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Lightweight Polypropylene Composites Reinforced by Long Switchgrass Stems

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Abstract

Switchgrass (SG) stems with lengths up to 10 cm have been used as reinforcement to make lightweight composites with polypropylene (PP) webs. The long SG stems, with simple cut or split and without chemical treatment, were used directly in the composites. Utilizing SG stems for composites not only increases the values of SG but also provides a green, sustainable and biodegradable material for the composites industry. Lightweight composites are preferred, especially for automotive applications due to the potential saving in energy. In this research, the effects of manufacturing parameters on the properties of composites have been studied. Although the tensile properties of SG stem are significantly worse than jute fiber, SG stem with low bulk density is found to better reinforce the lightweight composites. Compared with the jute-PP composites of the same density (0.47 g/cm^3), composites reinforced by the split SG stems have 56% higher flexural strength, 19% higher modulus of elasticity, 15% higher impact resistance, 63% higher Young's modulus, 52% lower tensile strength, and similar sound absorption property. The SG-PP composites with optimized properties have the potential to be used for industrial applications such as the support layers in automotive interiors, office panels and ceiling tiles.

Keywords: lightweight composites, switchgrass, polypropylene web, renewable resource

Introduction

This paper reports the properties of the lightweight composites reinforced by SG stems. Compared with the conventional compact composites, the lightweight composites much contain voids which are retained to reduce density during the manufacturing process. The densities of lightweight composites are lower than the densities of the materials used to build the composites. The use of lightweight composites can potentially help to save energy. For example, if the lightweight composites are used as interior materials in automobiles or aircrafts, they can help to improve the fuel efficiency. The lightweight composites made in this research aimed to be used in the automotive industry as support layers, such as headliner, door panels and cargo liners, in automotive interiors. However, the lightweight composite material should also pass the flame test and some other necessary tests before it can be used for industrial applications.

Regarding to the development of materials used as support layers, fiberglass reinforced composites were widely used as interior support layers in automobiles [1–3]. However, in last 15 years, most major automobile manufacturers tried to use lightweight composites reinforced by natural fibers, such as jute, hemp and flax, to take the place of fiberglass reinforced composites [4]. The advantages of using natural fibers were their low cost, low weight and biodegradability. However, the production 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 were high compared with some biomass materials. For example, raw jute at the grade of TD3 in India was about \$0.67/kg in January 2009 [5].

In this research, SG stems were used as reinforcements to make lightweight composites. SG is both a perennial and self-seeding crop. In addition, SG can grow on marginal lands and requires relatively moderate levels of chemical fertilizers. Generally, SG is considered as a resource-efficient, low-input energy crop from farmland [6–8]. The advantages of using SG in the composites are it is annually renewable, inexpensive, and environmentally friendly.

To the best of our knowledge, no literature was found related to lightweight composites made from long SG stems and PP nonwoven webs (a web-like material made from long PP fibers bonded together by heat treatment, neither woven nor knitted). Some references related to conventional compact composites and middle-density particle boards (with densities ranging from 0.70 to 0.90 g/cm³) reinforced by biological materials such as wheat straw, rice straw, corn stalk, cotton stalk and switchgrass [9–35]. There are two major differences between the composites reported in the literature and the lightweight composites developed in this research. First, the biological materials in the literature were made into particles or short fibers by using mechanical and/or chemical methods. However, in this research, SG stems were simply cut and split into long length (up to 10 cm), and were used directly in the composites without any chemical treatment. The simple mechanical treatments can reduce the cost for the preparation of materials. In addition, the long SG stems with large aspect ratios (length/width) can better reinforce the composites. Second, in this research, the PP webs were used as matrix materials to make composites. The use of PP webs as matrix materials has not been reported by any literature. There are two major advantages of using PP webs as matrix materials. First, the SG stems with large size can be used and distributed homogeneously in the composites. Because the SG stems can be spread on the PP webs, then the PP webs contained stems on the top can be stacked layer by layer together to make composites by compression molding. Second, the webs can potentially suit for the continuous production in the industry.

The lightweight composites, with low density of 0.47 g/cm³, inevitably have some voids in the composites. The voids create defects and decrease the mechanical properties of composites. The density of lightweight composites, which is largely affected by the amount of voids, becomes an important parameter for the mechanical properties of the composites. Thus, it is not proper to compare the lightweight composites with the conventional composites or matrix materials themselves without considering the differences in density. Therefore,

in this research, the properties of SG stems reinforced lightweight composites were compared with jute-PP lightweight composites with the same density.

The objectives of this research were to utilize long SG stems without any chemical treatment to make lightweight composites through a simple and cost-effective method, and to try to understand the relationship between the properties of composites and the manufacturing parameters.

