Melt Rheological Behavior of Intimately Mixed Short Sisal–Glass Hybrid Fiber-Reinforced Low-Density Polyethylene Composites. I. Untreated Fibers

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ABSTRACT: The melt rheological behavior of intimately mixed short sisal–glass hybrid fiber-reinforced low-density polyethylene composites was studied with an Instron capillary rheometer. The variation of melt viscosity with shear rate and shear stress at different temperatures was studied. The effect of relative composition of component fibers on the overall rheological behavior also was examined. A temperature range of 130 to 150°C and shear rate of 16.4 to 5470 s^{-1} were chosen for the analysis. The melt viscosity of the hybrid composite increased with increase in the volume fraction of glass fibers and reached a maximum for the composite containing glass fiber alone. Also, experimental viscosity values of hybrid composites were in good agreement with the theoretical values calculated using the additive rule of hybrid mixtures, except at low volume fractions of glass fibers. Master curves were plotted by superpositioning shear stress and temperature results. The breakage of fibers during the extrusion process, estimated by optical microscopy, was higher for glass fiber than sisal fiber. The surface morphology of the extrudates was analyzed by optical and scanning electron microscopy. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 432–442, 2003

Key words: melt; rheology; composites; fibers; glass; polyethylene (PE)

INTRODUCTION

In recent years, the incorporation of short cellulosic fibers and their alignment in thermoplastic and elastomeric matrices has gained much importance, mainly to reduce cost and achieve and superior mechanical properties.[1] The rheological properties of short fiber-reinforced thermoplastics may differ from those of normal unfilled polymers, but they are not grossly different. In some instances, the mechanical properties of aligned short fiber-reinforced composites can approach those of continuous fiber composites, with the added advantages of low production costs and greater ease of production. The choice of suitable processing conditions and fabrication of polymer products is mainly guided by the rheological characteristics of the polymer. A number of investigations on the rheological behavior of short fiber-reinforced thermoplastics and elastomers have been reported.[2–4] Incorporation of fillers in thermoplastics increases the melt viscosity, which may ultimately result in unusual rheological effects. Crowson et al.[5,6] reported in detail the flow behavior of short glass fiber-reinforced thermoplastics during injection molding. Gupta and Purwar[7] investigated the effect of glass fibers on the rheological behavior of thermoplastics. Gupta[8] reported that as the aspect ratio of fiber approaches unity, the behavior of short fiber-filled composites approaches that of the particulate-filled polymers. Khan and Prud'homme[9] reviewed the melt rheology of filled thermoplastics for fillers with various degrees of fiber alignment, aspect ratio of <200, and volume fraction of fibers of <30%.

Ghosh et al.[10] developed a theory to account for the orientation and rheology of fiber-filled thermoplastics using a conformation tensor to describe the fiber orientation. Advani and Tucker[11] proposed a tensor notation approach to describe the orientation of short fibers in polymeric matrices as flow progresses. Molden[12] developed a simple geometrical theory that has shown that the convergent flow is more effective than shear flow in aligning fibers. Subsequent shear flow through the die can cover a significant misalignment of fibers. In such cases, the fiber orientation at the exit of the capillary die will be a function of the flow rate and length-to-distance (l/d) ratio of the die. The most pronounced fiber alignment occurs with a very short die and high flow rate.

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TABLE I
Physical Characteristics and Mechanical Properties of LDPE, Sisal Fiber and Glass Fiber

Characteristic/Property	LDPE	Sisal	Glass
Melt flow index (g/10 min)	40	—	—
Density (g/cm^3)	0.92	1.4	2.5
Vicat softening point (°C)	85	—	—
Crystalline point (°C)	104	—	—
Tensile strength	9 MPa	0.4–0.7 GPa	1.7–3.5 GPa
Modulus of elasticity (MPa)	130	—	—
Elongation at break (%)	110	5–14	3
Young's modulus (GPa)	—	9–20	65–72
Diameter (μm)	—	100–300	5–25
Average fiber length (mm)	—	6	6

The dependence of fiber loading, fiber length, and fiber–matrix interactions on the melt viscosity of the composite are more predominant at lower shear rate than at a higher one. The melt rheological behavior of short sisal-, coir-, and pineapple-reinforced polymers systems have been reported from this laboratory by Thomas and co-workers.[13–16]

Recently, intimately mixed short sisal–glass hybrid fiber was used as an excellent reinforcing material for low-density polyethylene (LDPE), and the mechanical properties of these composites were studied in detail.[17,18] The present paper deals with the rheological behavior of intimately mixed short sisal–glass hybrid fiber-reinforced LDPE composites. The effects of relative composition of sisal and glass fibers, shear rate, and temperature on the melt viscosity of these composites were investigated. The hybrid effect in the melt viscosity values of the composites was calculated using additive rule of hybrid mixtures. Only limited studies have been published in the field of rheology of hybrid composites to date.

EXPERIMENTAL

Materials

Low-density polyethylene (LDPE; 16 MA 400) was obtained from Indian Petro Chemical Corporation Ltd., Vadodara, India. Glass fiber (E-glass) was supplied by Ceat India Ltd., Hyderabad, India. Sisal fiber [leaf fiber from the plant *Agave sisalana* (Kattarvazha in Kerala)] was obtained from local sources. The main physical characteristics and mechanical properties of these base materials are listed in Table I.

Preparation of composite sheets

Intimately mixed sisal–glass–PE blends were prepared by a solution mixing technique. The fibers were mixed with a slurry of LDPE, using toluene as the solvent, at 125°C. To avoid agglomeration of fibers during mixing, glass fibers were added first to the slurry followed by sisal fibers. The solvent was re-

moved by evaporation. The dry mix was then extruded through a ram-type hand extruder at a temperature of 125 ± 3°C. The extrudates, with diameters of 4 mm, were collected and cut into small pieces for the rheological study. The terms SRP, GRP, and SGRP used in this study correspond to sisal-reinforced PE, glass-reinforced PE, and intimately mixed glass/sisal-reinforced PE composites, respectively. All composites analyzed in this study contained the same volume percentage of fibers (20%).

