Using Hop Bines as Reinforcements for Lightweight Polypropylene Composites

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ABSTRACT: Whole hop bines (HBs), the peeled outer bark (OB) of HBs, and fibers chemically extracted from hop bark (HFs) were used as reinforcements to make lightweight composites with polypropylene (PP) webs or fibers as the matrix materials. Using discarded HBs for composites not only increases the value of hop crops but also provides a green, sustainable, and biodegradable material for the composite industry. Lightweight composites are preferred, especially for automotive applications because of the potential energy savings. In this research, the effects of the processing parameters on the properties of PP composites reinforced with HBs were studied. The composites reinforced with OB without any chemical treatment showed better properties than the composites reinforced with HFs or HBs. Compared with jute–PP composites of the same density (0.47 g/cm^3), composites reinforced with OB had 43% higher flexural strength, 46% higher impact resistance, 56% higher Young's modulus, similar modulus of elasticity, 33% lower tensile strength, and better sound-absorption properties. OB–PP composites with optimized properties have the potential to be used in industrial applications such as support layers in automotive interiors, ceiling tiles, and office panels. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 116: 2366–2373, 2010

Key words: biofibers; biopolymers; composites; mechanical properties; poly(propylene) (PP)

INTRODUCTION

This article reports the properties of lightweight polypropylene (PP) composites reinforced with hop bines (HBs), outer bark (OB), and fibers chemically extracted from hop bark (HFs). HBs, which form a major portion of the plant, are discarded after the farmers harvest the hop flowers, which are primarily used as flavoring and stability agents in beer production. The annual production of HBs in the United States was estimated to be approximately 652.5 million pounds in 2006 (based on information provided by the Washington Hop Commission, which reported that there usually are 29,000 acres of HBs grown annually in the United States, with 1500 bines per acre and 15 lbs per bine). The advantages of using wasted bines in composites are as follows: they are annually renewable, inexpensive, and environmentally friendly. The use of bines can help to increase the potential value of hop crops and may also increase the profit for the farmers.

Compared with conventional compact composites, the lightweight composites developed in this research contain voids that are retained on purpose to reduce the density of the composites. The densities of lightweight composites are lower than the combined densities of the materials used to build the composites. Because of the presence of voids, the properties of lightweight composites are inferior to those of conventional compact composites. However, the use of lightweight composites has the potential to save energy. For example, if lightweight composites are used as interior materials in automobiles or aircraft, they can help to improve the fuel efficiency. The lightweight composites made in this research are intended to be used as support layers in automotive interiors. Support layers, such as headliner composites, door panels, side walls, and cargo liners, should have excellent flexural strength to resist deformation during the lifetime of the automobile. These lightweight composites could also be used in the construction industry in products such as ceiling tiles and office panels.

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Traditionally, support layers for automobiles have been developed from glass-fiber-reinforced composites.[1–3] However, in the last 15 years, most major automobile manufacturers have preferred to use lightweight composites reinforced with natural fibers, such as jute, hemp, and flax, as replacements for fiber-glass-reinforced composites. The advantages of using natural fibers over glass fibers are the low cost, low weight, and biodegradability of natural fibers. However, the production and availability of these natural fibers may decrease in the future because of the increasing global population, which requires more land to grow food crops. The prices of these natural fibers are also high in comparison with some biomass materials.

Agricultural byproducts are inexpensive, abundant, renewable, and sustainable sources for developing composites in comparison with glass fibers and common natural cellulose fibers. Reports are available on developing conventional compact composites and medium-density particle boards (with densities ranging from 0.70 to 0.90 g/cm^3) reinforced by biomass such as wheat straw, rice straw, corn stalk, cotton stalk, and switchgrass.[4–24] In most of the reports, the biomass materials were made into particles or short fibers by mechanical and/or chemical methods with traditional composite-forming processes such as extrusion, injection, or compression molding. Coupling agents were also reported to be used to enhance the adhesion between the short reinforcements and matrix materials.

