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Comparison of performances of corn fiber plastic composites made from different parts of corn stalk

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ABSTRACT

Lignocellulosic fiber, as a reinforcing phase, significantly altered the mechanical properties of wood plastic composites (WPC). In this paper, the effects of the different parts of the corn stalk, i.e., the stem, ear, husk, cob and leaf, on the manufacture of corn fiber plastic composites (CFPC) were evaluated. Besides, the mechanical properties of the CFPC were affected by the composition in terms of the cellulose, hemicellulose and lignin fractions, which was also explored herein. Our data showed that hemicellulose and lignin have significant effects on all properties of CFPC. Typically, a high cellulose and lignin content improved the mechanical properties of the CFPC. The results indicated that when using the corn stem, with the highest cellulose content, as the reinforcement, the highest flexural strength (46.10 MPa) and tensile break strength (26.58 MPa) were achieved. However, the content of hemicellulose should be lower, which was correlated with the water resistance. Due to the high hemicellulose content in the corn leaf, the leaf-reinforced CFPC showed the poorest performance, with a flexural strength of 28.70 MPa and a tensile break strength of 15.98 MPa. Taken together, the results showed that the stem or cob was the more suitable corn fiber for the preparation of CFPC.

1. Introduction

Renewable resources such as lignocellulosic fibers have long been recognized as environmentally friendly and low-cost alternatives to replace synthetic fibers as the reinforcing phase in the manufacture of wood plastic composites (WPC) (Khan et al., 2009). Recycling wood processing residues by used in WPC would optimize the use of harvested trees or agricultural residues, increasing the entire value chain and reducing the environmental footprint.

Because of the wide range of properties of the lignocellulosic fibers determined by its type, the ultimate performance of the WPC depends on the lignocellulosic fibers (Wambua et al., 2003), which are mainly composed of cellulose, hemicellulose and lignin. These fractions are connected by hydrogen bonds and chemical bonds (Scheller and Ulvskov, 2010). The hydrophobic-hydrophilic interactions between the natural fiber and polymer matrices are critical to the WPC's properties, which mostly depend on the ratio of cellulose to hemicelluloses in the lignocellulosic fiber (Mohanty et al., 2005). In the lignocellulosic fiber, each component has its unique structure and property (Beaugrand et al., 2014), for example, the hemicellulose has a high hydrophilicity, and however, the lignin provides mechanical strength for the cell walls, which can serve as a matrix (Wood et al., 2011) in the WPC preparation. However, in a given lignocellulosic biomass resource, the tissues in different positions of the biomass show structural discrepancies, such as their stiffness, biodegradability, density, and the chemical composition of their cell walls.

Rongxian (Ou et al., 2014a,b) investigated the effect of the removal of hemicellulose and/or lignin on the mechanical properties and dimensional stability of the WPCs. They found that the proportion of the three components had a great influence on the final mechanical properties of the WPC. The decline of the hemicellulose proportion improved the tensile strength and water resistance of the composites, which may indicate a decrease in the hygroscopicity of the wood flour, better compatibility, and interfacial bonding between the filler and matrix (Hosseinaei et al., 2012). In previous studies, the fibers were characterized by their cellulose content, ash content, and fiber aspect ratio (Koubaa, 2014), Georgopoulos et al. (2005) demonstrated significant differences between different positions of maize straw. Different parts of the same biomass may hence cause differences in the performance of the resulting WPC.

The previous studies of WPC mostly focused on the average composition differences within a biomass species, but did not dis-

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cuss the different parts of the same biomass, such as corn. After the harvest, the cob, husk and stem (including the leaf and ear) are separate managed by mechanized operations (Ping et al., 2016; Di et al., 2016) separating the different parts of the corn stalk in an industrial context. The different growth parts of the corn stalk (corn stem, corn cob, corn ear, corn leaf, corn husk) have intrinsic properties because of their diverse compositions and structures (Safdari et al., 2011; Yemele et al., 2010) and material constitutions of their fiber microstructures (Yemele et al., 2013). Ethanol yield for different parts was different (Ping et al., 2016). And cob was more effective for ethanol production than other fibers. Di et al. (2016) investigated the effect of dilute alkaline pretreatment on the conversion of different parts of corn stalk to fermentable sugars and its application in acetone-butanol-ethanol fermentation. The application of different corn parts in fermentation is distinguishing. But no study explored the difference on the manufacture of corn fiber plastic composites (CFPC). Corn is a main food in China, especially in the northern area, such as Inner Mongolia. It is estimated that approximately 230 million lignocellulosic corn stalks are produced each year (Di et al., 2016). However, after the corn harvest, most farmers burn the stalk, which leads to environmental degradation, such as haze (Wang et al., 2011). Haze is a global issue, especially in China; therefore, the study of the application of corn stalks in CFPC is of great significance for China and the rest of the world.

