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The utilization of bamboo charcoal enhances wood plastic composites with excellent mechanical and thermal properties

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ABSTRACT

In order to enhance the mechanical properties and thermal properties of wood plastic composites (WPCs), bamboo charcoal (BC) was used as reinforcing filler of WPC, and a series of BC-WPC composites were prepared. The effect of BC and water treatment on water absorptions, morphologies, mechanical properties, the effect of water treatment on mechanical properties and thermal properties of the composites were investigated. The results showed that BC could have strong interfacial interaction in the WPC. The water resistance, flexural properties, tensile properties and thermal properties of BC-WPC were higher than WPC. The flexural and tensile properties were reduced and the impact strength was increased after water treatment. The presence of BC resists the influence of water absorption on composites mechanical properties.

1. Introduction

Wood has played a vital role in the social, economic and environmental development of human history. However, increasing demand for the limited forest resources in various applications has led to the shortage in wood supply. Thus, there is an urgent need to look for new materials as alternatives or substitutes of wood [1]. Among them, wood plastic composites (WPCs), manufactured products composed of woody materials and thermosetting/thermoplastic resins, are the potential materials since they are low-cost, biodegradable, renewable, and eco friendly [2–4]. WPC are initially used for decking and non-structural building applications, but now they have been extensively developed for a wider range of applications, including buildings and constructions, automotives and gardening and outdoor products. However, one of the lethal weaknesses of WPC is their poor mechanical properties, due to the weak interface between wood flour and polymer matrix [5–8]. On the other hand, wood flour (WF), one of the components of WPC, contains cellulose, hemicellulose and lignin, in which the hydroxyl groups build a large amount of hydrogen bonds between the macromolecules of the wood polymers [9]. The hydroxyl groups could form new hydrogen bonds with water molecules, which induce the water absorption, fiber swelling and creation of micro-cracks in the sample, resulting in debonding fibers and degradation of interface of fiber-matrix.

In order to improve the mechanical properties and water resistant of WPC, various approaches have been carried out. Some of them are concentrated on processing the WF, such as acetylation [10], silane treatment [11], heat treatment [7], and treatment with sodium hydroxide [12]. Besides, the incorporation of nanoparticles as reinforcing filler is another method for improving the overall properties of lignocellulosic-thermoplastic composites, such as silica nanopowder [8] and montmorillonite [13]. However, these methods have their own weaknesses, such as complicated processing processes and easy aggregation of nanoparticles which caused poor dispersion in polymer matrix and limited increase in overall properties of composites.

Bamboo charcoal (BC) can be produced from the widespread fast-growing speed and short growth period moso bamboo plants in China. The bamboo and bamboo residues can be transformed to BC at a high temperature under nitrogen atmosphere, which is a mature technology used in China [14]. In recent years, BC has attached great attention in many fields, such as supplier of negative ions, warming effect of far infrared rays, water purifying power of microbes, humidity regulator, oxidization prevention, and a rich source of minerals [15–17]. BC has countless small holes lengthwise and crosswise. The number of holes, mineral constituent and absorption efficiency of BC are about 5 times, 8 times and 10 times as many as those of wood charcoal [18]. A good deal of holes in BC might be able to stronger interface between filler and polymer matrix, because polymer chains could get into these holes when the polymer has good liquidity. Up to now, no published reports are available regarding the effect of BC on the mechanical properties, water resistant and thermal properties of WPC.

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BC powder contains many pores and gaps in its structure and low-density polyethylene (LDPE) have good liquidity. Therefore, incorporation of BC with LDPE would lead to a better interfacial adhesion between matrix and filler. The objective of this research was to investigate the effects of BC on water absorption, thermal properties and mechanical properties of WPC, and the effects of water absorption on mechanical properties of bamboo charcoal-wood plastic composites (BC-WPC).

2. Experiment

2.1. Materials

The bamboo charcoal (BC) was purchased from Shunfa Craft Production Factory (Shenzhen, China). Low-density polyethylene (LDPE) was purchased from China Petroleum & Chemical Co., Ltd. (Guangzhou, China). The lubricant (LEPA) was supplied by Ma Ji Sen composite materials Co., Ltd. Wood flour (WF) was supplied by Wei Hua spice Co., Ltd. (Guangdong, China).