Rheological measurements

The melt rheological measurements were carried out with an Instron Capillary Rheometer model 3211 at different plunger speeds (0.06–20 mm min^{-1}). The capillary used was made of tungsten carbide, with a length (l_c)-to-diameter (d_c) ratio of 33.4 and an angle of entry of 90°. The sample was placed inside the barrel of the extrusion assembly and forced down into the capillary with a plunger after a residence time of 5 min. The melt was extruded through the capillary at predetermined plunger speeds. The initial position of the plunger was kept constant in all experiments, and shear viscosities at different shear rates were obtained from a single charge of material. The measurements were carried out at three different temperatures (130, 140, and 150°C).

The shear stress (τ) at each plunger speed was obtained with the following equation:

$$\tau = \frac{F}{4A_p(l_c/d_c)} \qquad (1)$$

where F is the force on the plunger, A_p is the cross sectional area of the plunger, and l_c and d_c are the length and diameter of capillary, respectively. The shear rate ($\dot{\gamma}$) at the wall was determined by eq. 2:

$$\dot{\gamma} = \left[\frac{3n' + 1}{4n'}\right]\left[\frac{32Q}{\pi d^3 c}\right] \qquad (2)$$

where Q is the volumetric flow rate, which is given by

$$Q = \frac{V \times h}{60} \times \frac{\pi d_b^2}{4} \qquad (3)$$

where $V \times h$ is the plunger speed (mm min^{-1}) and d_b is the diameter of the barrel. The factor $3n' + 1/4n'$ is the Rabinowitch correction that is applied to calculate the shear rate at the wall. The flow behavior index (n') is given by

$$n' = \frac{d(\log \tau)}{d(\log \dot{\gamma})} \qquad (4)$$

Bagley's correction for the pressure drops at the capillary entrance was not applied because this correction factor becomes negligible for capillaries with high l/d ratios. The viscosity (η) is calculated with the following equation:

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad (5)$$

Extrudate morphology

The surface characteristics, cross section, and distortion of the extrudate were studied with optical and scanning electron microscopes (Jeol–JSM 35 C model).

Die swell behavior

The extrudates that emerged from the capillary die were carefully collected without any deformation. The diameter of the extrudate was measured after 24 h of extrusion with a travelling microscope. The die swell was calculated as d_e/d_c, where d_e is the diameter of the extrudate and d_c is the diameter of the capillary.

Fiber breakage analysis

The breakage of fiber during extrusion at different shear rates was analyzed by separating the fibers, dissolving the PE matrix from the extrudate, and measuring the fiber length with a travelling microscope.

RESULTS AND DISCUSSION

Effect of shear rate and relative composition of fibers on viscosity

Melt viscosity values of LDPE, SRP, GRP, and SGRP (with 80/20, 60/40, 50/50, 40/60, and 20/80 sisal–glass compositions) are shown in Figure 1 as a function of shear rate at 130°C. The curves reveal that all systems show pseudoplastic behavior. It is clear that among these composites, SRP shows minimum and GRP shows maximum melt viscosity. The viscosity
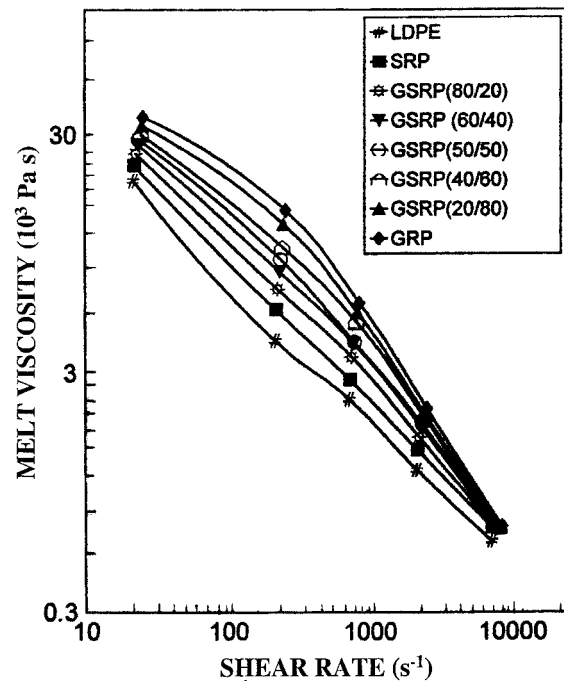

Figure 1 Variation of melt viscosity (η) with shear rate (γ) of LDPE, SRP, SGRP (sisal–glass), and GRP composites at a temperature of 130°C.

value of SGRP is in between that of SRP and GRP. In the case of SGRP, the viscosity increases with an increase in volume fraction of glass. Viscosity also increases because there is a better interaction of PE with glass than with sisal fiber. This result is analogous to those in our earlier study in which higher tensile strength was exhibited by glass-rich hybrid composites than by sisal-rich composites.[17] Another reason for the increase viscosity is attributed to the agglomerated fibers that form at high volume fraction of glass fibers. The optical micrographs of the cross section of the SGRP shown in Figure 2 provide evidence of this formation of agglomerated fibers at high volume fraction of glass (Figure 2b). The friction between agglomerated fibers is responsible for the enhancement in melt viscosity. But the increase in viscosity is more predominant at lower shear rate than at higher shear rate. The curves in Figure 1 can be represented by the power law equation:

$$\eta = K\gamma^{n-1} \qquad (6)$$

The flow behavior of polymeric composites can be explained in two ways.[4] First, if a system of asymmetric particles in which the particles are initially randomly dispersed is subjected to shear, the particles tend to align themselves with the major axis in the direction of shear, thus reducing the viscosity. The degree of alignment is a function of the deformation rate. At low shear rates, there is only a slight departure
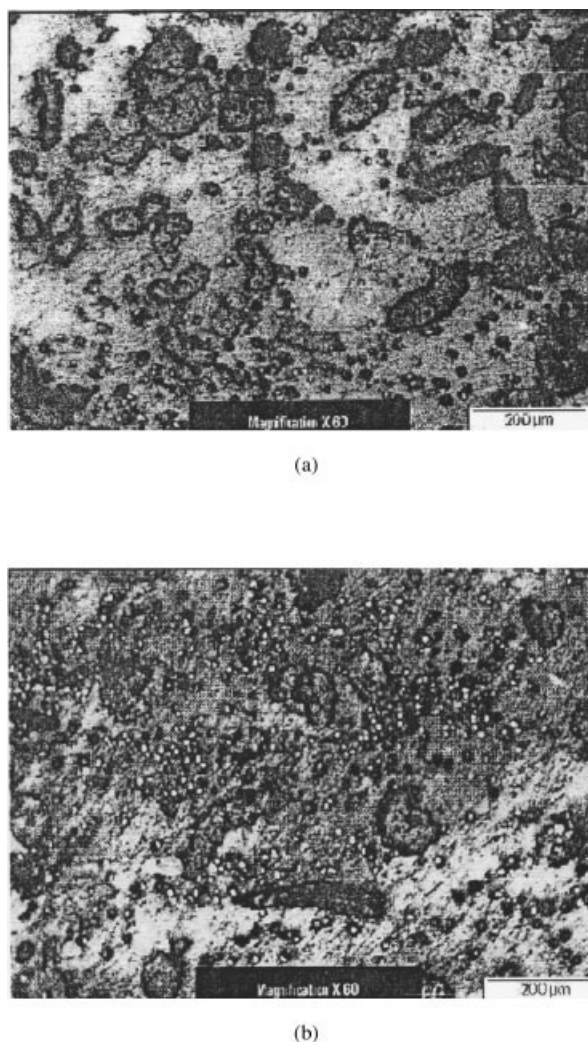
Figure 2 Optical micrographs of cross sections of (a) SGRP with 60/40 and (b) SGRP with 20/80 sisal–glass compositions.

from randomness, but at high shear rates, the particles are almost completely oriented.

A second explanation of flow behavior is that in highly solvated systems where chemical interaction among polymer solvated particles exists, the solvated layers may be sheared away with an increase of shear rate, resulting in decreased viscosity. All composites exhibit higher melt viscosity than pure PE at all shear rates. In fiber-filled systems, the fibers perturb the normal flow of polymer and hinder the mobility of chain segments in flow. Crowson et al. reported that when a melt passes from a wide to a narrow cross section, converging flow results in the die entrance region, causing extensive fiber alignment.[5,6] At low shear rate, the fibers are disoriented. The probability of fiber–fiber collision and friction is much higher for these disoriented fibers. But, at high shear rate, these fiber-to-fiber collisions are diminished because of the alignment of fibers along the tube axis. Therefore, the

increase in viscosity with volume fraction of glass fiber is less predominant at high shear rate. Goldsmith and Mason observed the radial migration of filler particles towards the capillary axis during shear flow.[19] A similar situation may be happening at high shear rate in this system also. As a result of these phenomena in fiber-filled thermoplastics, the region where most of the shear takes place (region closer to the tube wall) may be virtually fiber free. This lack of fiber where most of the shear takes place could be a reason for the close viscosity values of all the composites at higher shear rate. Wu[20] also reported a similar migration of glass fibers in aPE–terephthalate matrix. The very similar viscosity values at high shear rate for unfilled, sisal-rich, and glass-rich PE composites is an important factor in explaining the successful exploitation of these materials in injection moulding; that is, very little additional power will be required to injection mould the fiber-filled composite materials.

Effect of temperature

A study of the influence of temperature on the melt viscosity of polymer is important because substantial temperature changes occur at different stages during moulding. Generally, the viscosity of polymers and polymeric composites decreases with increases of temperature because of the accelerated molecular motion at higher temperature. In the present study, flow curves were obtained at 130, 140, and 150°C. The variations of the melt viscosity values with temperature at different compositions of sisal and glass and at different shear rate are depicted in Figure 3. As expected, viscosity decreases with the increase in temperature for all the systems. The enhancement in viscosity at high shear rate compared with that at low shear rate clearly indicates the pseudoplastic behavior of composites.

To further understand the influence of temperature on the viscosity of these composites, Arrhenius plots (log viscosity plotted versus reciprocal of absolute temperature) at constant shear rate were made. Linear plots were obtained (Figure 4). The flow activation energy values calculated from the slopes of the plots in Figure 4 are presented in Table II. The activation energy of a material provides valuable information on the sensitivity of material towards the changes in temperature. The higher the flow activation energy, the more temperature sensitive the material. The data in Table II indicate that the melt viscosities of all the composites are more temperature sensitive than that of the unfilled LDPE, as evidenced by the higher ΔE values of the composites. But, the ΔE value decreases as the amount of glass fiber increases. The flow of the short hybrid fiber-reinforced composites is dependent on the nature and volume fraction of individual fibers present in the composites in addition to temperature
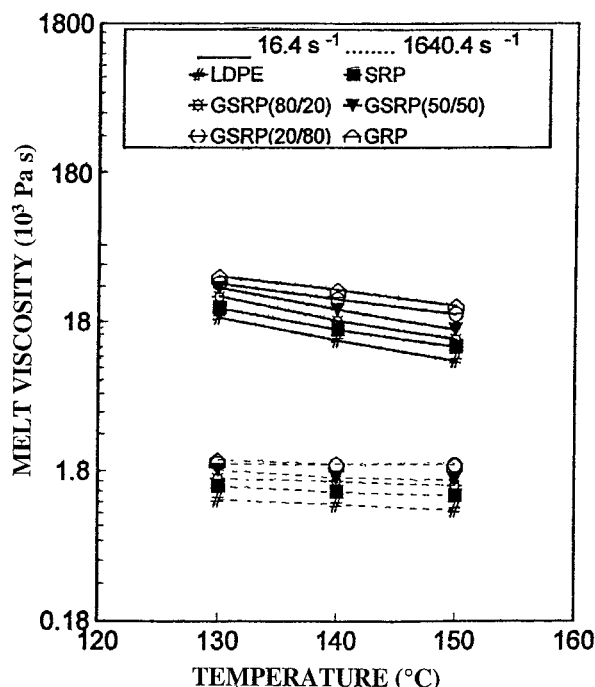
Figure 3 Variation of melt viscosity (η) with temperature at different shear rate and at different compositions of sisal and glass fibers.

