Injection-Molded Short Hemp Fiber/Glass Fiber-Reinforced Polypropylene Hybrid Composites—Mechanical, Water Absorption and Thermal Properties

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ABSTRACT: Natural fiber-based thermoplastic composites are generally lower in strength performance compared to thermoset composites. However, they have the advantage of design flexibility and recycling possibilities. Hybridization with small amounts of synthetic fibers makes these natural fiber composites more suitable for technical applications such as automotive interior parts. Hemp fiber is one of the important lignocellulosic bast fiber and has been used as reinforcement for industrial applications. This study focused on the performance of injection-molded short hemp fiber and hemp/glass fiber hybrid polypropylene composites. Results showed that hybridization with glass fiber enhanced the performance properties. A value of 101 MPa for flexural strength and 5.5 GPa for the flexural modulus is achieved from a hybrid composite containing 25 wt % of hemp and 15 wt % of glass. Notched Izod impact strength of the hybrid composites exhibited great enhancement (34%). Analysis of fiber length distribution in the composite and fracture surface was performed to study the fiber breakage and fracture mechanism. Thermal properties and resistance to water absorption properties of the hemp fiber composites were improved by hybridization with glass fibers. Overall studies indicated that the short hemp/glass fiber hybrid polypropylene composites are promising candidates for structural applications where high stiffness and thermal resistance is required. J Appl Polym Sci 103: 2432–2441, 2007

Key words: hemp fiber; biofiber; biocomposites; injection molding; mechanical properties

INTRODUCTION

For the last few years, thermoplastics as well as thermoset-based natural fiber composites (NFCs) have experienced a tremendous growth in the auto industry; the drive being environmentally friendliness, renewability of these fibers, good sound abatement capability, and improved fuel efficiency resulted from the reduced weight of the components.[1–5] These composite materials have received much commercial success in the semistructural as well as structural applications. For example, interior parts such as door trim panels from natural fiber–polypropylene (PP) and exterior parts such as engine and transmission covers from natural fiber–polyester resins are already in use.[6,7] Advantages of thermoplastic NFC over thermoset-based NFC include the greater design freedom, as they are suitable for injection molding and extrusion processing, in addition to the recycling possibilities. However, higher strength requirements are needed for these thermoplastic composite materials to be used in semistructural and structural applications in the auto industry.

Hemp fiber is one of the inexpensive and readily available bast natural fiber and has attracted considerable attention of researchers and auto-parts manufacturers in Europe and North America. It was reported that hemp contains about 61% cellulose (by weight), 24% hemicellulose, 10% lignin, and 3% extractives.[8] Several researchers exploited the reinforcing potential of hemp fibers for developing thermoplastic and thermoset composites using different processing techniques.[9–21] Hemp in the form of nonwoven fiber mat was used as reinforcement for thermoset resins such as soy oil-based resin,[9] unsaturated polyester resin,[10,11] novolac resin,[12] epoxy resin,[13] and acrylic resin[14] and for thermoplastics such as PP[13,15–17] and polystyrene.[18] In all these studies, the processing of the composites was mainly by compression molding, resin transfer molding, vacuum impregnation or film stacking followed by press molding or filament winding. Very little literature is available on the use of chopped or short hemp fibers as reinforcement.[16–20] It was reported by Wambua et al.[16] that 40 wt % of hemp fiber-reinforced PP prepared by film stacking followed by compression molding showed better strength and stiffness compared to the counter parts

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with fibers such as kenaf, coir, sisal, and jute. Mohanty et al.[19] used chopped industrial hemp fiber to reinforce biopolymers such as cellulose acetate and found that composites prepared by extrusion followed by injection molding exhibited high flexural strength and stiffness. These authors also reported the use of chopped hemp fiber as reinforcements in soy protein-based bio-plastics.[20]

Development of thermoplastic composites using natural fibers in combination with a small amount of moisture-resistant and corrosion-resistant synthetic fibers is one technique to enhance the strength and stiffness as well as moisture resistance of the resulted hybrid fiber composites. Hybrid fiber composite materials can compose of a combination of more than one type of fibers in the same matrix. Though in principle several fibers can be incorporated in to the hybrid system, a combination of only two types of fibers would be the most beneficial. By hybridization, it is possible to achieve a balance between performance properties and cost of the composites, which would not be obtained with a single kind of reinforcement. In other words, by careful selection of reinforcements and the processing techniques, it is possible to engineer the material to better suit for various practical requirements with economic benefits. Researchers have reported that incorporation of glass fibers with natural fibers like wood fibers, sisal, oil palm fibers, pineapple leaf fibers, and bamboo fibers in a thermoset as well as thermoplastic matrix resulted in improved performance.[21–27]

In this study, we tried to develop high performance PP composites, using short hemp fibers and glass fibers as reinforcement, to be used in semistructural or structural applications such as automotive interior parts. Composites were fabricated by melt processing followed by injection molding. Mechanical properties such as tensile, flexural, and impact strength of the composites were studied as a function of relative fraction of the fibers. Analysis of hemp and glass fiber length in the composites was performed to investigate the effect of fiber breakage on the performance of the composites. Long-term water absorption of the composites was studied by immersing the samples at room temperature for 5 months. Thermal properties were studied to investigate the thermal stability of the composites.

