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Role of surface treatment on water absorption of poly(vinyl chloride) composites reinforced by *Phyllostachys pubescens* particles

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ABSTRACT

Water absorption is one of key parameters in quality assessment of wood-plastic composites. The influence of surface treatment of lignocellulosic particles on water absorption of composites made from poly(-vinyl chloride) (PVC) and moso bamboo (*Phyllostachys pubescens*) particles was studied. The effect of modification with three kinds of chemical treatment agent (alkali, silica and oxidant) on particle surface was examined. The concentration and pH values of the agent aqueous solutions were analyzed and their relationships with water absorption, porosity ratio, thermal property, micro-structure and hemicelluloses content were evaluated. Results showed that pH values of aqueous solutions had little impact on water absorption of the composites while the types of treatment agents did. Alkali treatment lowered the content of hemicelluloses in moso bamboo particles and thus reduced corresponding water absorption. Water resistance improvements of silicate or oxidant treated particles reinforced composites were due to changes of porosity ratio. In general, surface treatment improved water resistance of moso bamboo particles reinforced PVC composites. Compared with the other two agents, sodium bisulfite enhanced the compatibility between cellulose particles and granulated PVC.

1. Introduction

Natural fiber composites are one of the outstanding topics nowadays to make reconciliation between industry and environment. Many efforts have been done to investigate the suitability of natural fibers as a reinforcing component of poly(vinyl chloride) (PVC) polymers during the last few years. A brief summary of tested materials and investigated parameters through Refs. [1–7] have been presented in Table 1. These composites show high mechanical and thermal properties, thus they are widely used in different purposes from construction materials to decorative parts and from aerospace components to vehicles' compartments. Moso bamboo (*Phyllostachys pubescens*) is a famous plant due to its broad applications in wood industry and constructional works. The natural fiber reinforced plastic composites that utilize this plant have drawn much attention because of their biodegradability and environmental friendly nature. Kim and his colleagues studied morphology and mechanical behavior of PVC/bamboo flour composites [8]. A comparison of tensile properties, morphology and thermal behavior between PVC composites containing bamboo flour and pine flour was done in another research work and showed their suitability as wood-like materials [9]. The role of wood particles in thermoplastic composites has been comprehensively studied in a number of researchers such as the work of Stokke and Gardner [10]. These composites often encounter limitations in application because of low water resistance. Researchers have previously found the water resistance of PVC composites proportionally dependent with the volume fractions of fibers as well as the interface bonding [11,12]. An improvement in water resistance of moso bamboo reinforced PVC composites would significantly enhance their qualities and consequently widened their applications.

An enormous amount of researches had been invested in studying the modification of natural fibers and their subsequent characterizations in composites. Kim et al. [8] used poly(styrene-co-maleic anhydride)–block–poly(styrene-co-acrylonitrile) as a novel coupling agent in making PVC/bamboo flour composites. Vilay and Cui et al. concluded that chemical treatment reduced the hydroxyl group in structural molecules of the cells' wall in natural fibers and resulted in lower water absorption of the composites [13,14]. Bilba et al. used silane to treat bagasse fiber and improved the hygroscopic behavior of its reinforced cementitious composites [15]. Bessadok et al. investigated influence of chemical modifications of *Agave* and Alfa (*Stipa tenacissima*) fiber [16,17] and found that both fiber and fiber interface would affect fibers' water sorption. Demir et al. regarded that water absorption was caused by hydrogen bonding between free hydroxyl groups in cellulose molecules and water molecules as well as the adhesion between fiber and matrix [18]. Acrylonitryl and anhydride acetic were also used to treat moso bamboo fibers [19,20]. However, roles of different types of surface treating solutions and their concentrations on water

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Table 1
Brief summary of investigated materials and parameters concerning natural fiber-PVC composites from selected researches.

Refs. no.	Type of fiber(s)	Polymer matrix and additive(s)	Investigated parameters
[1]	Bagasse, rice straw, rice husk, pine fiber	PVC + styrene-ethylene-butylene-styrene (SEBS)	Storage modulus, tensile strength, impact strength, glass-transition temperature, degradation temperature, thermal activation energy, water absorption, thickness swelling
[2]	Oil palm empty fruit bunch (OPEFB)	PVC + benzoyl chloride + NaOH	Tensile strength, impact strength, adhesion quality, water resistance, glass-transition temperature
[3]	OPEFB	PVC + epoxidized natural rubber (ENR) + poly methyl acrylate	Glass-transition temperature, thermal stability
[4]	OPEFB	PVC + ENR + poly methyl acrylate	Ultimate tensile strength, Young's modulus, elongation at break, flexural modulus, hardness and impact strength
[5]	Wood flour	PVC + Zn and Pb stearates + zeolite	Thermal stability, decomposition temperature
[6]	Rubber wood sawdust	PVC + low density poly-ethylene (LDPE), methyl methacrylate + silane	Tensile strength, impact strength, glass-transition temperature, morphological properties
[7]	Banana wood fiber	PVC	Tensile strength, impact strength, specific weight

absorption of moso bamboo particles reinforced PVC composites, especially prosperity ratio and compatibility changes still seem unclear.

