 2005

Key words: composites; reinforcement; impact resistance

INTRODUCTION

Hybridization with more than one fiber type in the same matrix provides another dimension to the potential versatility of fiber reinforced composite materials.[1,2] Properties of the hybrid composite may not follow from a direct consideration of the independent properties of the individual components.[3,4] A positive or negative hybrid effect can be defined as a positive or negative deviation of a certain mechanical property from the rule of mixture behavior respectively.[5] Studies on type 1 carbon–glass–epoxy hybrid composites showed that the failure strain of the carbon fibers can be increased to a value of about 1%. It has been observed that the addition of high performance polyethylene plies to the nonimpact side of a carbon laminate results in structural hybrid composites exhibiting a significantly better resistance to impact damage by altering the energy absorption mode via hybridization.[6] Lignocellulosic fibers are in general suitable to reinforce plastics (thermosets as well as thermoplastics) due to their relative high specific strength, stiffness, and low density.[7,8] Recently, a large number of studies have been published in this field.[9–14] In addition, Maldas et al. have studied hybrid fiber reinforced thermoplastic composites.[15,16]

Banana fiber at present is a waste product of banana cultivation. Moreover, without any additional cost input, banana fiber can be obtained in bulk quantity. In addition, earlier studies reported that banana fiber is found to be a good reinforcement in polyester resin.[17,18] Incorporation of 40% untreated fiber gives a 20% increase in the tensile strength and a 240% increase in impact strength. The fiber length was optimized as 30 mm. Recently, Thomas and coworkers[19–21] have extensively studied the properties of sisal-reinforced polyethylene, natural rubber, styrene butadiene rubber, and polystyrene composites. Sisal is also very important among the natural fibers, which exhibit comparatively high strength and modulus.[22–25]

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TABLE I
Mechanical Properties of Banana and Sisal Fiber

Fiber	Diameter (μ_m)	Density (Kg/m^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break (%)	Flexural modulus (GPa)	Lumen size (μm)	Micro fibrillar angle
Banana fiber	120 ± 5.8	1350	550 ± 6.7	20	5–6	2–5	5	11°
Sisal fiber	205 ± 4.3	1450	350 ± 7	12.8	6–7	12.5–17.5	11	20°

The structural aspects, mechanical behavior, surface morphology, quality, chemical constituents, etc. of sisal fiber have been studied. Thomas et al.[26] reported the impact properties of unidirectionally aligned sisal fiber/polyester composites. It was also reported that the tensile properties of short sisal fiber reinforced composites strongly depend on fiber length, fiber loading, fiber dispersion, fiber orientation, and fiber/matrix interfacial bond strength. Impact properties of sisal/glass hybrid laminates in polyester resin was studied by Pavitran et al.[27] They reported that the composites having glass core–sisal shell (SGS) laminates showed an improved impact performance compared to sisal core– glass shell laminates.

The physical properties of natural fibers are mainly determined by their chemical and physical composition, such as structure of fibers, cellulose content, angle of fibrils, and cross section, and by the degree of polymerization. When compared to other natural fibers, banana and sisal have good mechanical properties. The properties of banana fiber and sisal fiber are given in Tables I and II. In general, the strength of a fiber increases with increasing cellulose content and decreasing spiral angle with respect to the fiber axis. The cellulose content of sisal and banana fibers is almost the same, but the spiral angle of banana (11°) is much lower than sisal. Hence, the inherent tensile properties of banana fiber are higher than sisal fiber. The diameter of banana fiber is lower than sisal.[28] Therefore, the surface area of banana fibers in the unit area of the composite will be higher, and hence the stress transfer is increased in a banana reinforced composite compared to a sisal reinforced composite. Since the microfibrillar angle of sisal is high (20°), the impact performance of sisal will be higher.[28] The lumen size of sisal fiber is found to be greater than that of banana fiber. This also enhances the impact property of the sisal fiber. Since the elongation at break of these two fibers is almost the same, they are strain compatible. Hence, these fibers can be selected to hybridize so that the properties of the hybrid system can be improved by synergism. The typical properties of the resin are given in Table III.

Of late there is growing interest in hybridizing different natural fibers so as to produce high performance composite materials. Paiva[29] used plain weave hybrid ramie-cotton fabrics as reinforcement in a polyester matrix and showed the high potential of ramie fiber and weak contribution of cotton fiber as reinforcement in lignocellulosic fiber composites. Thomas et al.[30,31] studied the mechanical properties and cure characteristics of sisal and oil palm hybrid fiber reinforced natural rubber composites.

In the present work, the tensile properties of single banana and sisal fiber were studied, and a detailed study of the mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites has been made with reference to the relative volume fraction of the two fibers. The properties were analyzed for a constant total fiber loading of 0.40 V_f by varying the ratio of banana and sisal. Keeping the relative volume fraction of the two fibers constant, that is, banana : sisal = 4 : 1, the loading was optimized and different layering patterns were tried. Tensile strength, tensile modulus, elongation at break, flexural strength, flexural modulus, and impact strength of the composites were analyzed. Fiber/matrix interaction was studied by observing the fracture surfaces of the composites using a scanning electron microscope. Experimental tensile properties of the composites were compared with theoretical predictions.