2.2. Preparations of samples

Formulations of the mixtures and abbreviations used for the respective composites were illustrated in Table 1. The preparation processes of BC-WPC and WPC were schematically shown in Fig. 1. The mixtures were premixed before being fed into the first zone of the extruder. WPC and BC-WPC pellets were prepared by using a twin screw extruder (SHJ-20 with average screw diameter of 20 mm and average L/D ratio of 40), with a temperature profile of 80/130/135/140/145/150/145 °C and a rotating speed of 120 rpm, and then the extruded strands were passed through a trough and palletized. The pellets were injected into ISO standard specimens by using an injection molding machine (HMT OENKEY) at 155 °C.

Some of specimens were placed in a container filled with distilled water, supported on edge and entirely immersed for 4 months.

2.3. Characterization

Scanning electronic microscope (SEM) was performed on JSM-6330F scanning electron microscope with an accelerating voltage of 20.0 kV; the fracture surfaces of samples were coated with a thin layer of gold before analysis.

2.4. Water absorption properties

The water absorption test was conducted as per ISO standards 62: 2008 [19]. The conditioned specimens were placed in a container of boiling distilled water, supported on edge and entirely immersed. At the end of 30 ± 2 min, the specimens were removed from the boiling water and cooled in distilled water maintained at room temperature. After 15 ± 1 min, the specimens were removed from the water, and one at a time, all surface water was removed with a dry cloth. The water content at saturation was measured by re-immersing the test specimens and re-weighing them at an interval of 30 ± 2 min. After each of these intervals, the test specimens were removed from the water, cooled in distilled water, dried and weighed as described above. The percentage of water absorption was calculated according to the following equation:

$$WA(\%) = \left(\frac{W_2 - W_1}{W_1}\right) \times 100$$

Here W_1 is the weight of oven-dried composite sample before immersion and W_2 is the weight of the composite sample after immersion. The tests were made in quintuplicate and the results were reported as average.

Table 1
Formulations of the mixtures and abbreviations for respective composites.

Sample	LDPE (%)	WF (%)	BC (%)	LEPA (%)
LDPE	98	0	0	2
WPC	48	50	0	2
BC-WPC$_2$	46	50	2	2
BC-WPC$_4$	44	50	4	2
BC-WPC$_8$	40	50	8	2

2.5. Mechanical properties

The tensile and flexural tests were carried out by using a Universal Testing Machine (LLOYD LR100K) according to ISO standards 527-1 [20] and ISO standards 178 [21] respectively. The notched Izod impact strengths were conducted following ISO standards 179-1 [22] with impact type test machine (ZBC-50). Five samples of each category were tested and their average values were reported.

2.6. Thermal properties

Thermal behaviors of WPC and BC-WPC were examined using a thermogravimetric analyzer. Each composite was heated from room temperature to 800 °C at a rate of 10 °C/min. Thermal decomposition temperatures of the composites were examined under nitrogen atmosphere.

3. Results and discussion

3.1. Water absorption properties

Water absorption is one of the most important characteristics of WPC exposed to environmental conditions that determine their ultimate applications. Water absorption in composites can be mainly ascribed to the presences of lumens and hydrogen bonding sites in the WF and the gaps at the interface between matrix and reinforcement. Fig. 2 shows the percentages of the water absorption for the composites after immersion in boiling water, which varies depending upon the BC contents. Besides, it was observed that incorporation of WF into LDPE significantly increased the water absorption of material due to the surface hydroxyl groups of WF and inferior WF-matrix interface. Since LDPE material could not be large enough to cover the surface of WF completely due to large contents of WF, it would result in creating gaps between WF and LDPE and weaker interfacial bonding, which was proved by SEM images later on.

Theoretically, adding BC into WPC would improve the water absorption of composites because BC contains many pores and gaps in its structure. Nevertheless, the experiment data reversed with the result of theory, that is, incorporation of BC into WPC slightly improved the water resistance of composites. Moreover, with the increase of BC content, the water resistance also increased. The results suggested that the pores and gaps in structure of BC were filled by LDPE, and then the BC filled the gaps between WF and LDPE, which let more LDPE cover the surface of WF, resulting in strong WF-matrix interface. The water resistance increased with increasing content of BC. The result was attributed that the BC had homogeneous dispersion and strong interfacial interactions in the BC-WPC.