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Lightweight composites from long wheat straw and polypropylene web

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ABSTRACT

Whole and split wheat straws (WS) with length up to 10 cm have been used with polypropylene (PP) webs to make lightweight composites with properties superior to jute–PP composites with the same density. The effect of WS concentration, WS length, and split configuration (half, quarter, and mechanically split) on flexural and tensile properties of the composites has been investigated. The sound absorption properties of composites from whole straw and split straw have been studied. Compared with whole WS–PP composites, mechanically split WS–PP composites have 69% higher flexural strength, 39% higher modulus of elasticity, 18% higher impact resistance properties, 69% higher tensile strength and 26% higher Young's modulus. Compared with jute–PP composites, mechanically split WS–PP composites have 114% higher flexural strength, 38% higher modulus of elasticity, 10% higher tensile strength, 140% higher Young's modulus, better sound absorption properties and 50% lower impact resistance.

1. Introduction

The annual worldwide production of WS was estimated to be approximately 540 million tons in 2007 (Reddy and Yang, 2007). After harvest, most of these agricultural wastes are left on the ground to decompose (Schirp et al., 2006b). In some parts of the world, WS is burnt in open fields, causing air pollution (Li et al., 2007; Alemdar and Sain, 2008). Although a small portion of WS has been used as animal feed-stock and bedding (Panthapulakkal et al., 2006), industrial applications of WS are still under investigation.

One of such applications is using WS in composites. A major approach is to chop and mill WS directly into particles and then use the particles to make composites (Hervillard et al., 2007; Hornsby et al., 1997a; Han, 2001; Panthapulakkal and Sain, 2006; Schirp et al., 2006a,b; Shakeri and Hashemi, 2004). Other approaches include acid hydrolysis before milling (Digabel et al., 2004), steam explosion and thermo-mechanical processes (Avella et al., 1995; Halvarsson et al., 2009), chemical pulping before shearing (Panthapulakkal et al., 2006), and a chemi-mechanical technique to produce WS fibers (Ye et al., 2007; Alemdar and Sain, 2008). The most commonly used matrix materials for the WS composites are PP and high-density polyethylene (Avella et al., 1995; Digabel et al., 2004; Frounchi et al., 2007; Hornsby et al., 1997b; Johnson et al., 1999; Mengeloglu and Karakus, 2008; Panthapulakkal et al., 2006; Panthapulakkal and Sain, 2006; Schirp et al., 2006a,b; Shakeri and Hashemi, 2004). Other matrix materials used for the WS composites include urea formaldehyde (UF) resin (Han, 2001; Zhang et al., 2003) or melamine-UF resin (Halvarsson et al., 2008; Hervillard et al., 2007), starch-based thermoplastic polymer (Alemdar and Sain, 2008), soybean-based matrix material (Ye et al., 2005), polymeric methylene di-phenyl diisocyanate resin (Frounchi et al., 2007) and phenol–formaldehyde resin (Hervillard et al., 2007). Various coupling agents (Frounchi et al., 2007; Han, 2001; Hornsby et al., 1997a; Schirp et al., 2006a; Shakeri and Hashemi, 2004) or compatibilizers (Digabel et al., 2004; Frounchi et al., 2007; Panthapulakkal and Sain, 2006; Panthapulakkal et al., 2006) were also used to increase the adhesion between WS and resin for the improvement of the mechanical properties of the composites. In some literature, WS was treated with fungi (Panthapulakkal and Sain, 2006; Schirp et al., 2006a,b) or enzymes (Zhang et al., 2003) to improve its interactions with the matrix materials. Extrusion (Digabel et al., 2004; Hornsby et al., 1997a; Johnson et al., 1997; Panthapulakkal et al., 2006; Schirp et al., 2006a,b; Shakeri and Hashemi, 2004) and injection molding (Frounchi et al., 2007; Hornsby et al., 1997a; Johnson et al., 1999; Panthapulakkal et al., 2006; Panthapulakkal and Sain, 2006) were the most frequently used methods for making the WS composites, while compression molding (Avella et al., 1995; Frounchi et al., 2007; Hervillard et al., 2007) was also reported.

Most of the composites found in the literatures utilized straws in particle form at lengths ranging from 0.5 to 5 mm. The mechan-

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ical properties could potentially be increased by using longer straws. Chemical treatment to extract useable reinforcing materials from WS or to improve the adhesion between straws and the matrix polymer not only increases manufacturing cost but also poses an environmental challenge. Therefore, it is of significance to develop a process through which WS can be utilized in composites without milling or chemical treatment. Thermoplastic polymers such as PP or polyethylene (PE) in fibrous form are frequently used in cellulose-based thermoplastic composites. However, due to the long and stiff nature of WS, it is difficult, if not impossible, to mix the straws with polymeric fibers.

In this research, a novel method was applied to make PP composites reinforced with long WS (up to 10 cm). Nonwoven PP webs were used as a matrix. WS was spread randomly on the web, and then PP webs containing WS on the top were stacked layer by layer to make composites by compression molding. Using this method, the technical challenge of blending long WS with PP matrix has been overcome. The major advantage of this method is that the size and dimension of the reinforcing materials have virtually no influence on the composite manufacture process as long as the reinforcing material can be uniformly spread on the web. To the best of our knowledge, no literature exists related to composites from WS and the matrix in web form.