TABLE II
Composition of Banana and Sisal Fiber

	Banana	Sisal
Cellulose %	63–64	65
Hemicellulose %	19	12
Lignin %	5	9.9
Moisture content %	10–11	10

TABLE III
Typical Properties of Liquid Resin

Appearance	A clear pale yellow liquid
Viscosity at 25°C (cps) Brookefield viscometer	650
Specific gravity at 25°C	1.11
Typical properties of cured unreinforced resin (specimens cured for 24 h at room temperature followed by post curing for 4h at 80°C	
Tensile strength	33 MPa
Flexural strength	70 MPa
Impact Strength	9 kJ/m^2

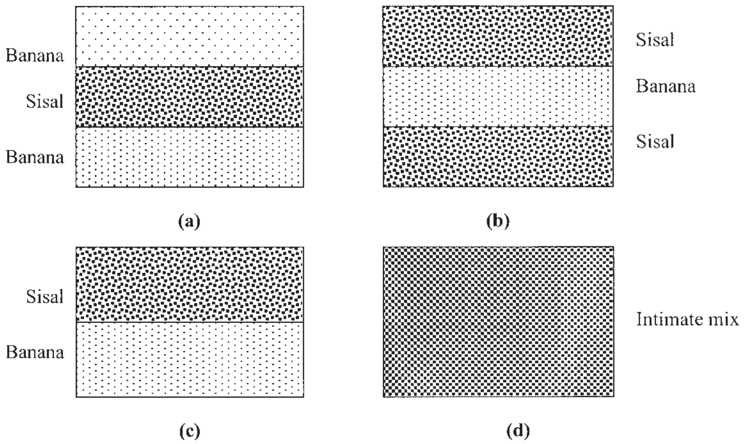

Figure 1 Schematic representation of different layering patterns of hybrid composites: (a) banana/sisal/banana, (b) sisal/banana/sisal, (c) bilayer, (d) intimate mix.

EXPERIMENTAL

Materials

Banana fiber and sisal fiber obtained from Sheeba Fibers and Handicrafts, Poovancode, Tamilnadu, India, were used in this study. The polyester used was an unsaturated polyester resin, HSR 8131, that was obtained from M/s. Bakelite Hylam Ltd. Hyderabad, India. The curing agent, methyl ethyl ketone peroxide, and catalyst cobalt napthenate used were of commercial grade obtained from M/S. Sharon Enterprises, Cochin, India.

Preparation of composites

Banana and sisal fibers were cut into 30 mm length and air-dried at 50°C for 5 h. The hand lay-up method followed by compression molding was adopted for composite fabrication. The curing of polyester was done by the incorporation of 1 volume percent methyl ethyl ketone peroxide. A 1% (volume percent) cobalt naphthenate was added as catalyst. The total volume fraction of the two fibers was kept constant, that is, $0.40V_f$, and composites were prepared by varying the relative volume fraction of the two fibers as well as varying the layering patterns. Composites were also prepared at different fiber loading ($0.2V_f$ to $0.5V_f$), keeping the ratio of relative volume fraction of the two fibers constant (banana : sisal = 4 : 1). Mats of chopped fibers were prepared and placed in a mold having dimension 150 mm × 150mm × 3 mm, and it was impregnated in polyester resin by pouring the resin mixed with curing agents on to the mat and squeezed using a flat wooden piece to ensure wetting of the mat and to remove the air bubbles. The mold was then closed and curing was done at a temperature of 30°C for 24 h under a constant pressure of 1MPa. For different layering patterns, such as bilayer (banana/sisal), trilayer (banana/sisal/banana, sisal/banana/sisal), and intimate mix composites, the ratio of V_f of banana and sisal was fixed to 4 : 1 (0.32 : 0.08). Using banana as the skin material and sisal as the core material, the composites were prepared for different fiber loading and different fiber ratio. For the bilayer and skin–core structure; mats of chopped banana and sisal fiber were prepared separately and then placed together to form the appropriate pattern. To prepare the intimately mixed composites, chopped banana and sisal fiber were placed together in small quantities and mixed thoroughly and then the fiber mat was prepared. In all cases, the fibers were randomly oriented by the hand lay-up method. The different layering patterns are schematically represented in Figures 1a, b, c, and d. In Figure 1a, banana is the skin material and sisal is the core material, and it is reversed in Figure 1b. Figure 1c represents the bilayer composite, and Figure 1d represents the intimate mix composite.

Mechanical tests

Mechanical testing of single banana and sisal fiber was carried out using a FIE universal testing machine of 500 KN capacity. About 30 samples were tested, and average values of mechanical properties were calculated. The fiber diameter was measured using a Leica (DMLP) Polarizing light microscope.

Test specimens were cut from the composite sheets having dimensions 100 × 15 × 3 mm, and tensile testing was carried out using a FIE universal testing machine with a gauge length of 50 mm and cross head speed of 50 mm/min. The flexural properties were determined using samples of dimensions 120 × 15 × 3 mm with a span length of 100 mm at a cross-head speed of 50 mm/min. The load displacement curves were obtained, and tensile as well as flexural strength and modulus were calculated.

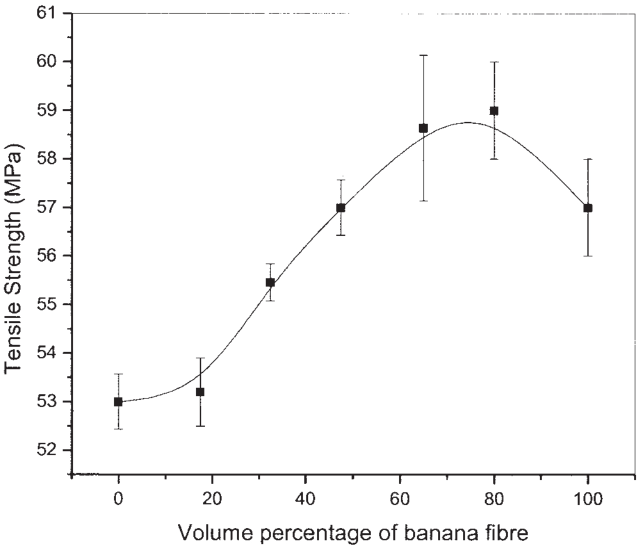

Figure 2 Effect of varying the relative volume fraction of banana and sisal on the tensile strength of banana/sisal hybrid fiber reinforced polyester composites at a total fiber loading of $0.40V_f$.