In this research, a recently developed method[25,26] was used to fabricate lightweight composites from HBs in their native form and PP webs as matrix materials. The biomass materials were cut or peeled into long lengths (up to 9 cm) and were directly used in the composites without any chemical treatment. Eliminating the chemical treatment will not only reduce costs but also make the process environmentally friendly. In addition, long biomass materials with large aspect ratios can provide composites with better properties. To the best of our knowledge, HBs have not been used to develop composites.

The objectives of this research were to use HBs to make lightweight composites through a simple and cost-effective method and to determine the relationship between the properties of the composites and the manufacturing parameters. The mechanical and acoustical properties of lightweight composites were studied and compared with those of jute-fiber-reinforced composites with the same density.

EXPERIMENTAL

Materials

HBs were obtained from a research field at Washington State University. The bines had considerable variations in diameter along their length and also had thin branches. Large, mature bines (7–16 mm in diameter) were too thick to be used in the composites, so the OB was peeled from these bines and used as a reinforcement. The effects of various widths and lengths of the OB on the composite properties were investigated. The bark peeled from the mature bines was cut to a length of 5 cm and to widths of 2, 4, and 6 mm. It was too difficult to peel bark of a uniform length with widths less than 2 mm, so the smallest width of the bark used was 2 mm. OB with widths greater than 6 mm would have resulted in inferior mechanical properties of the composites because of the large aspect ratio, so the largest width of OB used was 6 mm. Then, the OB width was fixed at 2 mm, which was determined to be the optimum condition, and the OB lengths were 5, 7, and 9 cm.

In addition, bines with an average diameter of 2.6 mm (standard deviation = 0.3) and branches with an average diameter of 1.3 mm and a standard deviation of 0.3 were collected. The 2.6-mm-diameter bines were from the middle and top of the plants and are called regular bines in this article. The 1.3-mm branches were more common at the top of hop plants and are called thin branches. The length of both the regular bines and thin branches was cut to 5 cm, and they were used for the study. Our previous research on wheat straw and switchgrass, which have shapes and bulk densities similar to those of HBs, has shown that 5 cm is the optimum size of the reinforcement materials for achieving the best mechanical properties. Therefore, the length of the HBs and thin branches was also fixed at 5 cm.

The peeled bark from the mature bines was used to extract fibers according to a method previously reported.[27,28] In brief, the peeled bark was boiled with 1*N* sodium hydroxide for 30 min with about 20% (w/w) material in the alkali solution. Fibers obtained after the alkali treatment were washed several times in warm water and finally in a diluted acetic acid solution [10% (w/w)] and dried under ambient conditions.

The effects of the HF length on the flexural, impact-resistance, tensile, and sound-absorption properties were studied. The mature bines were cut to 5, 10, and 20 cm to make fibers. After the chemical treatment and mechanical carding, the average fiber lengths were 4.3, 7.9, and 14.6 cm (the standard deviations were 0.8, 2.5, and 4.3, respectively). The properties of the hop fibers versus jute and cotton fibers are shown in Table I.

The samples from the composites reinforced with regular HBs, OB (7.0 cm long and 2.0 mm wide), and HFs (7.9 cm long) were used to study the sound-absorption properties and compared with jute–PP lightweight composites of the same density

TABLE I
Properties of the Natural Cellulose Fibers Chemically Extracted from Hop Bark Versus Cotton and Jute

	Fiber properties					
	Denier	Length (cm)	Strength (g/denier)	Elongation (%)	Modulus (g/denier)	Moisture regain (%)
Hop bark fibers	48 ± 19	3–20	4.1 ± 1.9	3.3 ± 1.2	161 ± 57	8.3 ± 0.4
Cotton	3–8	1.5–5.6	2.7–3.5	6.0–9.0	55–90	7.5–8.0
Jute	13–27	15–36	3.2–3.5	0.9–1.2	190–200	13.80

The data for the cotton are from Batra;[29] the data for the jute are from Reddy and Yang.[28]

and thickness, as reported by Huda and Yang.[25,26] The mechanical properties of the composites from HBs, OB, and HFs were also compared with those of jute–PP composites.