and rate of shear. The presence of fiber restricts the molecular mobility under shear. With the increase of temperature, the viscosity is reduced and the alignment of the fibers in the direction of flow becomes easier at the same rate of shear. This effect will be prominent in composites containing a higher amount of sisal fiber because, as temperature increases, the
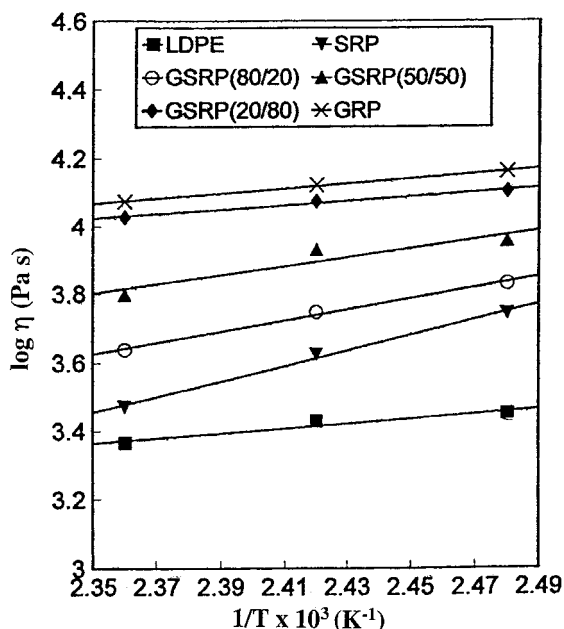
Figure 4 Variation of log η with absolute temperature ($1/T$) at a shear rate of 164 s^{-1}.

TABLE II
Flow of Activation Energies of LDPE, SRP, GRP, and SGRP Composites

System	Activation energy (J/mol)	
	164.04 s^{-1}	1640.4 s^{-1}
LDPE	85	38
SRP (20%)	273	63
SGRP (80/20)	192	47
SGRP (50/50)	160	64
SGRP (20/80)	89	45
GRP (20%)	88	42

alignment of fibers in the direction of flow becomes more difficult with glass than with sisal. Hence, hybrid composites containing a higher amount of sisal become more temperature sensitive than those with a lesser amount of sisal fiber. Composites containing sisal fiber only shows maximum energy of activation.

Shear stress–temperature superposition master curve

Anand[21] reported the importance of shear rate–temperature superpositioning in predicting the melt viscosity. The superposition shift factors were obtained by choosing a shear stress at the reference temperature of 140°C and shifting the corresponding points on the flow curves at other temperatures to coincide with these shear stresses. The shift factor (a_τ) values were calculated with the following equation:

$$a_\tau = \frac{\tau_{(ref)}}{\tau_{(constant)}} \tag{7}$$

The master curve obtained by plotting the product of shear stress and a_τ versus shear rate is shown in the Figure 5. The curves at different temperatures shift to a single reference temperature curve. The superpositioning of the data was achieved over the whole range of temperature and shear rate.

Hybrid effect calculation

The hybrid effect was theoretically calculated using the additivity rule of hybrid mixtures. According to this rule, hybrid viscosities are calculated with the following equation:

$$M_H = (MV)_1 V_1 + (MV)_2 V_2 \tag{8}$$

where M_H is the viscosity of the hybrid composite, $(MV)_1$ and $(MV)_2$ are the viscosities of individual sisal (SRP) and glass (GRP) fibers, respectively, and V_1 and V_2 are hybrid volume fractions of the individual SRP fibers and GRP fibers, respectively. Equation 8 is valid only if the total volume fraction of the reinforcements
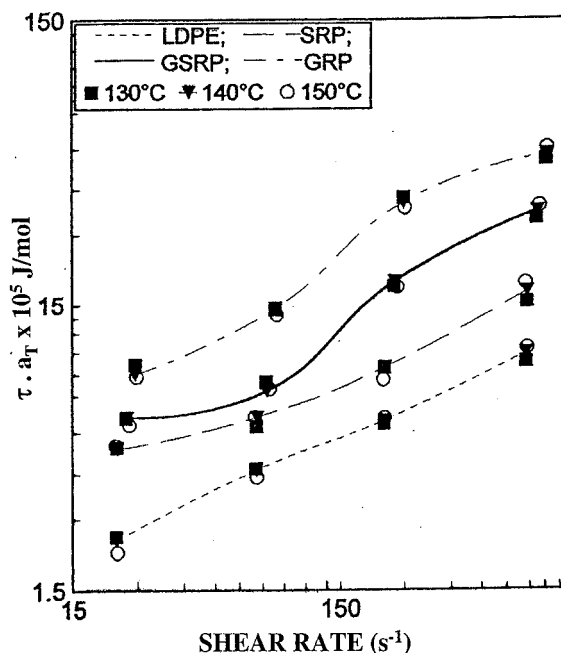
Figure 5 Shear stress–temperature superposition master curves of LDPE, SRP (20% sisal), GRP (20% glass), and SGRP (at different compositions of SRP and GRP).

Figure 6 Variation of melt viscosity of SGRP with volume fraction of GRP at a temperature of 130°C and at different shear rates.

is almost equal for all the hybrid composites,[22,23] which is true for all the hybrid composites in the present study. When the values of theoretically calculated properties of hybrid composites, using eq. 8, are higher than those of the experimental values, then a negative hybrid effect is observed. If the experimental properties are higher than the theoretically calculated properties, a positive hybrid effect is observed. The theoretical and experimental melt viscosity values as a function of volume fraction of glass fibers at three different shear rates and 130°C are shown in Figure 6. The points on the y-axis at zero and one volume fractions of the GRP indicate 100% SRP and GRP, respectively. It is evident from the figure that as shear rate increases, the negative hybrid effect decreases and is almost gone at high shear rate (1640 s^{-1}). However, at 16 and 165 s^{-1}, hybrid composites at low volume fraction of glass exhibit a small negative deviation from the rule of mixture behavior. This result indicates that at high volume fractions of glass, the decrease in the overall viscosity due to the presence of small amount of sisal fiber is highly compensated by the presence of agglomerated glass fiber (Figure 2b). Experimental and theoretical melt viscosities of SGRP as a function of volume fraction of glass at a shear rate of 164 s^{-1} and at different temperatures are shown in Figure 7.