The Izod impact test on unnotched specimens was determined using a 25 Joules pendulum impact testing machine. The tensile and impact fractured surfaces of the hybrid composites were observed under SEM. The fractured ends of the tensile and impact specimens were mounted on aluminum stubs and gold coated to avoid electrical charging during examination.

RESULTS AND DISCUSSION

Tensile properties

Various mechanical properties of banana and sisal fiber are reported in Table I. It is observed that the tensile strength and modulus of banana fiber is higher than that of sisal, whereas the diameter of banana fiber is much lower than sisal fiber.

Effect of varying the relative volume fraction of the two fibers

Figure 2 shows the effect of varying the relative volume fraction of banana and sisal on the tensile strength of the hybrid composites. It is observed in Figure 2 that the tensile strength of the hybrid composite containing 0.32 V_f of banana was increased by 112% as compared to the unhybridized sisal reinforced polyester composite. The tensile strength was increased when the volume fraction of banana was increased and that of sisal was decreased, that is, the reinforcing effect of banana is greater than that of sisal in polyester. The tensile properties of banana fiber are better than that of sisal fiber (Table I). Since the microfibrillar angle of banana fiber is less (11°) than that of sisal fiber (20°), the reinforcing ability of banana is more than that of sisal in a polymeric matrix. The surface area of the fiber in a unit area of the composite is higher in a banana/polyester composite than that of a sisal/polyester composite because the diameter of banana fiber is less than that of sisal fiber. Hence, physical interaction as well as stress-transfer in the unit area is higher in the case of banana filled composites.

The tensile modulus and elongation at break are given in Table IV. Tensile modulus of the composite having V_f of banana 0.32 was found to be increased 130% as compared to that of the unhybridized sisal/polyester composite, and tensile modulus was maximum when the volume fraction of banana was 0.26 (i.e., 160% compared to neat polyester). Since banana and sisal fiber have almost the same elongation at break, they are strain compatible. Hence, a synergistic strengthening of the fibers occurs. Dispersion of fibers will be higher in a hybrid composite compared to that of an unhybridized composite.[32] Earlier, it was reported that the criterion for optimum adhesion between a matrix and reinforcing fibers is based on maximizing the wetting tension.[33] It is shown that the maximum wetting tension criterion best fulfils two important requirements for a strong interface. The first is that the physical interactions at the molecular level between the resin and the fibers must be maximized, and the second is that the liquid resin must spontaneously wet the fiber surface to minimize the flow density at the interface. As the dispersion increases, wetting tension as well as physical adhesion between the fiber and the matrix increases.

TABLE IV
Tensile Modulus, Elongation at Break, and Flexural Modulus of Banana/Sisal Hybrid Fiber Reinforced Polyester Composites on Varying the Relative Volume Fraction of the Two Fibers, Keeping the Total Volume Fraction 0.40

	Relative volume percentage of banana fiber						
Properties	100 (banana alone)	80	65	47.5	32.5	17.5	0 (sisal alone)
Flexural modulus (Mpa)	2723	3151	3240	4226	—	3271	2737
Tensile modulus (MPa)	1385	1462	1516	1220	1217	1421	1130
Elongation at break (%)	6	8	7	6	5	6	7

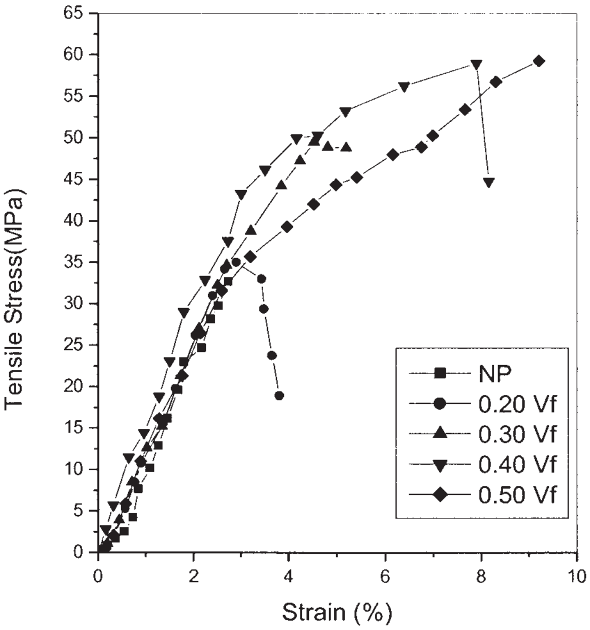

Figure 3 Tensile stress–strain behavior of neat polyester and banana/sisal/polyester composites having different fiber loading, keeping the ratio of banana and sisal 4 : 1.

Effect of fiber loading

Figure 3 shows the stress–strain behavior of banana/sisal/banana hybrid fiber reinforced polyester composites at different fiber loading, keeping the ratio of V_f of the two fibers constant (banana : sisal = 4 : 1). The behavior of neat polyester resin (NP) is also shown in Figure 3. The stress–strain curves of the composites show a linear behavior at low strains followed by a change in slope showing a non-linear behavior, which is maintained up to the complete failure of the composite. Fibers and matrix behave linearly at low strains. The second stage of the curve leading to decrease in slope corresponds to the plastic deformation of the matrix and to micro-crack initiation in the matrix. Randomly oriented fibers inhibit crack propagation, and gradual debonding of the fibers from the matrix occurs during plastic deformation. Unstable propagation of the initiated cracks through the matrix occurs, and the strength decreases abruptly to an almost zero value.