There were 51.52 million automobiles sold in the world in 2006; North America dominated with 36.2% of the total consumption. Therefore, utilization of WS composites in the automotive composites industry alone may potentially lead to utilization of substantial quantity of WS. Natural fibers such as jute, flax, and hemp are currently being used to reinforce composites in the automotive industry. However, WS is abundant and available at around \$0.04/kg, the cost to collect WS from the field (Reddy and Yang, 2007). The price for bast fibers is much higher. For example, jute price was about \$1.45/kg in May 2008 (Worldjute.com, 2008). Therefore, a substantial cost advantage can be achieved from composites reinforced with WS. Besides the automotive industry, composites from WS can also be used in construction, housing, office panels, and furniture industries.

The composites used as structural parts in automotive interiors are required to be light in weight. Lightweight composites are those composites with the densities lower than the summation of the density contributions from all the materials used to build the composites (Huda and Yang, 2009a,b, 2008a,b). For example, composites made from 50% polypropylene (density of 0.9 g/cm^3) and 50% jute fibers (density of 1.5 g/cm^3) with a density of 0.5 g/cm^3 are considered lightweight composites because $0.5 < (0.5 \times 0.9 + 0.5 \times 1.5) = 1.2$.

Obviously, the only way to make the lightweight composites using relatively heavier materials is to create voids inside the composites. These voids create defects and decrease the mechanical properties of the composites. Thus, the density of the composites, which is highly related to the amount of voids in the composites, becomes an important parameter for the mechanical properties of composites. In this research the properties from WS composites were compared with the properties from jute–PP composites with the same density instead of the properties from some compact composites with much higher density reported elsewhere.

The objective of this research was to utilize long and untreated WS to make lightweight thermoplastic composites through a simple and cost effective method. During the research, the effects of straw concentration, length of WS and split configuration (whole, half, quarter, and mechanical) on mechanical properties of composites were studied. In addition, sound absorption properties of WS composites have also been investigated. Mechanical and sound absorption properties of WS–PP composites have been compared with jute–PP composites.

2. Methods

2.1. Materials

WS were obtained from fully mature wheat crops. The major constituents of WS are 71.24% cellulose and hemicellulose, 23.22% lignin and 5.54% ash (Zhang et al., 2003). The wheat straw was cut into certain lengths (1, 5, and 10 cm) in order to investigate effect of length on composites properties. For the study of the effect of surface area of WS on composite, straws were split in half along the longitudinal direction using a knife to double the surface area. Straws were further split into quarter to investigate the effect of aspect ratio (length/width) on mechanical properties. In order to investigate the feasibility of utilizing a mechanical device to split WS for mass production, a two-roller laboratory milling machine (KICE Industries incorporation, Wichita, Kansas) was used to split WS.

Spunbonded PP web was provided by Spunfab Ltd. (Cuyahoga Falls, OH). The mass/area of the web was 23.7 g/m^2 (0.70 oz/yd^2), melting temperature was 162 °C, Melt Flow Index (MFI) was 38 g/10 min measured at 230 °C, and density was 0.90 g/m^3.

2.2. Composite fabrication procedure

The weight/area of all composites was set for 1500 g/m^2 at an area of 25.4 cm × 30.5 cm. Metal spacers were used to set a thickness of 3.2 mm during the compression molding, thus the density of the composites was 0.47 g/cm^3. The nonwoven PP webs were laid on a smooth table from a let-off shaft. Based on the WS concentration, composite weight, and web weight/area, the total area of required web was calculated and translated to the number of pieces of 25.4 cm × 30.5 cm PP web, which were left on the table. Weighed WS were laid randomly on the web through sprinkling in order to achieve random and homogeneous distribution. Some WS protruded from the edges of the web and were cut and put back on the web. The web with WS on top was cut carefully into 25.4 cm × 30.5 cm pieces and stacked one by one. Equal numbers of layers of PP webs were placed at the top and bottom of the composites with 98.6 g/m^2 weight/area to achieve smooth surfaces and to balance the composites. This also provides smoothness and keeps WS at the top and bottom from being exposed, reduces moisture absorption, and creates an I-beam structure, which leads to increased mechanical properties. The stacked layers were placed in between two aluminum sheets coated with Teflon and pressed in a laboratory-scale press (Carver Inc., Wabash, IN, USA) preheated to the desired temperature. The thickness was controlled by metal spacers.

This method is different from the ones used for typical compact composites reported in other literature because in this method, composites are made with built-in voids leading to lighter composites compared with the compact ones. After a desired holding temperature and time to make PP melt and bond to WS, the press was turned off and cooling system was turned on. When the temperature decreased to about 35 °C, the composite was removed from the press.

The holding temperature of compression molding was initially set at 185 °C, based on the results reported by Huda and Yang (2008a, 2009b) as the optimal parameter. The effect of holding time (40, 80 and 120 s) on flexural and impact resistance properties was studied at 60 wt.% and 5 cm WS. The results showed the composites had the best mechanical properties when the holding time is 80 s. Then the holding time was fixed at 80 s, and the effect of holding temperature (175, 185 and 195 °C) on flexural and impact resistance properties was studied at 60 wt.% and 5 cm WS. The results showed that the composites held at 185 °C had the highest modulus and were not statistically different in flexural and impact resistance properties compared to other two temperatures. Thus the holding