The bulk densities of the reinforcements were tested with the glass-bead-displacement method.[30] The bulk densities of the regular HBs, small HBs, OB, and HFs were found to be 0.65, 0.69, 0.58, and 1.03 g/cm^3, respectively. The tensile strengths of the regular HBs, small HBs, and OB were 31.5 ± 8.8, 23.2 ± 5.5, and 84.4 ± 11.0 MPa, respectively. Young's modulus of the regular HBs, small HBs, and OB were 3.2 ± 0.4, 2.6 ± 0.3, and 8.6 ± 0.9 GPa, respectively.

Jute fibers, supplied by Flaxcraft, Inc. (Cresskill, NJ), had a length of 5 cm, a fineness of 26 denier, a strength of 338 ± 6.3 MPa, and modulus of 9.4 ± 0.2 GPa. The bulk density of the jute fibers was 1.02 g/cm^3.

Nonwoven PP webs were purchased from Spunfab, Ltd. (Cuyahoga Falls, OH). The density of PP was 0.90 g/m^3, and the melting temperature was 162°C. The weight/area value of the PP webs was 23.7 g/m^2. The melt flow index of PP was 38 g/10 min at 230°C. PP fibers were supplied by Drake Extrusion, Ltd. The PP fibers had a fineness of 15 denier, a length of 84 mm, a width of 45 μm, a tensile strength of 4.0 g/denier, a melting temperature of 162°C, a melt flow index of 20 g/10 min at 230°C, and a crystallinity value of 50%.

Composite fabrication

The weight/area value of all the composites was set to 1500 g/m^2 with an area of 25.4 cm × 30.5 cm. Metal spacers were used to set the thickness of the composite at 3.2 mm during the compression molding so that the density of the composites would be 0.47 g/cm^3. The concentration of the reinforcements was set at 60%, the processing temperature for the materials was 185°C, and the holding time was 80 s. These conditions were chosen as the optimum conditions on the basis of our previous experience with developing PP composites reinforced with biomasses, such as wheat straw, cornhusks, and switchgrass.[25,26] After the required time, the heater was turned off, and the mold was cooled by running cold tap water until its temperature reached about 35°C; then, the composite was removed from the mold.

For the composites reinforced with HBs and OB with PP webs as the matrix materials, the total area of the required nonwoven PP webs was calculated on the basis of the HB and OB concentration, composite weight, and weight/area value of the PP webs. The area of the PP webs could be converted to the number of pieces of 25.4 cm × 30.5 cm web. The PP webs were laid on the table, and weighed HBs or OB were spread randomly on the webs to ensure random orientation and homogeneous distribution. The webs with HBs or OB on top were stacked one by one. Five additional layers of PP webs were placed on both the top and the bottom to achieve smooth surfaces, reduce moisture absorption, and create an I-beam structure that could also lead to improved mechanical properties. The stacked layers were placed between two aluminum sheets and pressed in a laboratory-scale press (Carver, Inc., Wabash, IN) preheated to the desired temperature.

For the PP composites reinforced with HFs or jute fibers, the HFs, jute fibers, and PP fibers were first individually opened in a Louet electric carder (Prescott, Ontario, Canada). The opened reinforcement and matrix fibers were mixed in the desired ratio and carded together several times until homogeneity was observed. Well-mixed fibers were then separated from the mat in tiny bundles and randomly placed in a 30.5 × 25.4 × 18.4 cm^3 container. Tap water was sprayed on the fiber mix at a high velocity with a multipurpose nozzle to improve the blending of the fibers. After a homogeneous mat was formed, water was filtered out, and the wet mat was dried for 24 h at 85°C to remove any remaining water. The dry mats were pressed to make composites.