Figure 4 shows the effect of fiber loading on the tensile strength of the hybrid composites. The tensile strength of the former increases with fiber loading. When the fiber loading is $0.40V_f$, the tensile strength is found to be increased by 149% as compared to that of neat polyester. The increase in tensile strength is due to the reinforcing action of the fibers. However, at $0.50V_f$, there is only a slight increase in tensile strength compared to $0.40V_f$, which emphasizes the maximum allowable fiber content. The tensile modulus and elongation at break at different fiber loading are given in Table V. By incorporating 0.20 and 0.40 V_f of fiber, the modulus is increased by 30% and 54%, respectively, as compared to neat polyester. As the fiber loading is increased, the elongation at break is increased. The addition of cellulose fibers makes the matrix ductile. The tensile modulus is found to be maximum when the fiber loading is $0.40V_f$, whereas at 0.50Vf, the modulus is decreased to 1355 from 1462 MPa (Table V). At high fiber loading, fiber agglomeration results, which leads to decrease in stress transfer between the matrix and fiber. As well as due to higher fiber loading, the possibility of microvoid formation is more. Figures 5a and b show the scanning electron micrographs of the tensile fracture surfaces of the composites at 0.20 and 0.40 V_f, respectively. Fiber/matrix debonding and fiber pull out is more evident in the composite having 0.20 V_f (Fig. 5a), where there is not enough fiber to transfer the stress effectively from the fiber to the matrix. It is interesting to note that there is better fiber/matrix bonding in the composite with 0.40 V_f (Fig. 5b), where fiber breakage can be seen in the fracture surface. Stress transfer takes place from the fiber to the matrix effectively at 0.40 V_f.

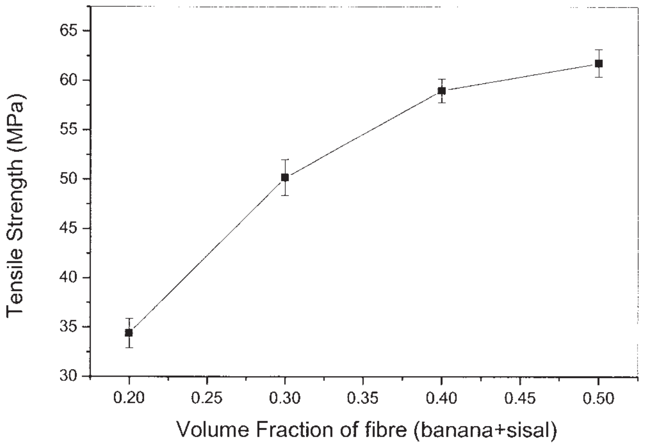

Figure 4 Effect of tensile strength on fiber loading of banana/sisal/polyester composites keeping the ratio of banana and sisal 4 : 1.

TABLE V
Tensile Modulus, Elongation at Break, and Flexural Modulus of Banana/Sisal Hybrid Composites at Different Fiber Loading, Keeping the Ratio of V_f of Banana and Sisal 4 : 1

	Volume fraction of the total fiber (banana + sisal)				
Properties	0	0.20	0.30	0.40	0.50
Tensile modulus (MPa)	950	1228	1328	1462	1355
Elongation at break (%)	2.8	4	6	8	9

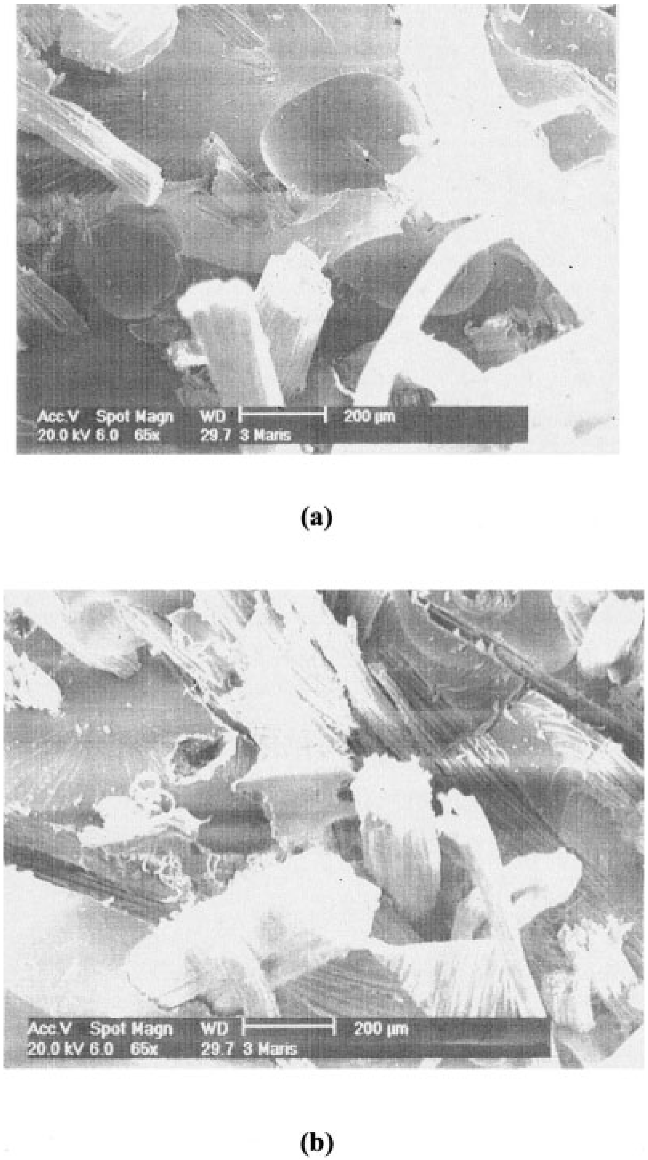

Figure 5 Scanning electron micrographs of the tensile fracture surfaces of hybrid composites at 0.20 (a) and 0.40 (b) V_f having volume ratio of banana and sisal 4 : 1.