EXPERIMENTAL

Material

Polypropylene PP 6331 with a density of 0.91 g/cc and melt flow index of 12 g/10 min obtained from Himont was used as the polymer matrix for hybrid composites. Short hemp fibers with an average fiber length of 10–12 mm used in the study was obtained from Hempline, Ontario. E-glass fibers with 10–12 mm length were used together with hemp fibers for making hybrid composites and were obtained from Plastic World, Canada. Compatibilizer used in the preparation of composites was Orevac-CA 100, which is a maleated polypropylene supplied by Arkema, Canada.

Processing

Formulation of the composites prepared for this study is given in Table I. Total weight percentage of the fibers in the composites was fixed at 40. The ingredients were melt-blended using a Brabender Plasticorder at 170°C and at 60 rpm for 5 min. The melt-blended materials were allowed to cool to room temperature and then granulated using C.W. Granulator. Granulates prepared were then injection-molded into standard ASTM test specimens for tensile, flexural, and impact strength determination. Injection molding conditions used were: injection temperature 205°C, injection time 8 s, cooling time 25 s, mold opening time 25 s.

Testing

Measurement of fiber length

Short glass fibers were isolated from the composite materials by pyrolysis in a muffle furnace for about 3 h at 600°C. An ash of fibrous material was left and some fibers were extracted from the sample ash and dispersed in acetone and placed on a glass plate. The glass plate was then placed on the observation stage of a calibrated graticule reflectance light microscope. The magnified fiber images were transmitted to paper sheet, with the calibrated ruler. A digital photo of the images was taken with a ruler in the frame for calibration. The images were loaded into a software package, an image processing analysis program called UTHSCA Image tool down loaded from http://ddsdx.uthsca.edu/dig/itdesc.html., and analyzed. The length of 400–500 fibers from each sample was measured and recorded.

Hemp fibers were extracted from the composites by dissolving the matrix in boiling xylene. The fibers obtained were suspended in acetone and placed on a glass plate. Length of the fibers was found by a similar procedure described for glass fibers.

TABLE I
Formulation of Composites

Designation of samples	PP (wt %)	Glass fiber (wt %)	Hemp fiber (wt %)	Compatibilizer (wt %)
A	55	0	40	5
B	55	5	35	5
C	55	10	30	5
D	55	15	25	5

Mechanical properties

Tensile and flexural properties were measured on a standard computerized testing machine (Sintech Model 20). Tensile properties were measured in accordance with the ASTM D-638 procedure at a cross head speed of 12.5 mm/min. Flexural properties were measured in accordance with the procedure in ASTM D790 using the aforementioned machine in the three-point bending mode at a cross head speed of 12.5 mm/min and with a span of 50.8 mm. Izod impact tests followed ASTM D 256 procedure using a pendulum type Impact machine. Tests were carried out on at least six specimens to obtain a reliable average and standard deviations. All the mechanical properties were performed at room temperature.

Water absorption

Water absorption studies were performed following the ASTM D570-98 method. Six injection-molded impact specimens of every sample were submerged in distilled water at room temperature. The samples were taken out periodically and weighed immediately, after wiping out the water on the surface of the sample, using a precise four-digit balance to find out the content of water absorbed. All the samples were dried until constant weight with the four-digit balance, previous to immersing in water. The percentage of water uptake was calculated by the following equation

$$\text{Water absorption } (\%) = \frac{W_t - W_0}{W_0} \times 100$$

where W_t is the weight of the sample at time t, and W_0 is the initial weight of the sample (at $t = 0$).

To study the effect of water absorption on the mechanical properties, tensile tests were performed on the wet samples after the samples reached the saturation limit.

Heat deflection temperature

Heat deflection temperature (HDT) test can be seen as a type of creep where temperature is being continually increased and is widely used in automotive applications. It is the temperature at which the material deflects by 0.25 mm at an applied force, where the specimen is placed in a three-point bending mode. HDT of PP, hemp fiber, and hemp/glass/PP hybrid composites was measured according to ASTM D 648. The test was conducted on two samples of each specimen with a load of 1.80 MPa.

Thermogravimetric analysis

Thermogravimetric analysis was performed to understand the degradation characteristics of the hemp/PP and hemp/glass/PP hybrid composites. Thermal degradation characteristics of composites were determined using a TGA Q 500 series thermogravimetric analyzer (TA Instruments, USA) with a heating rate of 10°C/min in a nitrogen environment.

Scanning electron microscopy

Fractographic studies with scanning electron microscopy (SEM) were carried out in detail on the tensile fracture surfaces of the hemp fiber and hemp/glass/PP hybrid composites using scanning electron microscope (model Hitachi S-2500, Tokyo, Japan). Prior to SEM observations, all fractured surfaces of the tensile specimens were sputter-coated with gold.

RESULTS AND DISCUSSION

Fiber length

Fiber breakage takes place during the processing of short fiber-reinforced composite materials. Length of fibers in the composite is one of the major factors influencing the ultimate properties of the hybrid composite materials in addition to fiber content, fiber–matrix interaction, extent of intermingling of different types of fibers, orientation of the fibers and hybrid design, etc. Fiber length of individual fibers in a hybrid composite depends on the fiber breakage, which in turn depends on the fiber–fiber interaction. Since the ratio of the two types of fibers in the hybrid composites varies, the extent of interaction between these fibers also changes leading to a difference in their fiber lengths.