Experimental

Materials

SG was obtained from a research field at the University of Nebraska-Lincoln East Campus, and SG stems were manually separated from the fully mature crops. In this research, two different stems according to the diameters were used to make composites, they were the regular SG stems (an average diameter of 3.3 mm with standard deviation of 0.75) and the small SG stems (an average diameter of 1.6 mm with standard deviation of 0.33) grown on the top of the plants. The tensile strength of the regular SG stem is 113.4 ± 24.9 MPa, with Young's modulus of 15.1 ± 2.9 GPa. The tensile strength of the small SG stem is 69.7 ± 16.4 MPa, with Young's modulus of 8.6 ± 1.2 GPa.

Jute fiber was supplied by Flaxcraft, Inc. (Cresskill, NJ), the length of jute fiber is 5 cm. The tensile strength of jute fiber is about 294.8 ± 15.2 MPa, with Young's modulus of 16.9 ± 0.8 GPa.

Nonwoven PP web was provided by Spunfab, Ltd. (Cuyahoga Falls, OH). The density of PP was 0.90 g/m³ and melting temperature was 162 °C. The weight/area of the PP web was 23.7 g/m². Melt Flow Index (MFI) of PP was 38 g/10 min at 230 °C. PP fibers were supplied by Drake Extrusion Ltd. For the 15-denier and 84 mm long PP fiber, width is 45 μm, tensile strength is 4.0 g/den, melting temperature is 162 °C, MFI is 20 g/10 min measured at 230 °C, and crystallinity is 50%.

Composites Fabrication

The weight/area of all the composites was set as 1500 g/m² with an area of 25.4 cm × 30.5 cm. Metal spacers were used [36] to set a thickness of 3.2 mm during the compression molding, so the density of the composites was 0.47 g/cm³. Based on the SG concentration, composite weight, and the weight/area of PP webs, the total area of required nonwoven PP webs was calculated and converted to the number of pieces of 25.4 cm × 30.5 cm web. The PP webs were laid on the table and weighed SG stems were laid randomly on the webs to achieve random orientation and homogeneous distribution. The webs with SG stems on top were stacked one by one.

Ten layers of PP webs were placed both at top and bottom in order to achieve smooth surfaces and reduce moisture absorption; the I-beam structure can also lead to increased mechanical properties. The stacked layers were placed between two aluminum sheets and pressed in a laboratory-scale "Carver" press preheated to the desired temperature.

In this method, voids were kept in the composites by controlling the thickness to make the density of the composites low. After a compression at 185 °C for 80 s to make the PP melt and bond to SG stems, the press was turned off and the cooling system was turned on. When the temperature decreased to about 35 °C, the composite was removed from the press.

Each data point in the paper was the average from five tests, which were from at least three composites made at different times using the same conditions. Samples were placed in the conditioning room set at 21 °C and 65% relative humidity for at least 48 h before testing.

Investigation of Manufacturing Parameters

As shown in Table 1, the effect of the concentrations of the SG stem (weight %) on flexural, impact resistant, and tensile properties was studied. The concentrations were chosen at 40, 50, 60 and 70 wt%. An attempt to use 30 wt% straw led to non-uniform mechanical properties because the stems with low weight were difficult to homogeneously cover the area of the PP webs. Thus, the lack of weight of stems and the uneven distribution of stems resulted in poor mechanical properties. On the other hand, making composites with 80 wt% SG stems

was extremely difficult, because there were not enough webs to hold the large quantity of the stems and to prevent the stems from sliding off the edges of the composites. The length of SG stems was set at 5 cm.

The effect of the lengths of SG stem on flexural, impact resistant and tensile properties was studied at 60 wt% concentration, which was determined to be the optimum condition from the first study. The lengths of SG stem were chosen at 1, 5, and 10 cm.

The effect of the diameters of SG stem on flexural, impact resistant, and tensile properties was studied at 60 wt% stem and 5 cm stem length, which were determined to be the optimum conditions. The small SG stems (an average diameter of 1.60 mm with standard deviation of 0.33) grown on the top of SG plants were used to make composites, which were compared with the previous composites reinforced by the regular SG stems (an average diameter of 3.30 mm with standard deviation of 0.57).