Effect of layering pattern

The tensile properties of different layering patterns of hybrid composites consisting of trilayer (such as banana/sisal/banana or sisal/banana/sisal), bilayer, and intimate mix composites are shown in Table VI. Since the relative volume fraction of the two fibers is the same (i.e., B : S = 4 : 1), there is not much difference in their properties. The tensile strength was observed to be higher when banana was used as the skin material and sisal as the core material. The tensile strength will be higher when the high strength material is used as the skin, which is the main load-bearing component in tensile measurements. The tensile strength of the intimate mix composite is almost the same as that of the composite having banana as the skin material and sisal as the core. Maximum stress transfer occurs in intimately mixed composites. In S/B/S, the value is slightly lower because the low strength sisal fiber is used as the skin material. In bilayer, the tensile strength is again lowered. The tensile modulus is found to be higher for the bilayer composite and almost the same in the other pattern.

Flexural properties

Effect of varying the relative volume fraction of the two fibers

Flexural stress–strain curves of the hybrid and the unhybridized composites having total volume fraction of 0.40 can be seen in Figure 6. MA1, MA2, MA3, and MA5 represent the hybrid composites having volume fraction of banana 0.32, 0.26, 0.19, and 0.08, respectively. Bt and S3 represent banana polyester and sisal polyester composites, respectively. The slope of the curve increases and the plastic deformation occurs at a higher stress level in hybrid composites compared to unhybridized ones. Figure 7 shows the effect of varying the relative volume fraction of the two fibers on the flexural strength of the hybrid composites. The flexural strength was found to be almost the same for the unhybridized composites. But upon hybridization, a positive effect is observed. All hybrid composites show higher flexural strength compared to unhybridized composites. The highest value is observed for 0.26 volume fraction of banana fiber. As explained earlier, higher compatibility and dispersion in hybrid com-

TABLE VI
Effect of Tensile Strength, Tensile Modulus, Elongation at Break, Flexural Strength, Flexural Modulus, and Impact Strength of the Composites Having Different Layering Patterns, Keeping the Ratio of Volume Fraction of Banana (B) and Sisal (S) 4 : 1

Properties	Pattern of composites			
	B/S (Bilayer)	S/B/S (Trilayer)	B/S/B (Trilayer)	Intimate mix
Tensile strength (MPa)	55	57	59	58.6
Tensile modulus (MPa)	1506	1459	1462	1459
Elongation at break (%)	5.2	6.9	7.9	5.6
Flexural strength (MPa)	73	65	61	57
Flexural modulus (MPa)	3926	2884	3151	3011
Impact strength (kJ/m^2)	34	30	33	29

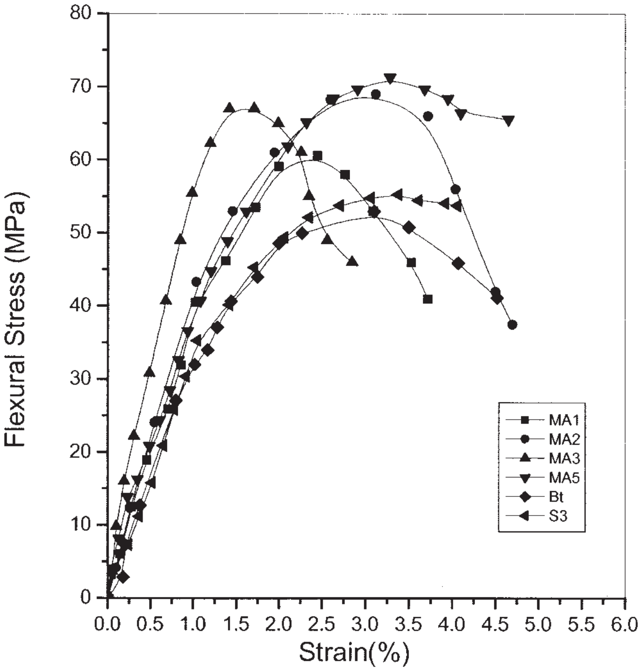

Figure 6 Flexural stress–strain behavior of banana/sisal/polyester composites on varying the relative volume fraction of the two fibers and that of unhybridized composites at a total volume fraction of 0.40.

posites are achieved, which lead to a better stress transfer ability in composites. Since both the sisal and banana have got almost equal extensibility,[28] the stress transferred from one fiber to another through the matrix can be propagated without any failure to the composite. This enhances the strength of the composite.

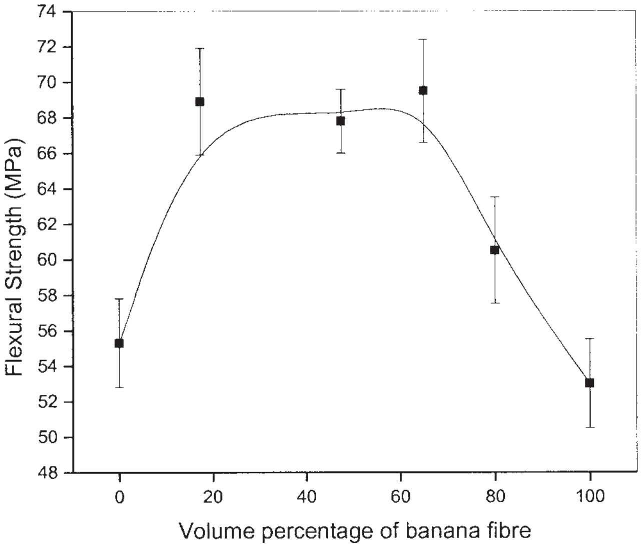

Figure 7 Effect of flexural strength on varying the relative volume fraction of banana and sisal in banana/sisal/polyester composites keeping the total fiber loading 0.40 V_f.