The effect of hybridization of hemp fiber composites on the mean hemp and glass fiber lengths in the composites is presented in Figure 1, where the total hemp and glass weight fraction is fixed at 40 wt %. It

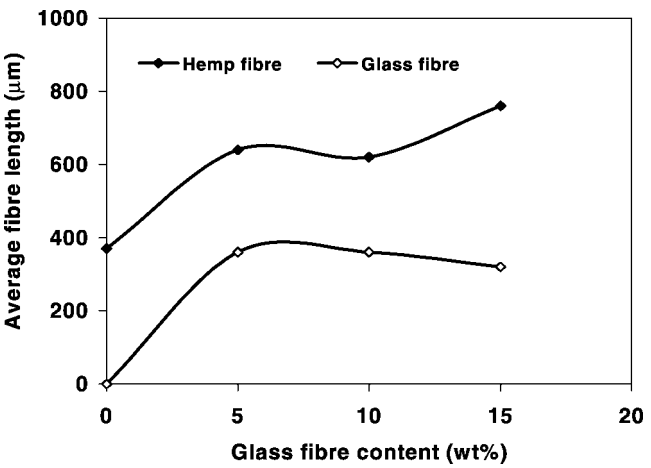

Figure 1 Number–average hemp and glass fiber length in hemp/PP and hemp/glass/PP hybrid composites.

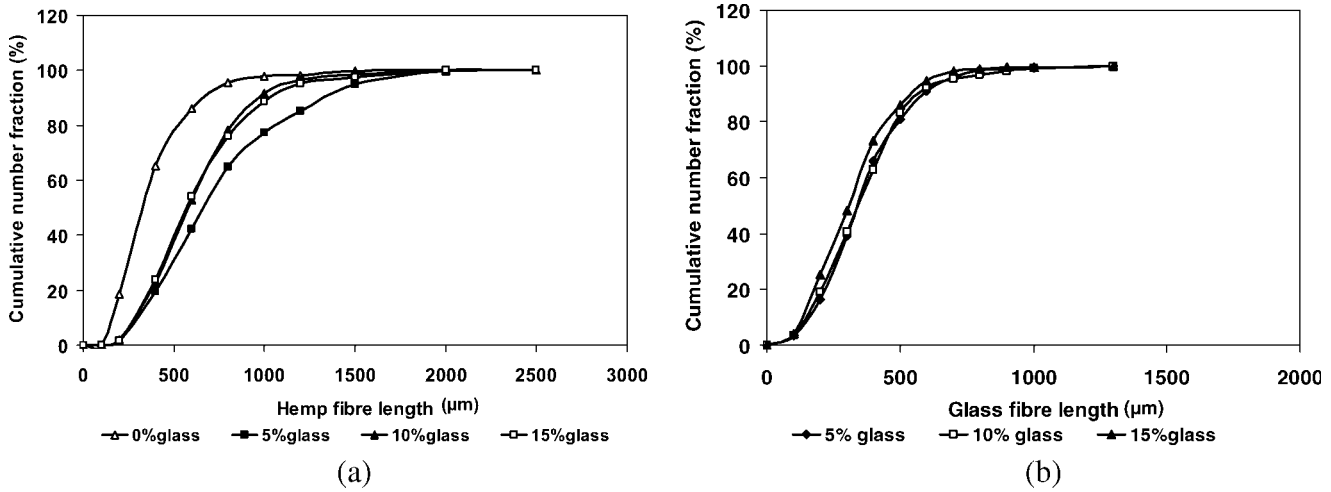

Figure 2 Hemp fiber (a) and glass fiber (b) length distribution in hemp/PP and hemp/glass/PP hybrid composites.

is of interest to note that the mean hemp fiber lengths increase and glass fiber lengths decrease with the increase of relative glass fiber content and the decrease of relative hemp fiber content. This indicates that interaction between glass fiber and hemp fiber resulted in more damage to the brittle glass fibers than the hemp fibers, while the same fiber interaction leads to less damage to the less brittle hemp fibers than the hemp–hemp interaction.

The hemp and glass fiber length distributions in the composites are shown in Figure 2(a,b). The hemp fiber length distributions shift toward the right side as a result of incorporation of 5 wt % of glass fibers [Fig. 2(a)]. This indicates that interaction between the brittle glass fiber and less brittle hemp fiber in the composites results in an increased damage to glass fiber, while decreasing the natural fiber length damage. Further increase in the glass fiber content shifts the hemp fiber distribution curve toward left side (except it is not clear between 10 and 15 wt %). More over, length distribution of glass fibers slightly shifts toward the left side as the glass fiber content increases [Fig. 2(b)]. This leads to the fact that, beyond a particular limit of glass fiber content, the raise in the interaction between the fibers increases breakage of glass fiber as well as natural fiber. Further to this, Figure 2 also shows that most of the glass fibers have a length less than hemp fibers, which may lead to glass fiber pull out instead of fiber fracture during loading of the composite. This is explained later in the tensile fracture studies.

Tensile stress–strain curves

Tensile stress–strain curves of PP, hemp fiber/PP, and hemp/glass/PP hybrid composites are shown in Figure 3. PP shows a ductile fracture where as both hemp/PP and hemp/glass/PP composites exhibit brittle fracture and show linear deformation at lower strain, where the matrix and fibers behave linearly and nonlinear deformation at higher strain, which continues until the complete failure of the composite. The nonlinear deformation behavior in the composites represents the (i) microcracks initiation at fiber end matrix interphase that propagates along the fiber lengths, (ii) plastic deformation of the matrix, and (iii) microcrack opening in the matrix and the slow crack propagation through the deformed matrix. At the end, catastrophic crack propagation takes place through the matrix pulling out the fibers from the matrix. The modulus and strength of PP become higher with the incorporation of fibrous fillers as anticipated. The composite strength increases as the glass fiber content increases and shows a maximum at 15% glass fiber content, which is due to higher strength of glass fiber compared to hemp fiber. Also, the failure strain