For the study of the effect of surface area of stems on composite, the effect of the split configuration of SG stem on flexural, impact resistant, and tensile properties was studied at 60 wt% of stem and 5 cm stem length. Each stem was split along the longitudinal direction of stem into 2 to 4 parts using a two-roller milling machine (KICE Industries incorporation, Wichita, Kansas). The mechanical properties of composites reinforced by split SG stems were compared with the composites reinforced by the whole stems. The samples from the three types of composites reinforced by the regular SG stems, small SG stems and split SG stems respectively were used to study the sound absorption properties. And then, the mechanical properties of SG

Table 1. Experimental design

	Investigation of parameters				
	Concentrations of SG (%)	Lengths of SG (cm)	Configurations of SG	Diameters of SG (mm)	Densities of composites (g/cm ³)
Effect of SG concentrations on the mechanical properties of composites	40, 50, 60, 70	5	Whole	3.3	0.47
Effect of SG lengths on the mechanical properties of composites	60	1, 5, 10	Whole	3.3	0.47
The effect of stem diameters on the mechanical properties of composites	60	5	Whole	3.3, 1.6	0.47
The effect of the split configuration on the mechanical properties of composites	60	5	Whole and Mechanically Split	3.3	0.47
Effect of composites densities on mechanical properties of composites	60	5	Mechanically Split	3.3	0.23, 0.47, 0.94
Comparison of sound absorption properties between SG-PP and jute-PP ^a composites	60	5	Whole, Mechanically Split	3.3, 1.6	0.47
Comparison of mechanical properties between SG-PP and jute-PP ^a composites	60	5	Mechanically Split	3.3	0.47

a. Jute-PP composites were prepared at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. The concentration of jute was 55%. The length of jute fiber was 5 cm [37]

stem-PP composites were compared with jute-PP composites of the same density and thickness as reported by Huda and Yang [37].

The relationship between the densities of composites and mechanical properties of the SG-PP and jute-PP composites was studied. The density was chosen at 750 g/m² (0.24 g/cm³), 1500 g/m² (0.47 g/cm³) and 3000 g/m² (0.94 g/cm³) with the same thickness of 3.2 mm. The SG-PP composites were made at 60 wt%, 5 cm long and split SG stems, and jute-PP composites were made at 60 wt% of jute concentration according to the previous studies.

Material Characterization

SEM Analysis

A Hitachi model S-3000N scanning electron microscope was used for SEM imaging. The cross section of samples was coated with gold palladium and observed under the microscope at a voltage of 25 kV.

Mechanical and Acoustic Testing

An MTS QTest\10 tester was used for flexural testing according to procedure A of ASTM D790-03. The size of samples was 20.3 cm × 7.6 cm with support length of 15.2 cm, and the load cell was 500 N with the crosshead speed of 10 mm/min for the three-point-bend tests.

Tensile tests were carried out on an MTS tester (QTest/10) according to procedure ASTM D638-03. The machine was equipped with an extensometer (model MTS 634.11F-24) and a 500 N load cell. The samples were cut into dog-bone shape using a Type I sample template. The sample length was 165 mm, with the width of the wide section of 19 mm, with the width of the narrow section of 13 mm, and with the gauge length of 115 mm. Tensile properties of SG stems were also measured by the MTS QTest/10 tester, with a crosshead speed of 5 mm/min and gauge length of 50 mm.

The impact resistance test was performed in a QC-639 Universal Impact Tester by Qualitest using procedure ASTM D256-03. Sample size was 63.5 mm × 10.2 mm. The notch was cut perpendicular to the cross section.

The sound absorption test was carried out in a small size Brüel & Kjær (type 4206 A) impedance tube at 0–3 kHz frequency based on the two-microphone transfer-function method followed by procedure ASTM E1050–98. The diameter of samples was 28 mm.

Void Content Calculation

The calculation of the void content percentage of the lightweight composites is based on the densities of

composites and PP, the bulk densities of reinforcements and the weight fraction of materials. There are three types of voids in the composites: the voids between PP and reinforcements, the inner voids of PP and the inner voids of the reinforcement. The voids between PP and reinforcements are considered as defects to decrease the mechanical performance of composites, thus the volume of these voids is calculated as void content. However the volume of the other two types of voids has not been calculated, because the volume of inner voids in the molten PP is negligible [37, 38] and the micro inner voids in the reinforcements (SG and jute) have much little influence on the mechanical properties compared to those large voids between reinforcement and matrix material [39, 40]. The densities of lightweight composites and PP are 0.47 and 0.90 g/cm³. The bulk densities of reinforcements are tested according to glass bead displacement method [41]. However, fine sands with an average diameter of 0.34 ± 0.11 mm were used as the displacement medium instead of glass beads. The calculation of void content percentage of lightweight composites is as follows:

$$\begin{aligned} \text{VCF} &= 1 - \frac{V_{\text{PP}}}{V_{\text{compo}}} - \frac{V_{\text{reinf}}}{V_{\text{compo}}} \\ &= 1 - \frac{W_{\text{PP}} \times \rho_{\text{compo}}}{\rho_{\text{PP}}} - \frac{W_{\text{reinf}} \times \rho_{\text{compo}}}{\rho_{\text{reinf}}} \end{aligned}$$

where VCF is the void content fraction of the composites; V_{PP} , the total volume of PP; V_{reinf} , the total volume of reinforcements; V_{compo} , the total volume of composites; ρ_{compo} , the density of composites; ρ_{PP} , the density of PP; ρ_{reinf} , the bulk density of reinforcements; W_{PP} , the weight fraction of PP in the composites; and W_{reinf} , the weight fraction of reinforcements in the composites.