The purpose of this study is to determine the composition differences between the five corn stalk parts (corn stem, corn cob, corn ear, corn leaf, corn husk) and their effect on the properties of CFPC. There are three aspects of comparison. First, different parts of the corn stalk were evaluated to determine the variations in composition. Second, the structural properties of the different corn stalk fibers, involving the surface free energy and functional groups were investigated. Third, the mechanical and physical properties of the CFPC were tested. The results presented here will show which corn fiber was suitable for the manufacture of CFPC. The performance of CFPC using the corn fibers as raw materials will be enhanced, since the corn fiber can be separated selectively by mechanized operations during the harvest.

2. Materials and methods

2.1. Corn fibers and sampling

Corn stalks were harvested on a local farm in Tong Liao, Inner Mongolia. The different parts of the corn stalk including the stem, cob, ear, leaf, and husk, were collected and dried at 105 °C overnight, followed by crushing and screening (the particle size is below 40 mesh).

2.2. Component analysis

One gram of corn fibers was used for the material component analysis using a raw fiber extractor (FIWE6, VELP, Italy) according to the Van Soest method (Van Soest et al., 1991). There are three groups of parallel test experiments. The significant digits of the results were determined based on the standard of the NREL (Sluiter et al., 2008).

2.3. Physical properties of corn fibers

2.3.1. Contact angle measurement and surface free energy

The contact angle (CA) on the surface of the sample was measured by a dynamic contact angle analyser (JC2000D, Powereach, Inc., China). The corn fibers were compressed into tablets at 10 MPa and mounted on a microscope stage. A drop of water was dropped on the surface, and the contact angle was calculated based on the height and chord of the droplet. Because the contact angle of the corn fibers can be neglected when nonpolar liquids are used, an equation of state was used to calculate the surface free energy (Owens, 1970).

$$\gamma_s = \gamma_s^D + \gamma_s^P \quad (1)$$

2.3.2. FTIR

The infrared spectra were recorded using KBr pellets on a Nicolet 6700 spectrometer (Thermo Fisher, USA) with a resolution of 4 cm^{-1}, and 32 scans were used. The corn fibers were grinded before the sample preparation (Părpăriţă et al., 2014).

2.3.3. XRD

X-ray diffraction (XRD) diagrams were recorded on a Bruker D 8 Advance X-ray diffractometer, filtered with Cu Kα radiation (k = 1.5406 A) in a 2 h range of 3° to 60° at a scan rate of 0.02°/s (Părpăriţă et al., 2014). The crystallinity index (CrI) is a parameter commonly used to quantify the amount of crystalline cellulose present in cellulosic materials (Lavoine et al., 2012; Hall et al., 2010) and was determined by the equation (Segal et al., 1959)

$$\mathrm{CrI}(\%) = (I_{002} - \mathrm{I_{am}})/\mathrm{I_{002}} \times 100\% \quad (2)$$

where I_{002} is the highest peak intensity (Ju et al., 2015) at the angle of diffraction of 2θ = 22.5°, whereas I_{am} is the peak for amorphous cellulose at 2θ = 18°.

2.4. Composite preparation

High-density polyethylene (HDPE600) plastic was purchased from Beijing Golden Horse Weiye Plastic Co., Ltd. MA-HDPE, stearic acid and polyethylene wax were used as coupling agents at contents of 3%, 4%, and 3%, respectively, and they are commercially available. The content of corn fiber is 50%, and the HDPE content is 40%. First, the corn fibers were adequately mixed with plastic and coupling agents, and then the mixture was extruded by a co-rotating twin-screw extruder (COPERION ZSK series, Werner & Pfleiderer, Germany) with zones heated to 140–175 °C. The standard specimens were injected using an injection moulding machine (HTF120X2, Haitian, China), the injection temperature was 140–165 °C, and the injection pressure was 60 MPa.

2.5. Mechanical properties

Mechanical properties including the flexural strength and tensile break strength, flexural modulus and tensile modulus, and elongation were tested using a materials testing machine (INSTRON 1185, USA) in accordance with a government standard of China (GB/T 24508-2009) (Wang et al., 2012). Five specimens of each composite were tested, and the result was reported as the average. Before each test, the size of the specimens should be measured accurately. The speed of the flexural test was 10 mm/min, and it was 20 mm/min for the tensile test.

2.6. Water absorption

The water absorption tests were conducted according to GB/T 24508-2009 (Wang et al., 2012) at a room temperature of approximately 20 °C. Five specimens of each composite were submerged in distilled water for 72 h. After immersion, the water on the surface of the samples was removed, and the samples were immediately weighed. The amount of water absorption (Mt) was calculated as

$$Mt = (m_1 - m_0)/m_0 \times 100\% \quad (3)$$

where m_1 is the weight of the sample after immersion and m_0 is the initial weight before the water immersion.

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