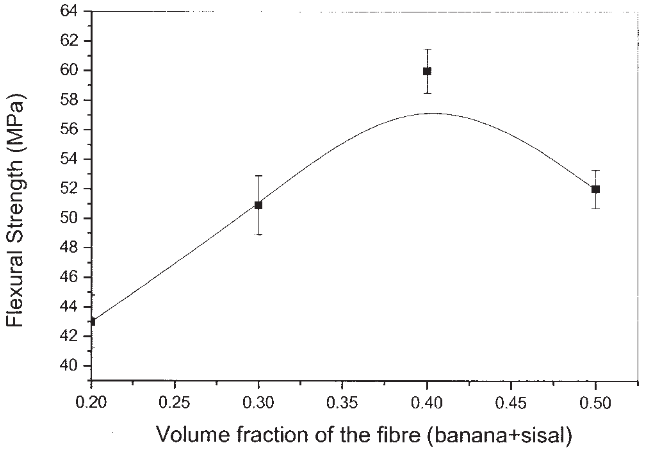

Figure 8 Effect of flexural strength on fiber loading of banana/sisal/polyester composites, keeping the ratio of banana and sisal 4 : 1.

Flexural modulus was also analyzed and can be seen in Table IV. When the volume fraction of banana was 0.19, flexural modulus was the highest. In flexural modulus, also, a positive effect is observed, that is, when the volume fraction of both the fibers are almost equal in the hybrid composite, high values are observed in flexural modulus also.

Effect of fiber loading

The variation of flexural strength with fiber loading can be seen in Figure 8. Earlier it was reported that the flexural strength of short banana fiber reinforced polyester composites was lower than that of neat polyester.[34] In the case of banana/sisal hybrid fiber reinforced polyester composites, also, the same trend is observed. The flexural strength linearly increases with fiber loading up to 0.40 V_f, and then the strength decreases. When the fiber loading increases from 0.20 to 0.40 V_f, a 40% increase in flexural strength is observed. Up to 0.40 V_f, the fiber/matrix interaction is improved; and on further loading, the fiber to fiber contact increases, the possibility of microvoid formation is more, and the strength decreases, as described earlier. Table VI shows that by increasing the fiber loading from 0.20 to 0.40V_f, the flexural modulus is increased to 138%. Again, on increasing the loading, the modulus is decreased.

Effect of layering pattern

The flexural properties of trilayer composites, such as banana/sisal/banana or sisal/banana/sisal, as well as intimate mix and bilayer composites were prepared by keeping the volume fraction of banana constant, that is, 0.32, which can be observed in Table VI. Flexural strength is found to be the highest in the bilayer composite and lowest in intimate mix composites. In trilayer composites, the values are in between the other patterns. Shear and tension are the main forces in flexural stress. Shear force will depend mainly on layering patterns. The delamination mechanism will be different in bilayer and trilayer composites. In trilayer composites, two interlaminar planes are there, and the possibility of delamination is higher. But in bilayer composites, only one interlaminar plane is there, and the possibility of delamination is lesser than that of trilayer composites. Hence, higher flexural strength is observed in the bilayer composites. Flexural modulus is also found to be the highest in the bilayer composites.

Impact properties

Effect of varying the relative volume fraction of the two fibers

The impact failure of a composite occurs by factors like matrix fracture, fiber/matrix debonding, and fiber pull out. Among these, fiber pull out is found to be an important energy dissipation mechanism in fiber reinforced composites.[35] Fiber–matrix debonding occurs when the applied load transferred by shear to fibers may exceed the fiber/matrix interfacial bond strength. When the stress level exceeds the fiber strength, fiber fracture occurs. The fractured fibers may be pulled out of the matrix, which involves energy dissipation.[36] Impact resistance of a composite is the measure of total energy dissipated in the material before final failure occurs.

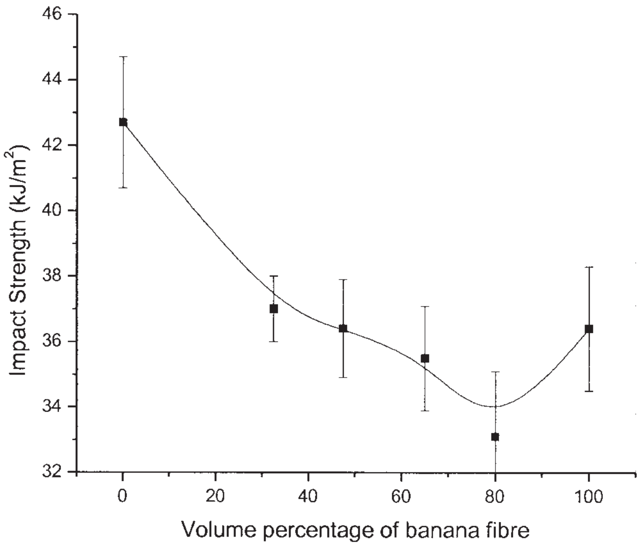

Figure 9 Effect of impact strength on varying the relative volume fraction of banana and sisal in the hybrid composites with respect to the unhybridized composites at a total fiber loading of 0.40 V_f.

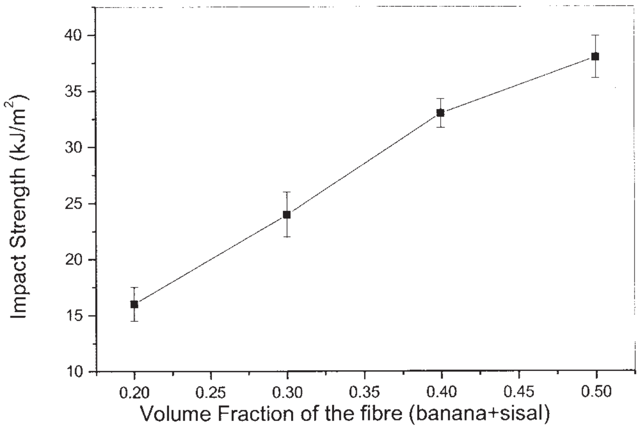

Figure 10 Effect of fiber loading on impact strength of the hybrid composites, keeping the ratio of banana and sisal 4 : 1.