Statistics Method

Fisher's Least Significant difference (LSD) was used to test the effect of various conditions on the properties of composites using SAS (SAS Institute Inc., NC). The p-value was set at 0.05.

Results and Discussion

The Effect of Stem Concentrations on the Mechanical Properties of SG-PP Composites

As demonstrated in Figure 1, flexural strength, modulus of elasticity, impact resistance properties and Young's modulus increased significantly (p value < 0.05) from 50 to 60% of SG stem concentration, and then decreased significantly from 60 to 70% of the stem concentration.

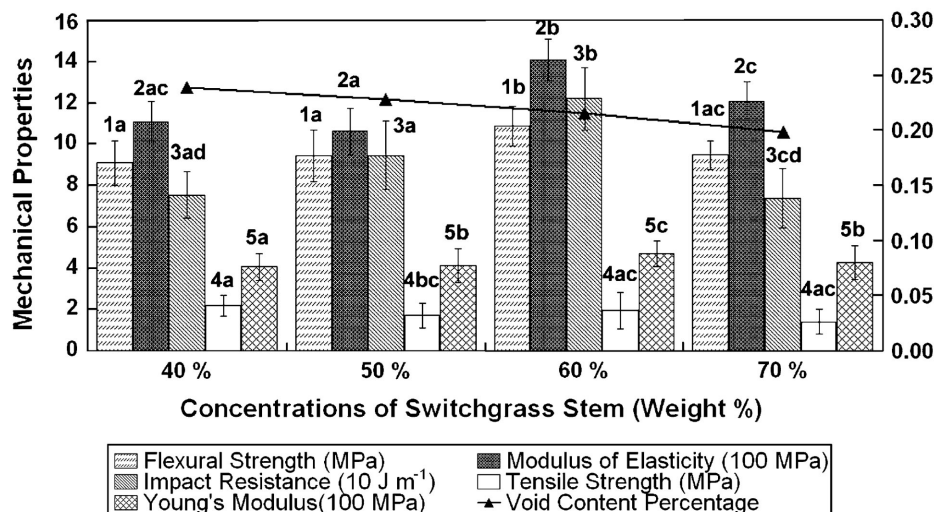


Figure 1. The effects of SG stem concentrations (40, 50, 60 and 70%) on flexural strength, modulus of elasticity, impact resistance, tensile strength and Young's modulus of SG-PP composites. Composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. SG stems were 5 cm long with regular-sized and whole configuration. 1, 2, 3, 4, 5: If data points had the same number, they represented the same mechanical property. a, b, c, d: If any two data points of the same mechanical property had totally different letters, the two data points were statistically different.

However, the tensile strength did not show significant differences among the concentrations of 50, 60 and 70%.

As shown in Figure 1, the void content percentages of composites showed a decrease from 23.9 to 19.8% as the concentration of SG increased from 40 to 70%. The bulk densities of SG were tested to be 0.42 ± 0.01 g/cm³ at 40% of SG concentration, 0.46 ± 0.02 g/cm³ at 50% of SG concentration, 0.49 ± 0.01 g/cm³ at 60% of SG concentration and 0.51 ± 0.02 g/cm³ at 70% of SG concentration. The increased bulk densities of SG are because SG was compressed more tightly at higher concentrations than lower concentration of SG.

When the concentrations of SG stems are low, at about 40%, there are not enough stems to reinforce the polymer matrix. In addition, the small amount of SG stems can only cover limited area on the PP webs and cannot be compressed completely. As demonstrated by the SEM image in Figure 2a, the visible voids were formed within the SG stems. The void content percentage of composites at 40% of SG also shows higher value than the composites with higher concentrations of SG. The voids in the composites lead to poor mechanical properties. With the increase of SG concentration, there are more SG stems to reinforce the composites. Meanwhile, the SG stems can cover large areas on the webs and occupy more volume in the composites because of the lower density of SG than PP, and results in a decrease of the amount of voids in the composites. As shown in Figure 2b and c, the amount of voids decreased and the SG stems were compressed tightly due to the high concentrations of SG stems. Both the increased concentration of SG stems and decreased

voids lead to the improved properties. However, as the stem concentration increases, as high as 70%, the flexural properties, impact resistance and Young's modulus decrease. This is because the density of the composites is fixed. The increase of SG concentration must decrease the weight percentage of the PP webs. These changes result in a decreased interaction between SG stems and PP webs at higher concentrations of SG stems. The poor interaction, because of the lack of matrix materials, results in the decrease of mechanical properties. The tensile strength did not show significant difference among concentrations because of the poor bond between PP and non-chemical treated SG.