Each data point in the article is the average of at least five tests of at least three composites made at different times under the same conditions. Samples were placed in a conditioning room that was set at 21°C and 65% relative humidity for at least 48 h before testing.

Composite characterization

An MTS QTest\10 tester was used for flexural testing according to procedure A of ASTM D 790-03. The size of the samples was 20.3 cm × 7.6 cm with a

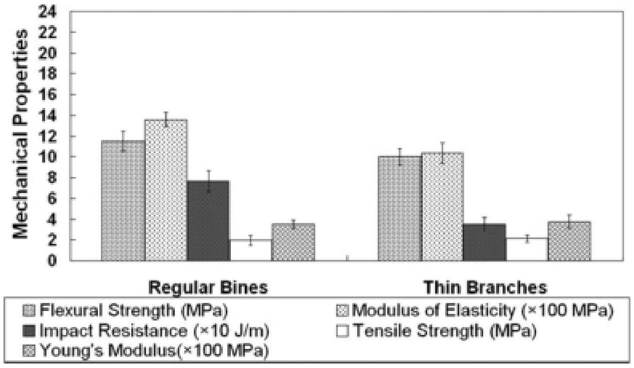

Figure 1 Effect of the HB diameter (regular and small) on the flexural, impact-resistance, and tensile properties. The composites were manufactured with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm, and they were compression-molded at 185°C for 80 s. The concentration and length of the regular bines and thin branches were fixed at 60 wt % and 5 cm. The average diameters of the regular and thin branches were 2.6 and 1.3 mm, respectively.

support length of 15.2 cm, and the load cell was 500 N with a crosshead speed of 10 mm/min for the three-point-bending tests.

Tensile tests were carried out with the MTS QTest/10 tester according to procedure ASTM D 638-03 with a 500 N load cell. The samples were cut into dog-bone shapes with a type I sample template. The sample length was 165 mm, the width of the wide section was 19 mm, the width of the narrow section was 13 mm, and the gauge length was 115 mm. The HB and OB tensile properties were also measured with the MTS QTest/10 tester with a crosshead speed of 5 mm/min and a gauge length of 50 mm. An Instron (Norwood, MA) model 4000 tensile testing machine was used to determine the tensile properties of HFs and jute fibers. A gauge length of 25 mm and a crosshead speed of 18 mm/min were used for the testing.

The impact-resistance test was performed in a plastic impact tester (QC-639 universal impact tester, model 7J, Cometech Testing Machines Co., Ltd., Taichung, Taiwan) according to ASTM procedure D 256-03. The sample size was 63.5 mm × 10.2 mm. The notch was cut perpendicularly to the cross section.

The sound-absorption tests were carried out in a small impedance tube at a 0–3-kHz frequency with the two-microphone transfer-function method followed by ASTM procedure E 1050-98. The diameter of the samples was 63 mm.

Statistical method

Fisher's least significant difference was used to test the effects of various conditions on the properties of the composites with SAS software (SAS Institute, Inc., Cary, NC). The *P* value was set at 0.05.

RESULTS AND DISCUSSION

Effects of the regular HBs and thin branches on the mechanical properties of the composites

As illustrated in Figure 1, the composites reinforced with regular HBs had significantly higher flexural strength, modulus of elasticity, and impact resistance (the *P* values were 0.0349 for the flexural strength, <0.0001 for the modulus of elasticity, and 0.0038 for the impact resistance) than the composites reinforced with thin branches. The tensile strength and Young's modulus from the composites reinforced with regular HBs and thin branches were similar.