Fiber breakage analysis

The sisal and glass fiber length distribution of SGRP hybrid composites before and after extrusion through
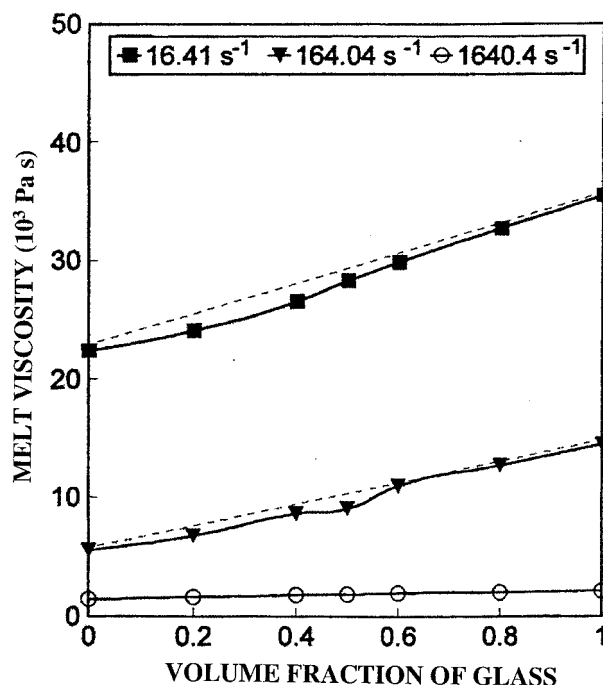
the capillary at three different shear rates are shown in Figures 8 and 9, respectively. During the extrusion process, there is great chance for fiber breakage because of high shear stresses. For example, before ex-
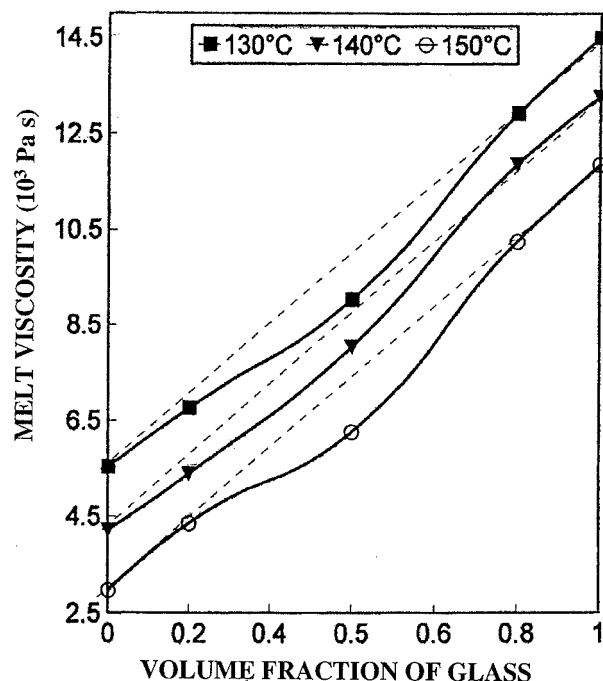

Figure 7 Variation of melt viscosity of SGRP with volume fraction of GRP at a shear rate of 164 s^{-1} and at different temperatures.
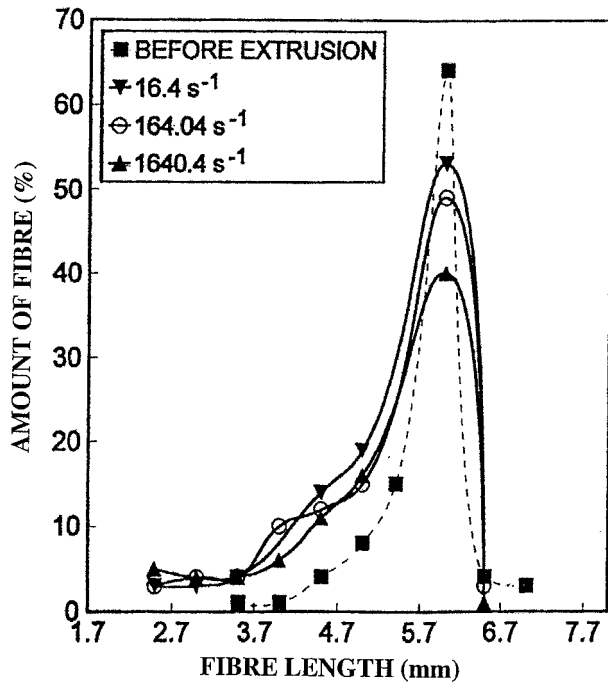
Figure 8 Fiber length distribution curves of sisal from the extrudate of SGRP (50/50, sisal–glass) extruded at a temperature of 130°C.

trusion, the hybrid composites contain 64% of original length (6 mm) sisal and 80% of original length (6 mm) glass fibers. During extrusion at low shear rate (16.4 s^{-1}), 53% sisal and 56% glass fibers retain their origi-
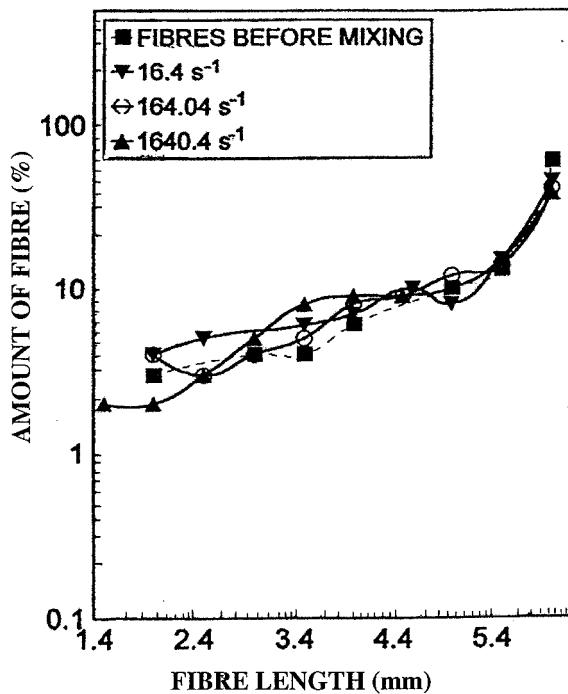
TABLE III
Die-Swell Values of LDPE, SRP, and SGRP at 130°C