The Effect of Stem Lengths on the Mechanical Properties of SG-PP Composites

As shown in Figure 3, the flexural strength, modulus of elasticity, impact resistance and Young's modulus first increased significantly with the increase of stem lengths from 1 to 5 cm and then decreased significantly with the increase of the length from 5 to 10 cm. The tensile strength did not show significant differences among the lengths of 1, 5, and 10 cm.

The increased length with unchanged width of the stem is directly related to the increase of the aspect ratio of the stem. Although the aspect ratio is usually applicable for much finer things such as fibers, the explanation using the theory of aspect ratio also suit for the discussion of the configurations of stems. The aspect ratio of the reinforcing materials is a critical factor in determining mechanical properties of composites [38]. The large

Figure 2. SEM images of the cross sections of SG-PP composites. Composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. SG stems were 5 cm long with regular-sized and whole configuration. a: 40 wt%, b: 60 wt%, c: 70 wt%, bar = 1 mm.

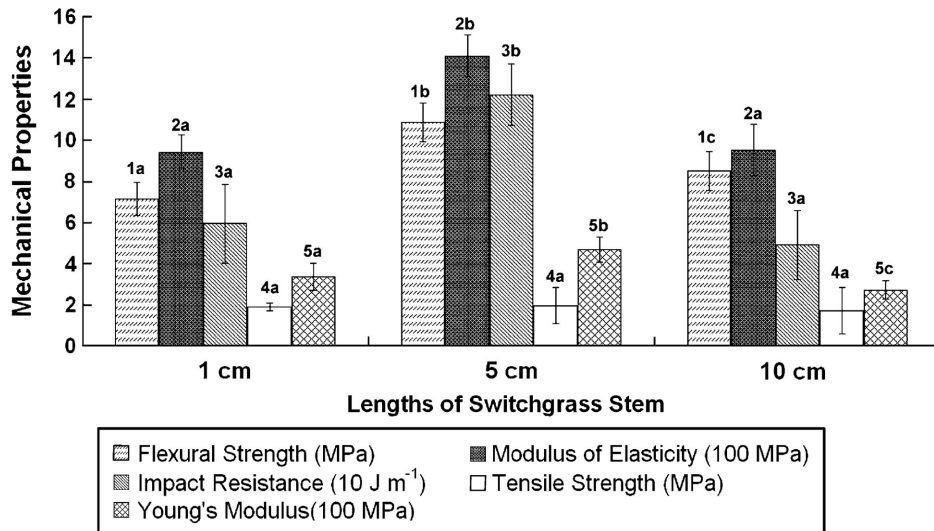
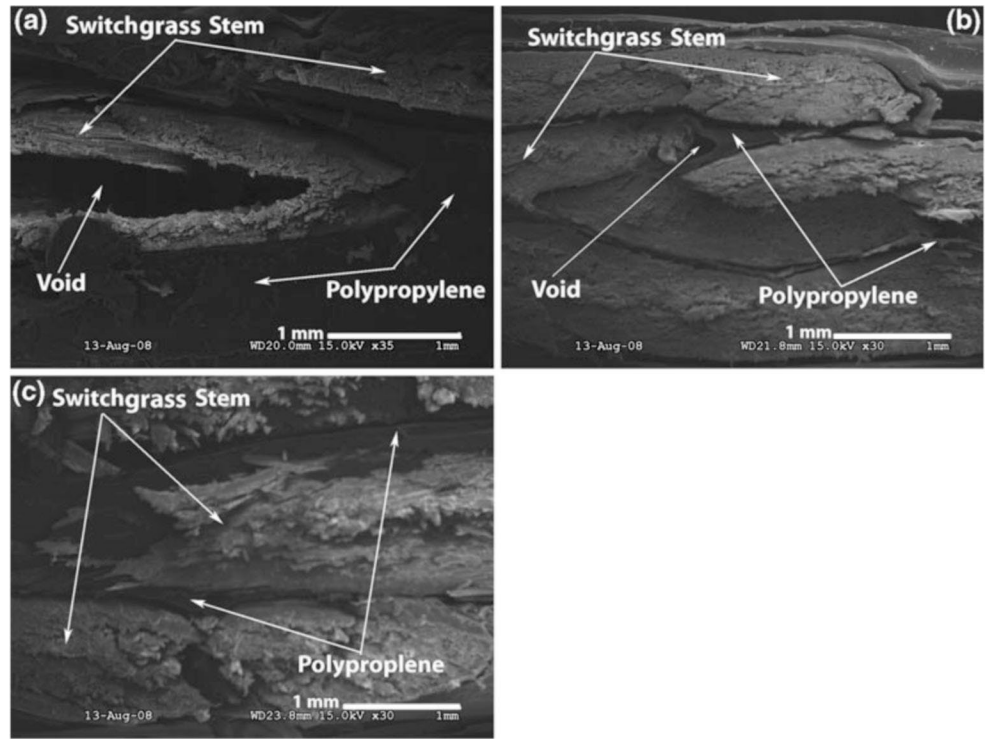