Figure 9 delineates the impact performance of the hybrid as well as the unhybridized composites when the relative volume fraction was varied at a constant fiber loading of 0.40 volume fraction. It is observed that the impact strength of the short sisal fiber reinforced composite is high compared to that of the banana fiber reinforced composite. Natural fiber reinforced plastics with fibers having a high microfibrillar angle indicated a higher composite fracture-toughness than those with small spiral angles. It was reported that composites with sisal fibers (spiral angle 20°) show good impact properties.[28] The microfibrillar angle of banana fiber is 11°, which has got lower fracture toughness compared to sisal fiber. The lumen size of sisal fiber is greater than that of banana fiber (Table II), which increases the porous nature of the fiber as well as the impact strength. It is found that on increasing the relative volume fraction of sisal, the impact strength of the banana/sisal hybrid fiber reinforced polyester composite is increased. Upon hybridization, a negative hybrid effect is observed in impact properties. The highest impact strength is observed in the sisal/polyester composite. Better compatibility of the fiber, as already mentioned, will decrease the impact strength due to the least possibility for fiber pull out in the hybrid composites.

Effect of fiber loading

Figure 10 shows the relationship between fiber loading and impact strength of the composites. When the fiber loading increases, impact strength also increases. When the volume fraction increases from $0.20V_f$ to 0.30 and $0.40V_f$; the increase in impact strength was found to be 37 and 58%, respectively. At $0.40V_f$, the impact strength of the hybrid composite was found to be 214% higher than that of neat polyester. The neat polyester sample shows very low impact strength (Table III). The main disadvantage of thermoset moldings

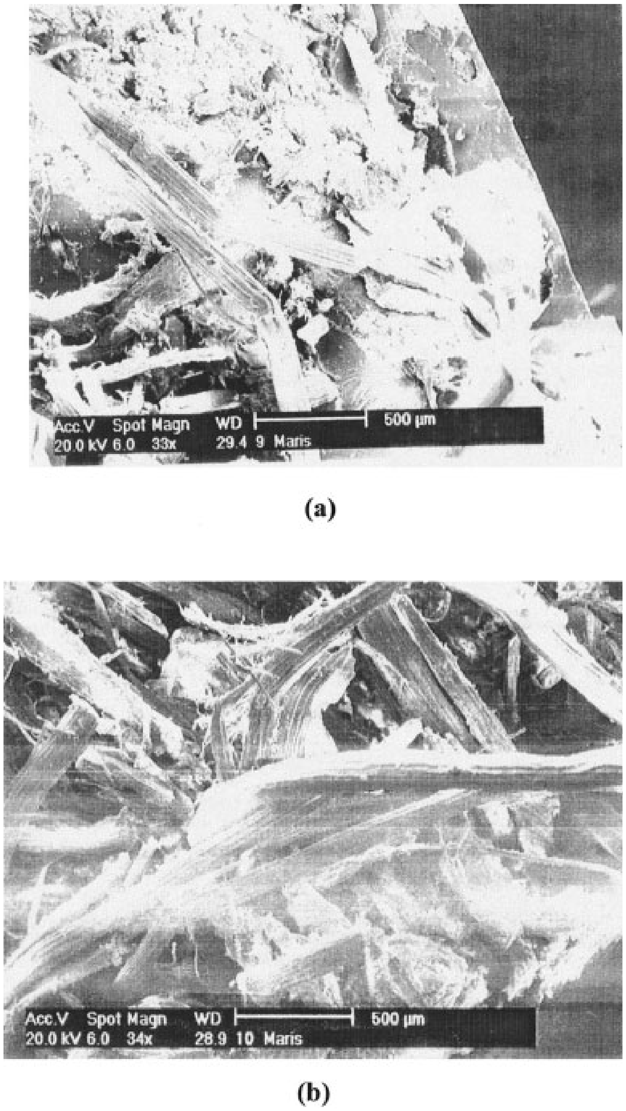

Figure 11 Scanning electron micrographs of the impact fracture surfaces of hybrid composites at 0.20 (a) and 0.40 (b) V_f having volume ratio of banana and sisal 4 : 1.

is high shrinkage during curing, high brittle behavior, and surface cracking. But on adding cellulose fiber, these drawbacks are almost eliminated. At lower fiber loading, fibers are found embedded in the matrix and, hence, fiber breakage and fiber pull out occurs on the application of a sudden force. The fiber crowding leads to easy debonding at high loading, which increases the impact resistance. Since cellulose fibers are more porous, when loading increases, the impact strength also increases. The scanning electron micrographs of the impact fracture surfaces of composites having 0.20 and 0.40 V_f can be seen in Figures 11a and b. Since fiber content is less in 0.20 V_f, premature matrix fracture takes place and fiber pull out is less. At 0.40 V_f, the fiber content is higher and the given energy will be used for fiber pull out.

Effect of layering pattern

By keeping the volume fraction of banana constant, 0.32 V_f, the impact strength of bilayer, sisal/banana/sisal, banana/sisal/banana, and intimate mix composites were determined, and these can be seen in Table VI. Highest impact strength is observed in the bilayer composite. This is because sisal, which has high fracture toughness compared to banana, is present on one side of the composite. Intimate mix composites have the lowest impact strength, which is due to the better stress-transfer that takes place in this composite compared to other patterns. Trilayer composites have almost the same strength. The layering pattern has no significant effect in the impact performance of the system. Since the volume fraction of sisal is less in these composites (i.e., 0.08 V_f), the impact strength is very low (30% less) compared to that of unhybridized sisal reinforced polyester composites.