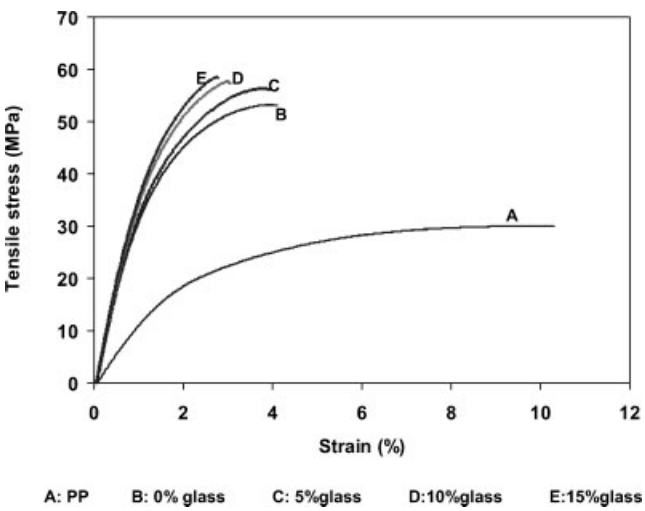

Figure 3 Tensile stress strain curves of PP, hemp/PP, and hemp/glass/PP composites.

for the hybrid composites decreases with increasing glass fiber content and may be attributed to the brittle nature of glass fiber compared to hemp fiber.

Tensile properties

Variation of tensile strength with glass fiber content in hemp/glass fiber hybrid composite is shown in Figure 4. Total fiber content of the composite is maintained at 40 wt % and the glass fiber content varied from 0 to 15 wt %. All the composites contain 5 wt % compatibilizer to improve the interfacial adhesion between the fiber and the matrix. Tensile strength of PP used is 30.1 MPa and reinforcement of the matrix with 40 wt % short hemp fiber shows a tensile strength of 52.5 MPa. Further increase in strength values are observed with the incorporation of glass fibers. Incorporation of 15 wt % glass fiber content increased the tensile strength by 13%. The increase in the strength of NFCs as a result of hybridization is expected as the glass fiber is stronger and stiffer than natural fiber and is reported by other researchers.[21,22,24–27] Kalaprasad et al.[22] reported that hybridization of sisal with relatively small volume fraction of glass fiber increased the tensile strength of oriented sisal polyethylene composites by 80%. Sixty six percent enhancement in tensile strength was reported by Mishra et al.,[27] when pineapple leaf-reinforced polyester composites hybridized with 8.6 wt % woven glass mat using press molding. Comparatively, lower improvement in the hemp/glass fiber PP composites may be attributed to the processing technique and the glass fiber form used. Thwe and Liao[24] reported that addition of 20 wt % of short glass fiber to short bamboo fiber-reinforced PP composites prepared by melt mixing followed by compression molding increased the tensile strength by 7% and tensile modulus by 12.5%, respectively. Our previous studies also showed that

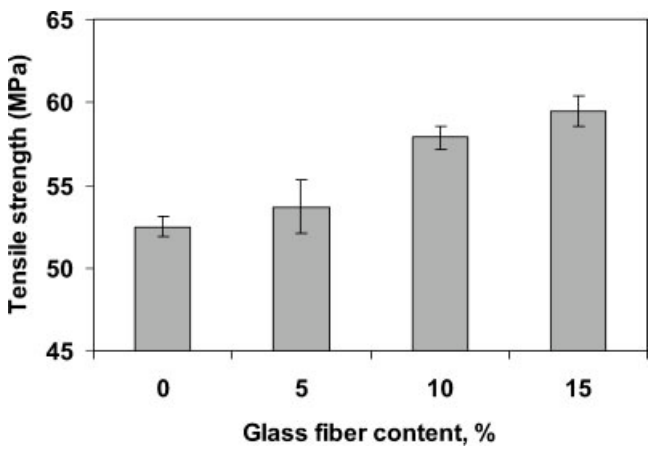

Figure 4 Effect of glass fiber content on the tensile strength of hemp/glass fiber hybrid polypropylene composites.

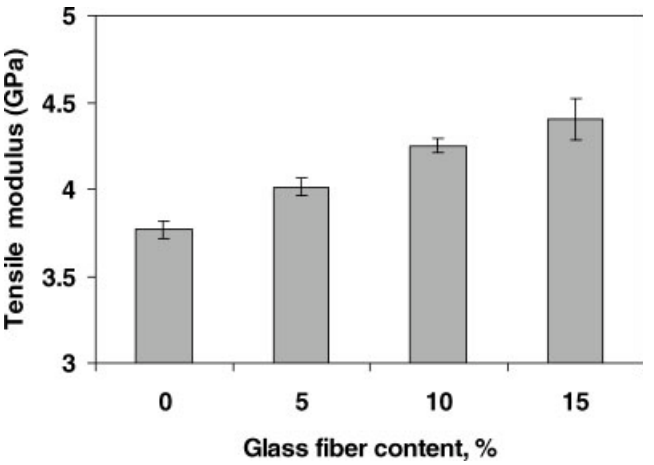

Figure 5 Effect of glass fiber content on the tensile modulus of hemp/glass fiber hybrid polypropylene composites.

strength properties of glass fiber composites prepared by melt mixing followed by injection molding was not higher than that of the NFCs prepared by the same processing method.[17] This indicates that effect of hybridization cannot be exploited completely unless the glass fiber breakage is minimized by modification in the processing techniques.