Figure 3. The effects of lengths of regular SG stem (1, 5 and 10 cm) on flexural strength, modulus of elasticity, impact resistance, tensile strength and Young’s modulus of SG-PP composites. Composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. The concentration of SG stems was 60%. 1, 2, 3, 4, 5: if data points had the same number, they represented the same mechanical property. a, b, c: If any two data points of the same mechanical property had totally different letters, the two data points were statistically different.

aspect ratio can promote the transfer of stress from reinforcements to matrix materials, and finally results in the increase in mechanical properties. However, when the lengths of SG stem further increased from 5 to 10 cm, the distribution of the stems on PP webs became less homogeneous due to the larger size of the stems. The lessened homogeneity leads to an increase in the amounts of defects, and results in the reduction of the mechanical properties.

The Effect of Stem Diameters on the Mechanical Properties of SG-PP Composites

Compared with the composites reinforced by the regular SG stems, the composites reinforced by the small SG stems have significantly higher modulus of elasticity and tensile strength, as shown in Figure 4. Although the tensile properties of the small SG stem are significantly worse than the regular SG stem (the datum for the stem

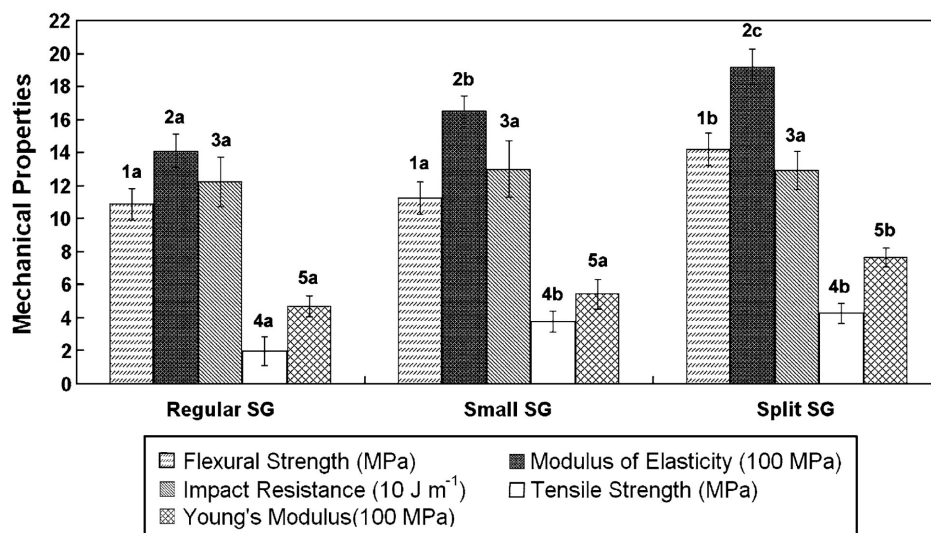


Figure 4. The effects of the split configuration and diameter of SG stem on flexural, impact resistance properties and tensile properties of SG-PP composites. Composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. The concentration of SG stem was 60%. The length of the SG stem was 5 cm. **1, 2, 3, 4, 5:** if data points had the same number, they represented the same mechanical property. **a, b, c:** If any two data points of the same mechanical property had totally different letters, the two data points were statistically different.

properties were presented at the experimental section), the aspect ratio and bulk density play more important roles in determining the properties of the composites. The decreased diameter with unchanged length of the stem leads to an increased aspect ratio which helps to improve the transfer of stress between the stems and the PP to achieve higher properties of composites. The lower bulk density of the small SG stem (0.42 ± 0.03 g/cm³ at 60% of SG concentration) than that of the regular stem (0.49 ± 0.01 g/cm³ at 60% of SG concentration) allows the stems to be used in larger volume and cover more area on the webs to decrease voids and improve the properties. However, other mechanical properties of the composites reinforced by the small SG stems do not show significant differences from the composites using regular SG stems.