The better mechanical properties of the composites reinforced with regular HBs are mainly related to the lower bulk density and better tensile properties versus those of the thin branches. As reported in the Experimental section, the bulk density of the regular HBs was 0.65 g/cm^3, which was lower than that of the thin branches (0.69 g/cm^3). The regular HBs also had better tensile strength and modulus than the thin branches (as reported in the Experimental section). The bulk density of the reinforcements is a very important parameter in lightweight composites. With the same weight of the reinforcing materials in the composites, bines with a low bulk density are used in a high volume, and this results in composites with reduced voids between the bines and PP and leads to an improvement in the mechanical properties. The better tensile properties of the regular HBs versus the thin branches also provide better reinforcement of the composites.

Effects of the OB width on the mechanical properties of the composites

As shown in Figure 2, the composites reinforced with 2-mm-wide OB possessed better mechanical properties than the composites reinforced with 4- or

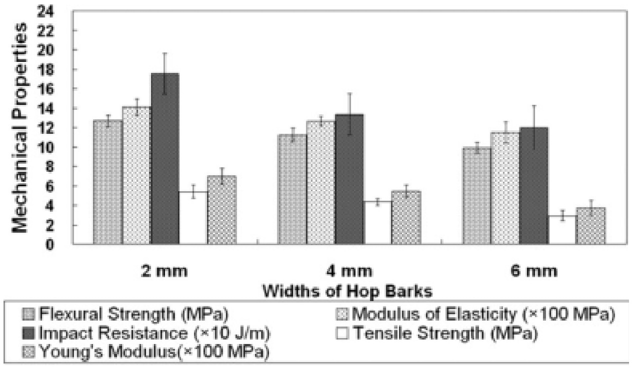

Figure 2 Effect of the OB width on the flexural, impact-resistance, and tensile properties. The composites were made with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm, and they were pressed at 185°C for 80 s. The OB concentration and length were fixed at 60 wt % and 5 cm. The OB widths were 2, 4, and 6 mm.

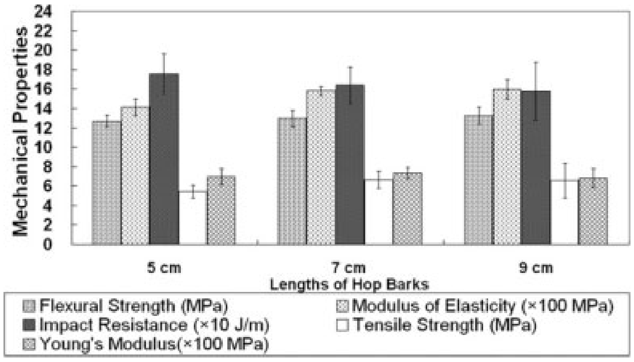

Figure 3 Effect of the OB length on the flexural, impact-resistance, and tensile properties. The composites were developed with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm, and they were pressed at 185°C for 80 s. The OB concentration and width were fixed at 60 wt % and 2 mm. The OB lengths were 5, 7, and 9 cm.

6-mm-wide OB. Compared with the composites reinforced with 4-mm-wide OB, the composites reinforced with 2-mm-wide OB had significantly higher flexural strength, modulus of elasticity, impact resistance, and Young's modulus (the *P* values were 0.0375, 0.0165, 0.0038, and 0.0009, respectively). There were no statistical differences in the mechanical properties between the composites reinforced with 4-mm-wide OB and those reinforced with 6-mm-wide OB.

Increasing the OB width without changing its length decreased the aspect ratio (length/width) of the bark. The aspect ratio of reinforcing materials is a critical factor in determining the mechanical properties of composites.[25,26,31–33] A larger aspect ratio leads to better adhesion between the reinforcements and matrix materials and results in improved mechanical properties. Although the mechanical properties of the composites reinforced with 4- or 6-mm-wide OB did not show significant differences, the standard deviations for the composites reinforced with 6-mm-wide OB were larger than those of the composites reinforced with 4-mm-wide OB. The larger standard deviations were due to the increased size of OB (from 4 to 6 mm). The increased size made the OB more difficult to spread homogeneously on the PP webs, and this resulted in larger deviations of the properties.