The hybrid effect of short glass fiber and hemp fiber on the tensile modulus of hemp/glass–PP composite is shown in Figure 5. Tensile modulus of PP is 1.1 GPa and is increased to 3.8 GPa by the reinforcement of 40 wt % hemp fiber. It is observed that tensile modulus of hemp fiber PP composite showed a steady increase with an increase in the glass fiber content, similar to that of tensile strength. Increase of glass fiber content from 5 to 15 wt % increased the tensile modulus by 6–17%.

Tensile fracture studies

Figure 6(a,b) represent the SEM micrographs of the tensile fracture surfaces of a hemp fiber (40 wt %) and hybrid hemp/glass/PP composite with 15 wt % glass fiber at two different magnifications. The brittle fracture of the matrix can be clearly seen in both the composites (Fig. 6). Dispersion of the hemp fibers in the PP matrix seems to be good. The strength of the composite is dependant on the crack initiation characteristics and its propagation through the matrix. This depends on the shape and orientation of the reinforcements in the matrix. The short fiber fractions create more fiber ends, which lead to stress concentrating regions where the cracks can easily develop during the loading of the composites. In hybrid composites, short hemp and glass fibers are intimately mixed in the matrix [Fig. 6(b)] and can be easily distinguished by their different diameter. Figure 6(b) shows that glass fibers exhibited a large extent of pull-outs (see the pulled out fibers and the

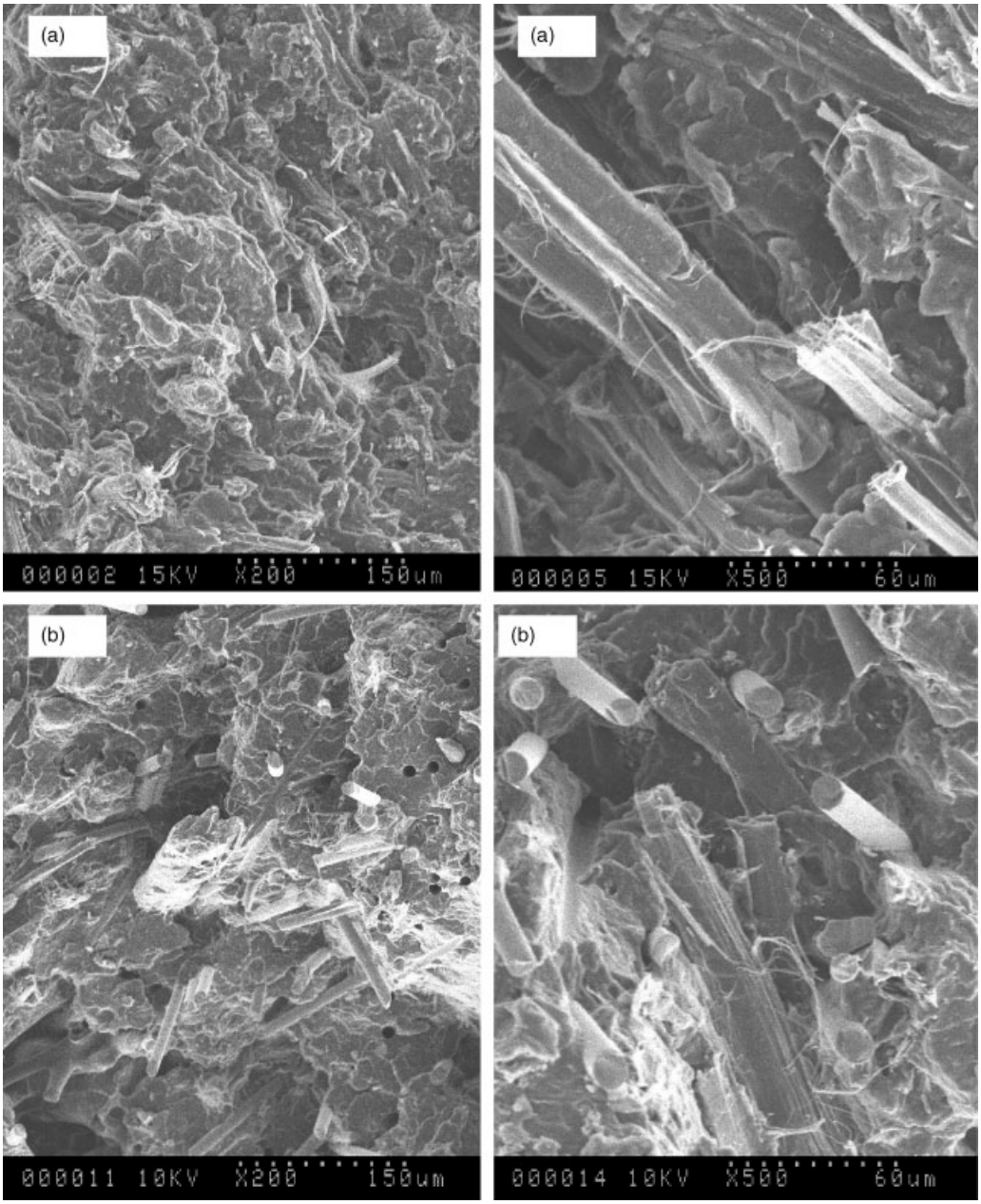

Figure 6 SEM micrographs of tensile fracture surfaces of a hemp (a: 40 wt %) and hybrid hemp/glass/PP composite (b: hemp/glass: 25 wt %/15 wt %) under different magnifications (×200 and ×500).

pull-out holes) in the hybrid composites compared to hemp fiber. This is because most of the glass fibers are shorter than the hemp fiber and may be less than their critical fiber lengths. In addition to fiber pull-out, fiber breakage (mainly natural fiber), and fracture mechanisms like matrix cracking and fiber–matrix debonding are also clear from the Figure 6.