The Effect of the Split Configuration on the Mechanical Properties of SG-PP Composites

As shown in Figure 4, the flexural strength, modulus of elasticity, tensile strength and Young's modulus of the

composites reinforced by the split SG stems were significantly higher than those of the composites reinforced by the regular SG stems. The regular SG stems (round with a hollow center) were split into two to four parts in order to increase the aspect ratio and enlarge the surface area. The opened inner and rough surface can improve the adhesive property between the stems and the matrix materials. The increased aspect ratio also leads to the improved mechanical properties.

Comparison of the Mechanical Properties Between SG-PP and Jute-PP Composites

As shown in Table 2, composites from mechanically split SG stem had nearly 56% higher flexural strength, 19% higher modulus of elasticity, 15% higher impact resistance, 63% higher Young's modulus, and 52% lower tensile strength compared with jute composites based on the data of jute-PP composites reported by Huda and Yang [37]. However, the tensile properties of SG stems were much worse than that of jute fiber. The regular SG stem had 113.4 MPa tenacity, 0.9% breaking elongation,

Table 2. Comparison of mechanical properties of composites from mechanically split SG stem and jute

Composites	FS (MPa)	MOE (GPa)	IR (J/m)	TS (MPa)	YM (MPa)
Mechanically Split SG Stem-PP	14.2 ± 1.0	1.9 ± 1.0	129.4 ± 11.6	4.3 ± 0.6	763.6 ± 58.4
Natural Jute-PP ^a	9.1 ± 0.4	1.6 ± 1.0	112.3 ± 8.6	8.9 ± 0.8	469.3 ± 30.1

Both composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm (0.47 g/cm³), and pressed at 185 °C for 80 s. The concentration of SG stem and jute was 60%. The length of the split SG stem and jute fiber was 5 cm
 FS = flexural strength, MOE = modulus of elasticity, IR = impact resistance, TS = tensile strength, YM = Young's modulus
 a. Jute data is from Huda and Yang [37]

and 15.1 GPa modulus compared with 295 MPa tenacity, 1.1% breaking elongation, and 16.9 GPa modulus for jute [38]. The reasons for the better mechanical properties, except the tensile strength, of composites reinforced by SG stems are mainly because of the low bulk density of SG stem. The bulk density of the stem is $0.49 \pm 0.01 \text{ g/cm}^3$ at 60% of SG concentration. That is lower than the bulk density of jute fiber ($1.02 \pm 0.04 \text{ g/cm}^3$). The void content percentage of SG-PP composites at 60% of SG concentration is 21.6%, which is much lower than the void content percentage of jute-PP composites (51.5% of void content). With the same weight of the reinforcing material in the composites, the lower bulk density of the stem allows the SG stems to be used in a higher volume that leads the stems to cover a larger area on the webs and to be packed very tightly in composites. During compression molding, the voids between stems and PP are reduced, due to the highly packed SG stems, to improve the mechanical properties.

Effect of Composites Densities on Mechanical Properties of SG-PP and Jute-PP Composites

For lightweight composites, the density of composites plays a critical role in determining the mechanical properties of the composites. When the density of composites is low, there are many voids in the composites. These voids create defects and decrease the mechanical properties of composites. The increasing of the density of composites leads to the increasing of the weight of both reinforcing materials and matrix materials, as well as the decreasing of the amount of voids. These changes lead to better mechanical properties than the composites at low density. As shown in Table 3, both mechanical properties of SG stem-PP and jute-PP composites increase greatly as the densities increase. The relationship between densities (750, 1500 and 3000 g/m^2 with fixed thickness of 3.2 mm) and mechanical properties was found to be linear with R^2 higher than 0.92.

Effect of the Whole and Split Configurations of SG Stems on Sound Absorption Properties of SG-PP Composites

As seen in Figure 5, composites from the regular SG stem have slightly higher sound absorption coefficients than composites from the small SG stem and split SG stem. The composites reinforced by the split SG stems have the lowest sound absorption coefficients in the comparison. This is because the split SG stems with larger surface area can cover more area in the composites, and are highly packed in the composites and leave a few amounts of micro voids in the composites. The micro voids can help to absorb the energy of sound waves

Table 3. Comparison of mechanical properties of composites among different densities of composites