Effects of the OB length on the mechanical properties of the composites

As shown in Figure 3, the modulus of elasticity and tensile strength significantly increased when the OB length increased from 5 to 7 cm (the *P* values were 0.0053 and 0.0322, respectively). However, other properties did not show statistically significant differences between the composites reinforced with 5- and 7-cm-long OB. When the OB length further increased from 7 to 9 cm, none of the mechanical properties showed statistically significant differences. However, the standard deviations of the properties of the composites reinforced with 9-cm-long OB were larger than those of the properties of the composites reinforced with 7-cm-long OB.

Increasing the OB length without changing its width increased the aspect ratio (length/width). As discussed previously, the aspect ratio of the reinforcing materials plays an important role in determining the mechanical properties of composites. A larger aspect ratio results in better adhesion between the reinforcements and matrix materials and leads to an increase in the mechanical properties. However, in this study, many properties, such as the flexural strength, impact resistance, and Young's modulus, did not show significant increases, and the reasons are not clear. When the OB length was further increased from 7 to 9 cm, the distribution of the OB on the PP webs became less homogeneous because of the larger size of the bark. Composites with poor homogeneity of the reinforcing and matrix materials had defects, so large standard deviations of the mechanical properties were observed.

Effects of the HF length on the mechanical properties of the composites

As shown in Figure 4, the flexural strength, modulus of elasticity, impact resistance, tensile strength, and Young's modulus increased significantly when the fiber length increased from 4.3 to 7.9 cm (the *P* values were 0.0063, <0.0001, 0.0028, <0.0001, and 0.0004 for the flexural strength, modulus of elasticity, impact resistance, tensile strength, and Young's modulus, respectively). When the fiber length further increased from 7.9 to 14.6 cm, the tensile

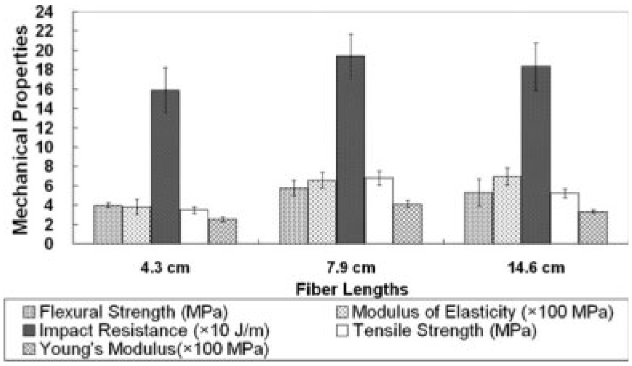

Figure 4 Effect of the HF length on the flexural, impact-resistance, and tensile properties. The composites were made with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm, and they were pressed at 185°C for 80 s. The HF concentration was 60%. The average fiber lengths were 4.3, 7.9, and 14.6 cm.

TABLE II
Comparison of the Mechanical Properties of the Composites from Regular HBs (5 cm Long), OB (7 cm Long and 2 mm Wide), HFs (7.9 cm Long), and Jute Fibers

Material	FS (MPa)	MOE (GPa)	IR (J/m)	TS (MPa)	YM (MPa)
Regular HB–PP	11.5 ± 1.0	1.4 ± 0.1	76.6 ± 10.2	2.0 ± 0.5	349.1 ± 40.2
HF–PP	5.8 ± 0.8	0.7 ± 0.1	193.9 ± 23.4	6.8 ± 0.7	410.2 ± 34.5
OB–PP	13.0 ± 0.9	1.6 ± 0.1	163.8 ± 18.9	6.7 ± 0.9	733.6 ± 56.8
Jute–PP*	9.1 ± 0.4	1.6 ± 0.1	112.3 ± 8.6	8.9 ± 0.8	469.3 ± 30.1

All composites were manufactured with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm (0.47 g/cm^3), and they were pressed at 185°C for 80 s. The reinforcement concentration was 60%. FS = flexural strength; IR = impact resistance; MOE = modulus of elasticity; TS = tensile strength; YM = Young's modulus.