Flexural properties

Flexural strength of the PP is 44.2 MPa and the strength improved significantly by the addition of 40% hemp fiber. The percentage improvement in flexural strength, resulting from the reinforcement of the matrix by hemp fiber, is 108%. The effect of glass fiber content on the flexural strength and modulus of hemp/glass hybrid PP composite is shown in Figures 7 and 8. Hybrid composites are found to be stronger and stiffer than unhybridized hemp fiber PP composite. Increasing the glass fiber content from 0 to 15 wt %, increased the flexural strength from 97.5 to 101 MPa, and modulus from 4.5 to 5.4 GPa, respectively. Though in three-point bending tests, the failure is due to the bending and shear failure, the improvement in flexural strength and modulus is consistent with the results of tensile strength and modulus.

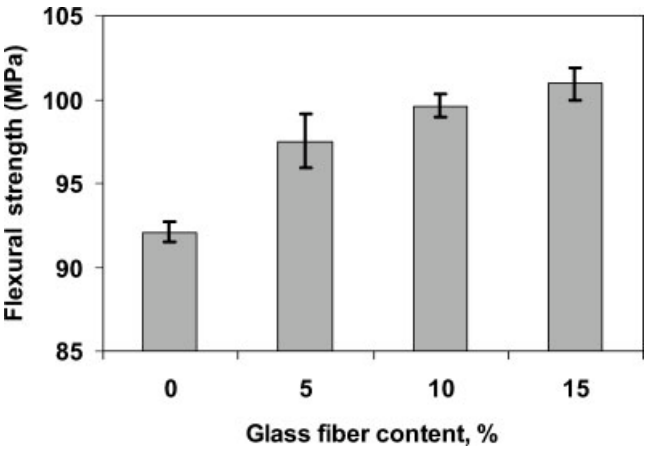

Figure 7 Effect of glass fiber content on the flexural strength of hemp/glass fiber hybrid polypropylene composites.

To have a comparison, commercially available 40% glass fiber filled PP pellets were injection-molded and the flexural and tensile strengths were compared. Tensile strength of 40% long glass fiber-filled PP is about 101 MPa, which is not attained by the natural fiber/glass fiber hybrid composites; the value of flexural strength is in the same range (101 MPa), which is 164 for 40% glass fiber-filled PP. However, bending stiffness values of short hemp/glass hybrid PP composites (5.5 GPa) are more or less similar to that of glass fiber (6 GPa) PP composites. It would be possible to prepare high strength materials from short natural fiber hybrid composites with proper selection of fibers and modified processing techniques.

Impact strength

Impact strength of a composite is a measure of the ability of the material to resist the fracture failure under stress applied at high speed and is directly related to the toughness of the material. The fibers play an important role in the impact resistance of fiber-reinforced composites as they interact with the crack formation and act as stress-transferring medium. The virgin PP shows very low impact strength (22 J/m). Addition of 40 wt % of hemp fiber increased the impact strength by 86%. Further increase in the impact strength is expected by the addition of glass fibers. Variation of Izod impact strength of hemp/glass hybrid PP composites with glass fiber content is shown in Figure 9. The impact strength of 40 wt % hemp fiber-reinforced PP composite is 41 J/m. With increase in glass fiber content from 0 to 15 wt %, impact strength of the composite increased by 35% and this may be attributed to the improved resistance offered by the glass fibers in the composites.

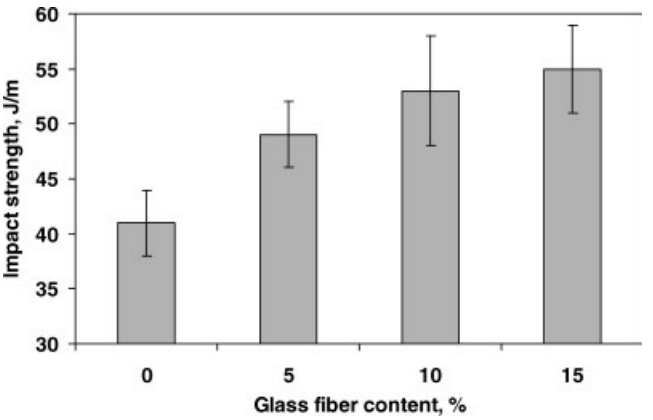

Figure 9 Effect of glass fiber content on the impact strength of hemp/glass fiber hybrid polypropylene composites.

Water absorption

Water absorption curves of PP and its composites (A–D) at room temperature are shown in Figure 10, where percentage of water absorbed is plotted against the square root of the soaking time. Each data point repre-

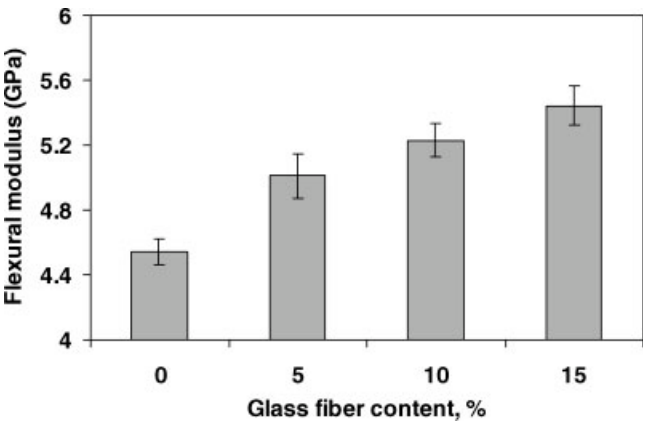

Figure 8 Effect of glass fiber content on the flexural modulus of hemp/glass fiber hybrid polypropylene composites.