This article presents an experimental assessment of different types of aqueous solutions as surface treating agents, including alkali solution, silicate solution and oxidizing solution as well as their concentrations on water absorption of moso bamboo particles reinforced PVC composites. Concentration and pH value were employed as the characteristics of different aqueous solutions. Water absorption, porosity ratio, thermal behavior and micro-structure morphology were adopted to evaluate the manufactured composites. The mechanism of surface treatment of moso bamboo particles and its effects on water absorption and other mentioned parameters in bamboo fiber reinforced PVC composites were analyzed by consideration of the impact of type and concentration of above mentioned chemical solutions. This experimental procedure laid a framework for a systematic study of surface treatment and its influence on water resistance of natural fiber reinforced composites and aimed to find the most effective treatment agent among the investigated chemical solutions and its optimum concentration.

2. Materials and methods

2.1. Materials

Sawdust of moso bamboo was collected from a local moso bamboo processing factory in Lin'an, Zhejiang, China. The moso bamboo was dried at 75 °C to 3% moisture content and then ground by a hammer mill to a particle size range of 200–400 μm. Granulated PVC (M-1000, about 300 μm diameter) from Shanghai Chlor-Alkali Chemical Co., Ltd. (Shanghai, China) was used as the polymer matrix. Sodium hydroxide (purity >96%) was supplied by Hangzhou Chemical Reagent Co., Ltd. (Hangzhou, Zhejiang, China). Sodium silicate was bought from Rugao Zhongbang Chemical Co., Ltd. (Shanghai, China). Sodium bisulfite was supplied by Shanghai No. 4 Reagent & HV Chemical Co., Ltd. (Shanghai, China).

The moso bamboo particles were soaked in sodium hydroxide, sodium silicate, sodium bisulfite solutions (solutions temperature was 20 ± 3 °C) at different concentrations (0.5%, 1%, 2%, 5% and 10%) for 15 min, then washed with distilled water for several times. After that they were dried in a blast drying oven (GZX-9140 ME Electric Blast Drying Oven, Shanghai Boxun Co., Ltd.) at 75 °C.

2.2. Preparing the composite specimens

Closed mould hot compressing technique was used to fabricate bamboo–PVC composites in this study. Inner size of the mould was 152 × 152 × h mm, where h was the thickness of the composites. The bamboo–PVC mixing ratio as well as operational parameters (temperature, pressure and time) was adopted according to preceding research work [11]. Moso bamboo particles obtained after surface treatment were mixed with PVC at a weight proportion of 7:3. Then they were put into the mould homogeneously and molded in a hot press molding machine (GT-7014-A50C, GOTECH). The mould was preheated at 170 °C for 3 min, and pressed at 180 °C by a pressure of 10 MPa for 5 min. In this study five replicates of each sample were taken and the average values were calculated for the following analysis.

2.3. Characterizations

2.3.1. Water absorption of the composites

Water absorption tests were conducted in accordance with ASTM D570-98 [21]. The specimens were dried at 75 °C for 4 h and weighed (W_o), then immersed in distilled water at room temperature (20 °C) for 2 h and 24 h respectively. The composites specimen was removed from water afterwards and dried with bibulous paper to remove the water present on composites' surface and weighed again to measure the saturated weight (W_t). The water absorption was calculated as follows:

$$\text{Water absorption } (\%) = \frac{W_t - W_o}{W_o} \times 100 \qquad (1)$$

2.3.2. Hemicellulose content of moso bamboo

Wood extractives were removed prior to analyze of structural components of moso bamboo by the use of water according to TAPPI T264 [22]. Sugars were analyzed by 3,5-dinitrosalicylic acid (DNS) according to Miller (1959) [23]. Determination of γ-cellulose was carried on according to TAPPI T203 om-93 [24] with two replicates per sample. This method was chosen due to lack of an adequate method for analysis on degraded wood. Therefore, γ-cellulose mainly represented hemicellulose in moso bamboo with this method.

2.3.3. Porosity ratio of the composites

The terms commonly used in composites are porosity and air filled porosity, also known as free air space (FAS) [25]. Porosity of composite samples is defined as the ratio of void volume to total volume of the sample, including air and water filled voids. Eftoda and McCartney [26] proposed that the total volume of air in a composting matrix could be further divided into inter-particle and intra-particle air voids based on whether it was contained in interstitial voids between particles or in pore spaces within particles respectively. They distinguished the first one as the readily