	Die swell values	
System	164 s^{-1}	1640 s^{-1}
LDPE	1.4	2
SRP (20%)	1.3	1.5
SGRP (80/20)	1.3	1.5
SGRP (60/40)	1.3	1.5
SGRP (50/50)	1.3	1.5

nal length. At high shear rate (1640 s^{-1}), ~40% of sisal and 38% of glass fibers retain their original length. These results indicate that glass fiber undergoes more severe breakage than sisal fiber at all shear rates. It is interesting to note that at all shear rates, the most probable length is 6 mm. However, for most of the fibers, the length probably decreases with increase of shear rate, and the decrease is associated with breakage of fibers at high shear rate.

Die swell ratio

When a polymer melt flows through the capillary, the polymer molecules undergo orientation under the applied force.[24] As the melt comes out of the die, reorientation and recovery of deformed molecules occurs, leading to the phenomenon of die swell. In the case of short hybrid fiber-reinforced composites, orientation of polymer and both fibers takes place in the direction
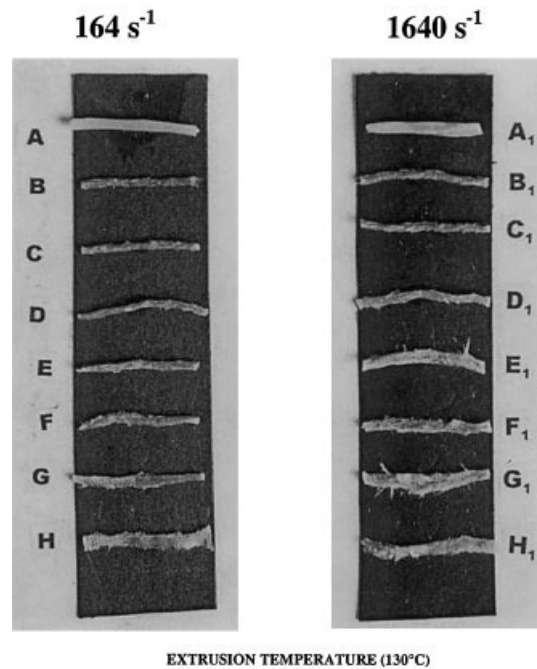

Figure 9 Fiber length distribution curves of glass from the extrudate of SGRP (50/50, sisal–glass) extruded at a temperature of 130°C.

Figure 10 Ordinary photomicrographs of the extrudates at two different shear rates: A, B, C, D, E, F, G, H indicate the LDPE, SRP, SGRP (80/20, 60/40, 50/50, 40/60, 20/80 composition of sisal–glass) and GRP.
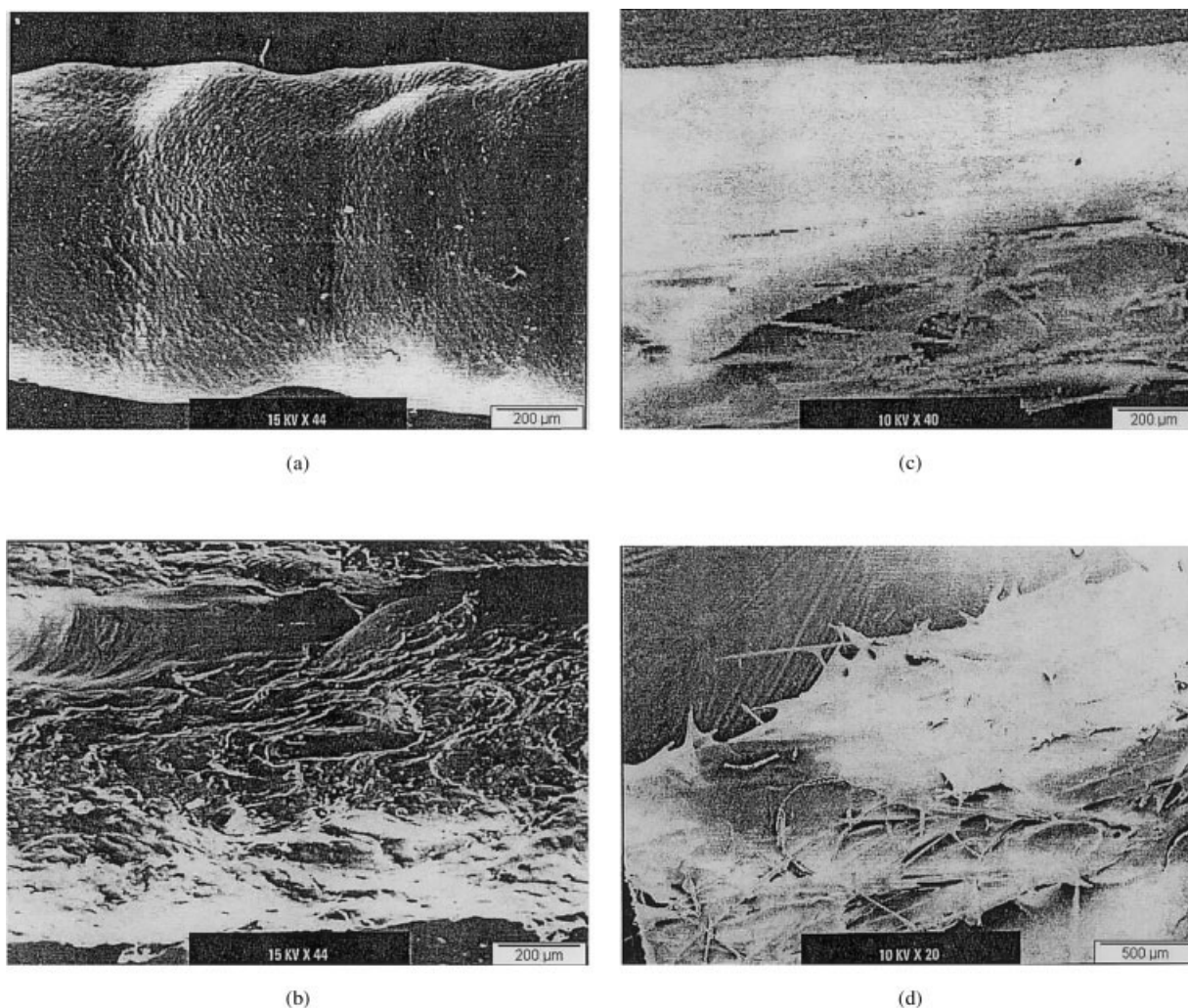
Figure 11 Scanning electron micrographs of the surface of the extrudates at a shear rate of 164 s^{-1}: (a) LDPE, (b) SRP, (c) SGRP (40/60, sisal–glass), and (d) GRP.