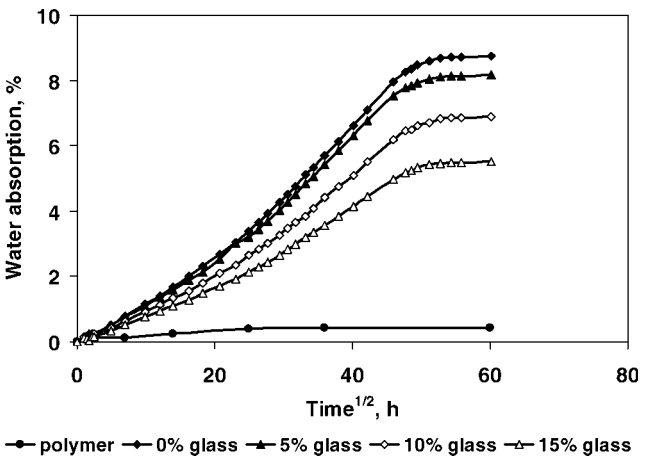

Figure 10 Water absorption curves of polypropylene and hemp/glass fiber hybrid composites.

TABLE II
Equilibrium Moisture Content of Polypropylene and Composites A–D at Room Temperature

Sample no.	Equilibrium moisture content (%)
PP	0.40
A	8.73
B	8.14
C	6.87
D	5.49

sents the average of six samples. In all the composites, percentage moisture absorption, M_t, increases steadily with $t^{1/2}$ in the initial stage and then tends to level-off following the saturation point. Equilibrium moisture content of the polymer and composites is given in Table II. Water absorption of PP is 0.40% and is negligible compared to the water absorption of 40% hemp fiber-reinforced PP (8.73%). Incorporation of glass fiber in the hemp fiber PP composites decreased the equilibrium moisture content significantly. This is attributed to the hydrophilic character of natural fibers, since the matrix and glass fibers had little effect on the amount of water absorbed. A high amount of natural fiber in the composite shows a high uptake of water. Moisture absorption further decreases with the increase of glass fiber content and is attributed to the removal of hydrophilic natural fiber with the glass fiber in the composite.

Effect of water absorption on the tensile properties

To study the effect of water absorption on the tensile properties, tensile tests were performed on wet samples after the saturation level (3624 h) is reached. Strength and stiffness of PP and the composites A–D before and after aging is given in Table III along with the percentage retention. A significant reduction in strength and stiffness is observed for all composites and is because of the changes occurred to the fibers, mainly natural fibers, and the interface between the matrix and fiber, as the effect of water absorption on thermoplastic matrix is only secondary. Swelling of natural fiber as a result of prolonged exposure to water leads to the reduction in the stiffness of the fibers and also results in the development of shear stress at the interface that causes debonding of the fibers from the matrix. The loss in strength and modulus values of the hemp fiber composites are believed to be the inability of the swelled natural fiber to carry the stress transferred from the matrix through the disrupted interface as a result of water absorption. Despite the reduction in the equilibrium moisture content in hybrid composites, glass fibers did not alter the degradation of the hemp fiber composites. This may be due to the degradation of natural fiber coupled with the stress corrosion of glass fiber even in the absence of stress (it has been reported that stress corrosion of glass fibers results in the strength degradation[28]) and the dissimilar stress developed at the interface as a result of prolonged period (3624 h) of immersion of composites in water. This is contrary to the earlier studies reported where incorporation of glass fiber decreases the degradation of NFCs.[24,27] The degradation in mechanical properties depends on the period of immersion and hence the resultant changes in the properties also differ from the earlier reports. Percentage retention in modulus is increased with the glass fiber content, despite the decrease in the retention in tensile strength. This is because, modulus is the slope of the initial stress–strain plot, where the interfacial strength does not play an important role as in the case of tensile strength.

Heat deflection temperature

Heat deflection temperature (HDT) is an essential piece of information for the product design and is a measure of the upper boundary for the dimensional stability and stability of the material under a particular load and temperature. In other words, HDT is the ability of the material to retain its stiffness at elevated temperatures. High HDT value is desirable to attain better performance during high temperature service conditions. HDT of neat PP and its composites are shown in Figure 11. The HDT value of neat PP was 53°C and was increased twice by the incorporation of hemp fibers. HDT usually increases with incorporation of fillers. Further improvement was observed as a result of hybridization and the maximum value of HDT is exhibited by the hybrid composite with 15 wt %

TABLE III
Tensile Strength and Modulus of Polypropylene and Composites A–D Before and After Aging

Sample designation	Tensile strength (MPa)			Tensile modulus (GPa)		
	Original	Wet sample	Retention (%)	Original	Wet sample	Retention (%)
PP	30.1 ± 0.1	29.9 ± 0.5	99	1.10 ± 0.03	0.89 ± 0.03	81
A	52.5 ± 0.6	34 ± 0.6	65	3.77 ± 0.05	1.64 ± 0.04	44
B	53.7 ± 1.6	34.8 ± 1.6	65	4.07 ± 0.05	1.74 ± 0.03	43
C	57.9 ± 0.7	34.9 ± 0.9	60	4.25 ± 0.04	2.04 ± 0.05	48
D	59.5 ± 0.9	35.5 ± 0.5	65	4.4 ± 0.01	2.32 ± 0.12	53