Composites density (g/m^3)	Flexural strength (MPa)		Modulus of elasticity (MPa)		Impact resistance (J/m)		Tensile strength (MPa)		Young's modulus (MPa)	
	SG	Jute	SG	Jute	SG	Jute	SG	Jute	SG	Jute
0.24	2.8 ± 0.3	1.5 ± 0.3	442.3 ± 57.1	227.2 ± 95.6	0	24.3 ± 4.5	0	1.2 ± 0.2	0	81.1 ± 15.2
0.47 ^a	14.2 ± 1.0	9.1 ± 0.4	1917.6 ± 106.8	1635.0 ± 99.0	129.4 ± 11.6	112.3 ± 8.6	4.3 ± 0.6	8.9 ± 0.8	764.2 ± 58.4	469.3 ± 30.1
0.94	37.4 ± 1.8	25.3 ± 2.1	5151.5 ± 223.7	4100.8 ± 178.1	259.5 ± 29.0	464.2 ± 21.4	12.2 ± 0.9	16.2 ± 0.6	1435 ± 61.5	1004.8 ± 67.3
R^2	0.99	0.99	0.99	0.99	0.97	0.96	0.99	0.94	0.95	0.99

Both composites were fixed at a thickness of 3.2 mm, and pressed at 185 °C for 80 s. The concentration of SG stem and jute was 60%. The length of the split SG stem and jute fiber was 5 cm. Different composites densities were chosen at 750 g/m^2 (0.24 g/cm^3), 1500 g/m^2 (0.47 g/cm^3) and 3000 g/m^2 (0.94 g/cm^3) with the same thickness of 3.2 mm.

a. Jute composites (0.47 g/m^3) data is from Huda and Yang [37].

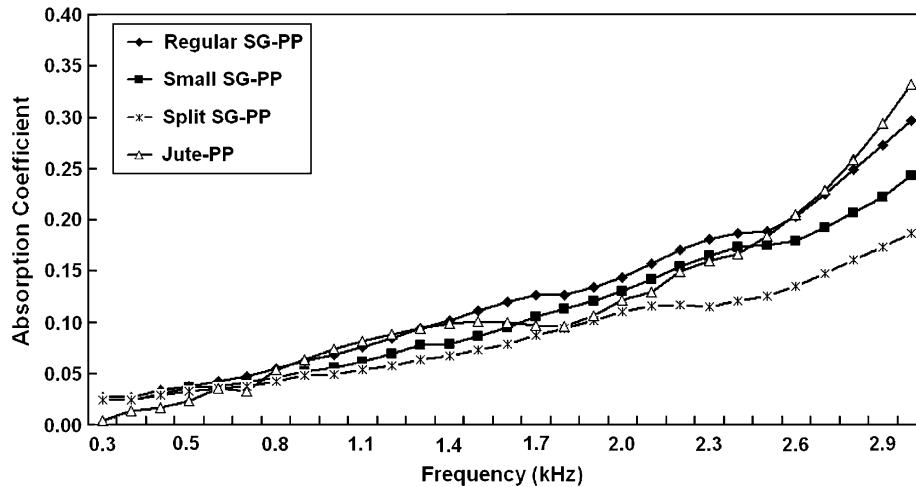


Figure 5. The effects of the regular SG stem (3.31 mm average in diameter), small SG stem (1.61 mm average in diameter) and split SG stem on sound absorption properties of SG-PP composites. The sound absorption of jute-PP composites was compared. Composites were fixed at weight/area of 1500 g/m² and thickness of 3.2 mm, and pressed at 185 °C for 80 s. The concentration of reinforcements was 60%. The length of SG stem or jute fiber was 5 cm.

when sound waves travel through different phases. Thus, the lower micro-voids content of composites reinforced by split SG stem leads to lower sound absorption abilities compared to the composites reinforced by the regular and small SG stems. Compared to jute-PP composites, the composites reinforced by the whole SG stems (the regular and small SG stems) have similar sound absorption properties, while the composites reinforced by the split SG stems have slightly worse property than jute-PP composites. However, good sound absorption property at low frequency (below 1.5 kHz) is desired for automotive composites because this frequency zone corresponds with noise from tires, the running engine, road, conversations, and wind. Thus SG-PP composites have similar sound absorption behavior as the jute-PP composites.

Conclusions

In this research, a newly developed method was applied to make lightweight composites from long SG stems and PP nonwoven webs. When the manufacturing parameters are set at 60% concentration of SG stems and 5 cm long with split configuration of stems, the SG-PP composites showed the best mechanical properties among the conditions studied during the compression molding at 185 °C for 80 s. Composites from mechanically split SG stem have 56% higher flexural strength, 19% higher modulus of elasticity, 15% higher impact resistance, 63% higher Young's modulus and 52% lower tensile strength and similar sound absorption property compared with jute-PP composites. Although the tensile properties of SG stem are much worse than jute fi-

ber, SG stems with low bulk density are found to better reinforce the lightweight composites. Except for the tensile strength, the superior mechanical properties of SG-PP compared with jute-PP composites, provide an opportunity for applications of SG composites in automotive interiors where composites reinforced by natural fibers are currently being used as support layers, and in the construction industry with the products such as ceiling tiles and office panels.

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