* The data for the jute are from Huda and Yang.[25]

strength and Young's modulus decreased significantly (the *P* values were 0.0050 and 0.0462, respectively). The flexural strength, modulus of elasticity, and impact resistance did not show statistical differences between the composites reinforced with 7.9-cm-long HFs and 14.6-cm-long HFs.

Increasing the HF length from 4.3 to 7.9 cm led to an increased aspect ratio and, therefore, improved adhesion between the reinforcements and matrix materials and improved mechanical properties. When the HF length further increased from 7.9 to 14.6 cm, although the fibers had an increased aspect ratio, the longer fibers were more likely to entangle with one another and posed difficulties in the carding and mixing processes; this led to poor homogeneity and, therefore, inferior mechanical properties.

Comparison of the mechanical properties of the HB–PP, OB–PP, and HF–PP composites

As shown in Table II, the OB-reinforced composites generally had better mechanical properties than the composites reinforced with HFs and regular HBs. Compared with the composites reinforced with HFs (7.9 cm long), the composites reinforced with OB (7 cm long and 2 mm wide) had significantly higher flexural strength, modulus of elasticity, and Young's modulus, significantly lower impact resistance, and similar tensile strength. Compared with the composites reinforced with regular HBs, the composites reinforced with OB had significantly higher flexural strength, modulus of elasticity, impact resistance, tensile strength, and Young's modulus.

The better mechanical properties, except for the impact resistance, for the composites reinforced with OB versus those reinforced with HFs were mainly due to the lower bulk density of OB (0.58 g/cm^3) versus that of HFs (1.03 g/cm^3). With the same weight of the reinforcing materials in the lightweight composites, the lower bulk density of OB allowed OB to be used in a higher volume, and this led OB to be packed tightly with fewer voids in the composites. During compression molding, the voids between OB and PP were reduced because of the highly packed OB, and this led to improved mechanical properties. However, the higher impact resistance of the composites reinforced with HFs versus the composites reinforced with OB is difficult to explain.

The better mechanical properties of the composites reinforced with OB versus the composites reinforced with regular HBs were mainly due to the larger aspect ratio and better tensile properties of OB versus regular HBs. Although the bulk density of OB was similar to that of regular HBs, the cross section of OB (2 mm wide and 0.4 mm thick on average) was much smaller than that of regular HBs (ca. 2.6 mm in diameter). The flat configuration of the bark allowed it to cover more area on the PP webs than cylindrical HBs and resulted in a decreased number of voids. The small cross section of OB also resulted in a large aspect ratio and improved mechanical properties. Meanwhile, the better tensile properties of OB versus regular HBs also helped to better reinforce the mechanical properties.

Comparison of the mechanical properties of the hop–PP and jute–PP composites

Compared with the jute–PP composites, the composites reinforced with OB had 43% higher flexural strength, 46% higher impact resistance, 56% higher Young's modulus, similar modulus of elasticity, and 33% lower tensile strength according to the data for jute–PP composites reported by Huda and Yang,[25] although the tensile properties of OB were much worse than those of jute fiber, as reported in the Experimental section. The main reason for the better mechanical properties of the composites reinforced with OB was the low bulk density of OB. As discussed previously, the low bulk density of the reinforcement is a critical factor in determining the mechanical properties of lightweight composites.

Although HFs showed better tensile properties than jute fibers and similar bulk density, the mechanical properties (except for the impact resistance) of jute–PP composites were significantly better than those of the composites reinforced with HFs. The