of flow during their flow through the capillary. On emerging from the capillary, the composite tries to retract by the recoiling effect of the polymer chains. The sisal and glass fibers, being different in their elastic character, exert retractive forces differently. The unequal retractive forces exhibited by the three components (glass fiber, sisal fiber, and PE matrix) lead to redistribution of the fibers. Because the periphery of the extrudate undergoes maximum deformation, the retractive forces on the polymer molecules and fibers will also be higher at the periphery. Thus, the reorientation and migration of the fibers take place at the expense of retractive forces, which are mainly responsible for the die swell in short fiber-reinforced composites. The die swell values of LDPE, SRP, and SGRP (different compositions of sisal and glass) at two shear rates are shown in Table III. The die swell values of LDPE decrease to SRP containing 20% sisal fibers. Chan et al.[25] reported that the incorporation of fibers causes a

very significant reduction in die swell of the parent melt. When fibers are incorporated with LDPE, the shear strain that occurs in the capillary is low, which reduces the die swell values. Die swell values are almost unchanged further by the additional incorporation of small amount glass fibers. Addition of a low quantity of glass fiber helps to improve the dispersion of sisal fibers.[17] But at high volume fraction of glass ($\geq$50/50), die swell has no meaning because the extrudate shape of SGRP and GRP has changed from cylindrical to a flattened ribbon shape (melt fracture). This change in shape will be explained in the next section (Extrudate characteristics). It has been reported that melt fracture occurs when shear stress exceeds the strength of the composite melt.[4] Another reason for the ribbon-shaped nature of the extrudate is the comparatively higher rigidity of glass fiber than sisal fiber. The results in Table III also show that die swell increases with increase of shear rate.
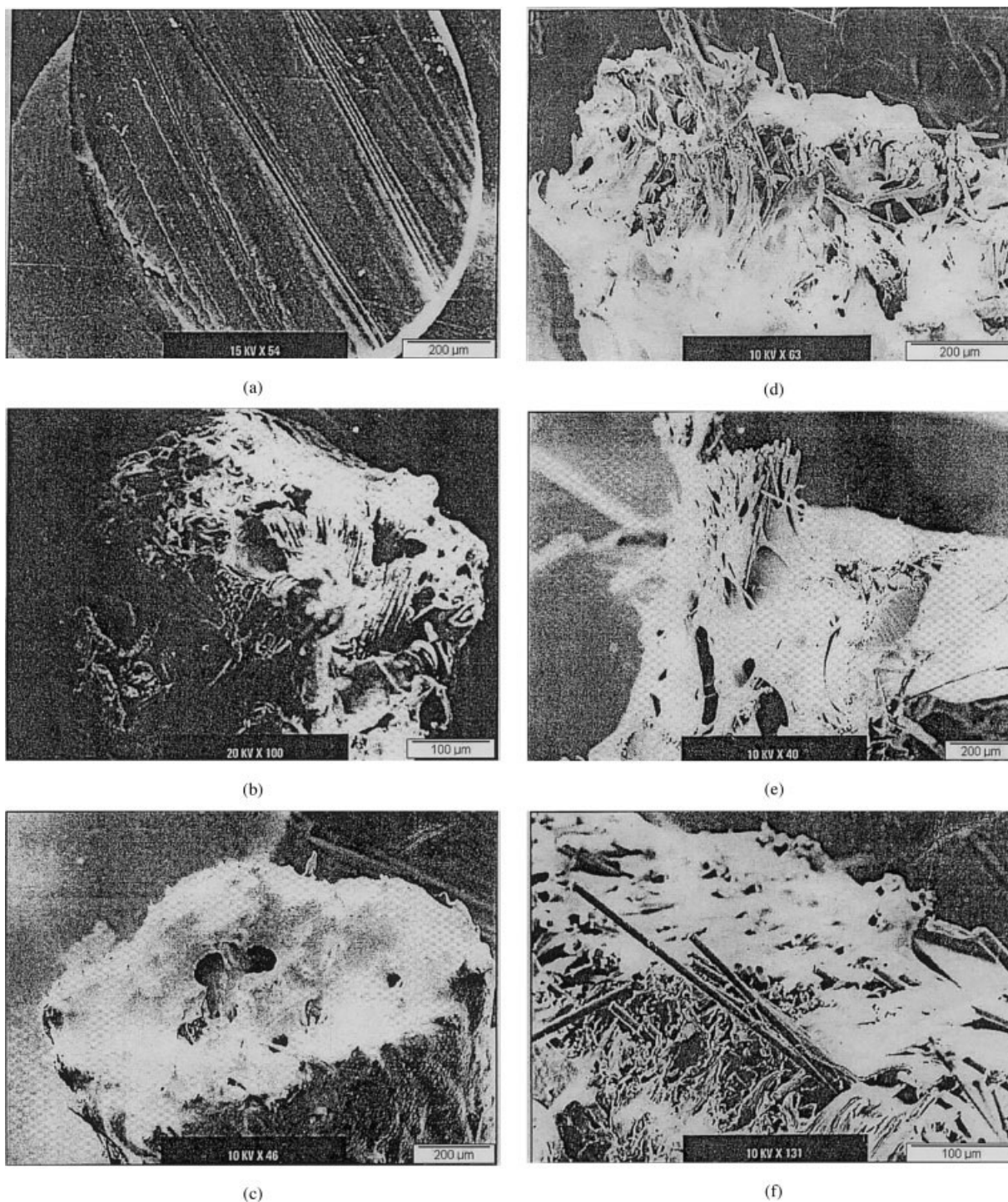
Figure 12 Scanning electron micrographs of the cross section of the extrudates: (a) LDPE, (b) SRP (20% sisal), (c) SGRP (80/20, sisal–glass), (d) SGRP (50/50, sisal–glass), (e) SGRP (20/80, sisal–glass), and (f) GRP (20% glass).