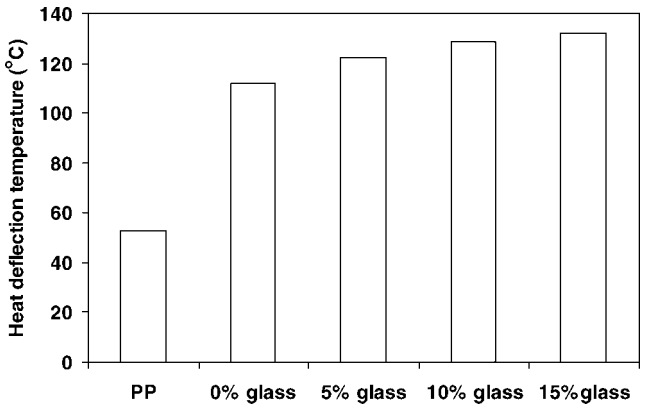

Figure 11 Heat deflection temperature of PP, hemp/PP and hemp/glass/PP composites.

of glass fibers (132°C). HDT of the composites is increased with the stiffness of the composites. Increased stiffness indicates a reduction in the free volume present in the system, which enhances the dimensional stability of the composites and hence the HDT values.

Thermogravimetric Analysis

Thermal stability of hemp/PP and hemp/glass/PP composites was investigated with thermogravimetric analysis. Both hemp and hybrid fiber composites showed a two-step degradation (Fig. 12). The degradation starts around 250–400°C and is due to the decomposition of the cellulosic and hemicellulosic components of the natural fiber in the composites. The onset of degradation occurs at around 250–300°C. Five percentage of weight loss was observed at 279°C for hemp fiber composites and for hybrid composites this weight loss occurred at 281, 291, and 309°C

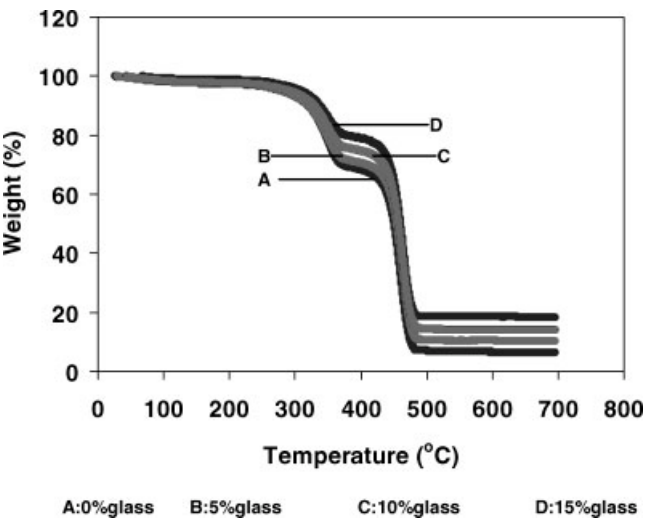

Figure 12 Thermograms of hemp/PP and hemp/glass/PP composites.

TABLE IV
Thermal Characteristics of Hemp/PP and Hemp/Glass/PP Hybrid Composites

Sample designation	T_{25} (°C)	T_{50} (°C)	T_{75} (°C)	Residue remaining after 600°C (%)
A	354	450	464	6.6
B	360	455	469	10.5
C	395	457	471	14.2
D	433	460	474	18.5

respectively, for composites with 5, 10, and 15% glass fiber content. Temperatures corresponding to a weight loss of 25, 50, and 75% respectively, are summarized in Table IV along with the residue remaining after 600°C. The values in the Table IV indicate that incorporation of glass fiber in the hemp fiber composite shifts the temperature of degradation to a higher value (T_{25} shifts from 354 to 432°C; T_{50} shifts from 450 to 460°C; and T_{75} shifts from 464 to 474°C) indicating an increased thermal stability of the hybrid composites. The residue remaining after 600°C is increased with glass fiber content and is because the residue is mainly coming from the lignin component of hemp fibers in the case of hemp/PP composite, whereas glass fiber is also responsible in the case of hybrid composites.

CONCLUSIONS

This article reports the mechanical, water absorption, and thermal properties of short hemp/glass fiber-reinforced hybrid PP composites prepared by injection molding. Incorporation of glass fibers is found to improve the tensile, flexural, and impact properties of short hemp fiber composites. The strength properties are increased with the increase of glass fiber content and the hybrid composite with 15 wt % of short glass fiber content exhibited a flexural strength of 101 MPa and a modulus of 5.5 GPa. Fiber length distribution in the composites demonstrated that glass fiber undergoes extensive break down compared to natural fibers and incorporation of glass fiber reduced the breakage of natural fiber in the hybrid composites. Bending stiffness of the hybrid composites is found to be comparable with that of the commercially available 40% long glass fiber-filled PP composites. It is also observed that water absorption tendency of the hemp fiber composites decreased by hybridization with glass fibers. However, prolonged immersion of the samples in water decreased the strength and modulus of all the composites. HDT of PP is increased considerably by the incorporation of hemp fibers and hybridization with glass fiber further increased the HDT. Thermogravimetric studies indicated that addition of glass fibers improved the thermal stability of

hemp fiber PP. All these results indicated that injection-molded short hemp/glass/PP hybrid composites resulted in enhanced performance properties and may find technical applications such as automotive interior parts. However, to maximize the effect of hybridization, processing techniques has to be modified to reduce the glass fiber breakage.

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