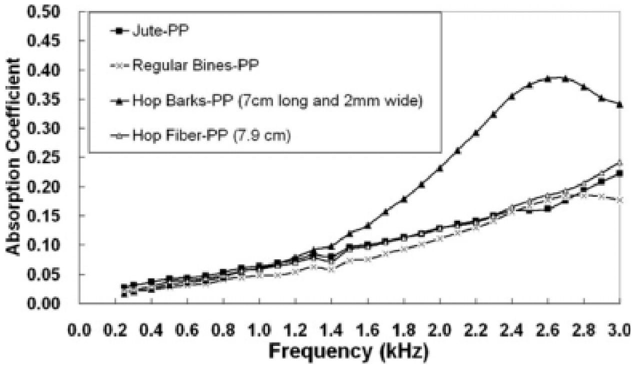

Figure 5 Comparison of the sound-absorption properties of the lightweight composites reinforced with HBs, OB, HFs, and jute fibers, respectively. The composites were manufactured with a weight/area value of 1500 g/m^2 and a thickness of 3.2 mm, and they were pressed at 185°C for 80 s. The reinforcement concentration was 60%. The length of the regular HBs and jute fibers was 5 cm. The OB was 7 cm long and 2 mm wide. The HFs were 7.9 cm long.

reason for the poor mechanical properties of the HF–PP composites might be that some HFs were entangled together after the chemical treatment and mechanical opening. The entangled fibers resulted in poor adhesion between HFs and PP and led to poor mechanical properties. However, the reason for the high impact resistance of the composites reinforced with HFs is still unclear at this time.

Comparison of the sound-absorption properties of the hop–PP and jute–PP composites

As shown in Figure 5, the composites reinforced with HFs had sound-absorption performance similar to that of the composites reinforced with jute fibers. The composites reinforced with regular HBs had slightly lower sound-absorption behavior than jute–PP composites. However, the composites reinforced with OB showed the best sound-absorption properties of the composites, especially when the frequency of the sound ranged from 1.6 to 3.0 kHz.

The similar properties of the composites reinforced with HFs and jute fibers were mainly due to the similar bulk densities of the fibers, similar sound-absorption properties of the cellulose fibers, and similar structures of the composites because both types of composites were made with the same manufacturing method. Although the bulk density of OB was similar to that of regular HBs, OB had a larger aspect ratio and a flat configuration that made the bark cover a larger area on the PP webs and distribute more homogeneously in the composites. The composites reinforced with OB were more compact with fewer voids in comparison with the composites reinforced with regular HBs. Thus, sound energy was more likely to be absorbed when the sound waves went through different phases of the matrix and reinforcement materials rather than directly through the voids. However, composites with good sound-absorption properties at a low frequency (<1.5 kHz) are desired for automotive interiors because this frequency zone corresponds to noise from the tires, running engine, road, conversations, and wind. Thus, the composites reinforced with regular HBs, OB, and HFs had sound-absorption behavior similar to that of the jute–PP composites in the frequency zone of 0–1.5 kHz.

CONCLUSIONS

In this research, lightweight composites were developed with HBs and OB as the reinforcement materials and nonwoven PP webs as the matrix material; the OB–PP composites showed better properties than similar PP composites reinforced with jute fibers. In addition, natural cellulose fibers obtained from HBs were also used as reinforcements in the composites. The OB–PP composites showed the best mechanical properties under the studied conditions when the OB was 7 cm long and 2 mm wide and the OB concentration was set at 60 wt %. One of the findings of this research is that lightweight composites with better properties can be achieved directly with bark rather than fibers chemically extracted from the bark. In addition to better mechanical properties, using bark directly would also lead to substantial simplifications in manufacturing and reductions in cost. Composites from OB and PP webs had 43% higher flexural strength, 46% higher impact resistance, 56% higher Young's modulus, similar modulus of elasticity, 33% lower tensile strength, and better sound-absorption properties in comparison with jute–PP composites. Although the tensile properties of OB were much worse than those of jute fibers, OB with a low bulk density was found to better reinforce the lightweight composites. The superior mechanical properties of OB–PP in comparison with jute–PP composites provide an opportunity for applications of OB–PP composites in automotive interiors, in which composites reinforced with natural fibers are currently being used as support layers, and in the construction industry for products such as ceiling tiles and office panels.

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