Theoretical modeling

Several theories have been proposed to model the tensile properties of composite material in terms of different parameters. The Series and Hirsch models are found to be useful in determining the tensile properties of randomly oriented fibers in a rigid matrix.

According to the Series model

$$X_c = \frac{X_m X_f}{X_m V_f + X_f V_m} \tag{1}$$

where X_c, X_f, and X_m are the characteristic strength property of composite, fiber, and matrix, respectively. V_f is the volume fraction.

According to the Hirsch model

$$X_c = x(X_m V_m + X_f V_f) + (1 - x)\left(\frac{(X_f V_m)}{X_m V_f + X_f V_m}\right) \tag{2}$$

where x varies between 0 and 1. The value of x determines the stress transfer between fiber and matrix. The value of x is the determining factor in describing the real behavior of short fiber composites.[26]

The tensile strength and tensile modulus of the composites having different relative volume fraction of banana and sisal were calculated using the above models, and it was incorporated in the additive rule of mixtures.

$$X_h = X_1 V_1 + X_2 V_2 \tag{3}$$

where X_h is the characteristic property of the hybrid composites. The theoretical and experimental values of tensile strength and tensile modulus are shown in Figures 12 and 13, respectively. From Figure 12, it is observed that as the relative volume fraction of banana is increased, the tensile strength of the composites is increased. When the relative volume fraction of banana is lower, there is agreement with the Series model in the case of tensile strength. At higher volume fraction of banana, the Hirsch model is in more agreement. While considering the tensile modulus, the Hirsch model is found to be in agreement with experimental results.

CONCLUSIONS

Mechanical properties, such as tensile, flexural, and impact properties, of short banana/sisal hybrid fiber reinforced polyester composites were evaluated by varying the relative volume fraction of banana and sisal at a total constant fiber loading of 0.40 volume fraction. The tensile strength is found to be increased in banana/sisal hybrid fiber reinforced polyester composites when the volume fraction of banana is increased. A positive hybrid effect is observed for tensile properties. Higher compatibility is obtained in hybrid composites, which leads to better stress transfer ability in composites. When the V_f of sisal is 0.26, the maximum modulus is obtained. There is an irregular trend in the elongation at break of the composites. A positive hybrid effect can also be observed for flexural strength and flexural modulus. When the V_f of banana is 0.19, the flexural modulus is maximum. The impact strength of the composites is increased when the V_f of sisal is increased, Upon hybridization, a negative effect is observed for impact properties. Fiber loading was optimized and different layering patterns were studied by keeping the ratio of V_f of banana and sisal 4 : 1. The optimum loading was found to be $0.40V_f$. In the case of layering patterns, the bilayer gives higher flexural strength. Tensile strength is maximum for the composite with banana as the skin material and sisal as the core material. The experimental and theoretical tensile properties were compared. Finally, it can be concluded that the reinforcement of banana and sisal fiber in polyester results in a positive hybrid effect for tensile and flexural properties. Therefore, value added and cost-effective composites having high tensile and flexural properties could be well developed by the judicious selection of banana and sisal fiber.

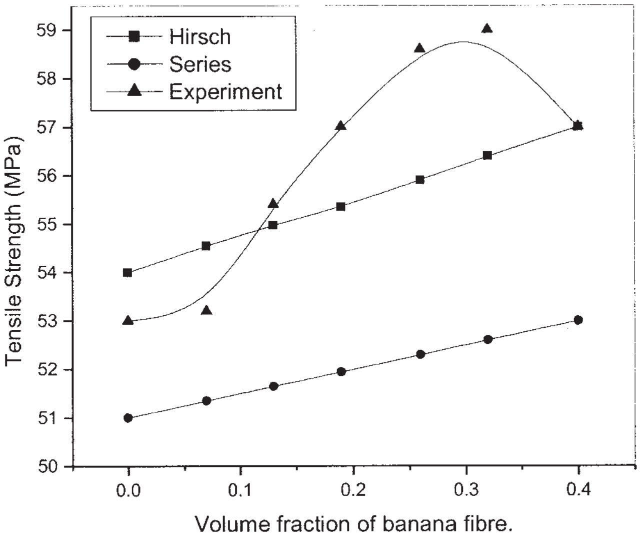

Figure 12 Experimental results and theoretical predictions of tensile strength in the hybrid composites when the relative volume fraction of the two fibers are varied at a total fiber loading of 0.40 V_f.

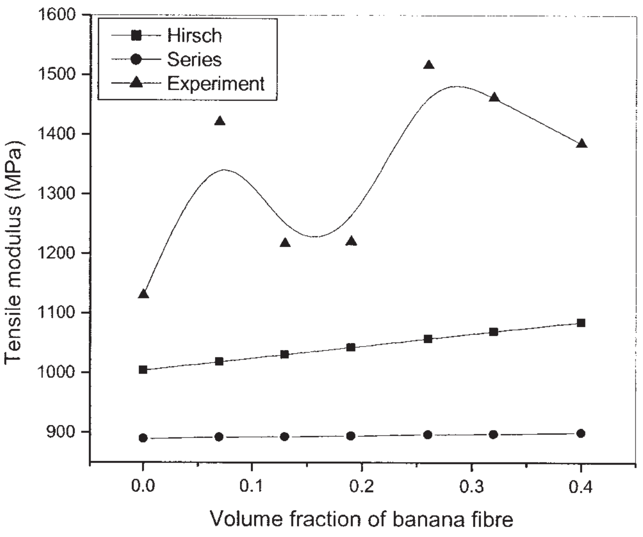

Figure 13 Experimental results and theoretical predictions of tensile modulus in the hybrid composites when the relative volume fraction of the two fibers are varied at a total fiber loading of 0.40 V_f.

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