Extrudate characteristics

An optical micrograph of the extrudate from various composites at two shear rates is shown in Figure 10. The extrudate from LDPE is more deformed and less uniform in diameter than extrudate from SRP. This deformation may be associated with the melt nonuniformity occurring when the shear stress exceeds the strength of the melt. But, as volume fraction of glass fiber increases, the deformity and nonuniformity in diameter of the extrudate again increases. This change is due to the melt fracture associated with the comparatively high rigidity of glass fiber compared with that of sisal fiber. From the photographs it is observed that as the composition of SGRP changes from 50/50,

TABLE IV
Flow Behavior Index (n') of Various Composites

System	Flow behavior index (n')		
	130°C	140°C	150°C
LDPE	0.431	0.425	0.418
SRP (20%)	0.425	0.411	0.403
SGRP (80/20)	0.395	0.380	0.372
SGRP (50/50)	0.357	0.346	0.331
SGRP (20/80)	0.323	0.321	0.301
GRP (20%)	0.304	0.302	0.295

the cylindrical shape of the extrudate is transformed in to a flattened ribbon like structure. The photographs also show that as the shear rate increases from 164 to 1640 s^{-1}, the deformation of the extrudate also increases.

The scanning electron micrographs of the surface of the extrudate at a shear rate of 164 s^{-1} and a temperature of 130°C for different sisal–glass combinations [viz., LDPE, SRP, and SGRP (40/60-sisal–glass)] and GRP are shown in Figures 11a–d, respectively. It is clear from these photographs that the surface irregularity increases as the volume fraction of glass increases. The surface irregularity of glass-rich hybrid composites and GRP is due to the highly rigid nature of the glass fiber compared with sisal fiber.

The extrudate cross sections of LDPE, SRP, SGRP, and GRP with different compositions of sisal and glass at a shear rate of 164 s^{-1} are shown in Figure 12. From these photographs it can be seen that the fiber dispersion is varied according to the composition of the fibers in them. In the case of SRP, crowded sisal fibers are observed on the fracture surface of the extrudate (Fig. 12b). In SGRP (50/50 sisal–glass), both fibers are somewhat uniformly distributed throughout the matrix (Fig. 12d). But agglomerated glass fiber bundles are observed (Fig. 1e). The cross section of the GRP extrudate reveals that the glass fibers are not well oriented in the extrusion direction, as in the case of sisal fibers.

flow behavior index (n')

The influence of composition of fibers and temperature on the flow behavior index (n') is shown in Table IV. Non-Newtonian pseudoplastic fluids have values of n' below unity. Therefore, a high value of n' represents a low pseudoplastic or non-Newtonian nature of the system. The n' values of all systems are less than unity (Table IV), indicating the pseudoplastic nature of the composites. At each temperature, the degree of pseudoplasticity increases from LDPE to SRP, increases further in SGRP with an increase in volume fraction of glass fibers, and is highest for GRP composites. This behavior is evidenced from the decrease in n' values from LDPE to GRP. These observations

support the fact that the presence of fiber restricts molecular mobility. The agglomerated glass fibers at high volume fractions of glass in the polymer melt prevent the easy flow of the composite melt and thereby decreases the n' values. Finally, the results in Table IV show that pseudoplasticity increases with temperature.

CONCLUSIONS

The melt rheological behavior of intimately mixed short sisal–glass hybrid fiber-reinforced LDPE composites was studied as a function of composition of the fibers, shear stress, shear rate, and temperature. The viscosity of the system increased with increase in volume fraction of glass fibers due to the stronger interaction of the PE matrix with glass fibers than with sisal fibers. The hybrid composites exhibited pseudoplastic behavior that can be represented by power law equation. The melt flow studies were carried out in the temperature range 130–150°C, and the activation energy of the system was calculated with the Arrhenius equation. The viscosity of the composite melt decreased with increasing temperature. This change was associated with the molecular motion or easy alignment of fibers in the flow direction due to the availability of greater free volume and weaker intermolecular or fiber–matrix interactions. A comparison was made between the experimental and theoretical viscosity using the additive rule of mixtures. The experimental viscosity values of hybrid composite were in good agreement with the theoretical values except at low volume fractions of glass fibers. Using an arbitrary reference temperature, a superposition method was applicable over the entire region of shear stress and temperatures. Flow curves at various temperatures were superimposable by the application of this method. Fiber breakage analysis was carried out to study the sisal and glass fiber distribution in the extrudates of hybrid composites. The extent of glass fiber breakage was higher than that of sisal fiber. Cross sectional and surface morphology of the extrudates were analyzed by optical and scanning electron microscopy. At high volume fractions of glass fiber in SGRP, the extrudates were extremely melt fractured or highly deformed (from a cylindrical to a ribbon-like shape) because of the comparatively higher rigidity of glass fiber than sisal fiber.

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