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Effects of different thermal modification media on physical and mechanical properties of moso bamboo

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HIGHLIGHTS

- Green modification and sustainable green material are presented for future development.
- Physical and mechanical properties of heat-treated bamboo are investigated.
- Well dimensional stability of the heat-treated bamboo are demonstrated.
- Bamboo heat treated in oil achieved a relatively better ASE and good anti-moisture effectiveness.

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ABSTRACT

This study employed thermal modification technology to modify moso bamboo (*Phyllostachy edulis*) and explore its future development as a sustainable green material. Experimental studies were conducted on heat treatments of moso bamboo in three media, namely air, nitrogen and linseed oil. Under the different treatment media, moso bamboo was heated to 4 temperatures (150, 170, 190 and 210 °C) for 3 treatment durations (1, 2 and 4 h) to investigate the thermal, physical, surface, dimensional stability and mechanical properties of the heat-treated bamboo. The results showed that higher temperature treatments could not only lead to decreases in the equilibrium moisture content and density of bamboo, but to an increase in mass loss. Bamboo treated in linseed oil attained a higher density, mainly due to the oil infiltrating the bamboo cell walls. The anti-shrinking and moisture-excluding efficiencies of the treated bamboo improved as the treatment temperature increased, indicating considerably good dimensional stability. In addition, the results of mechanical tests indicated certain decreases in mechanical properties as the treatment temperature increased in all the three treatment media.

1. Introduction

The growing demand for forest resources has resulted in annual declines in the availability of logs and high-quality timber. Many countries have implemented restrictions for tree logging; therefore, exploring alternative materials for the replacement of solid wood has become increasingly critical. Bamboo is considered a favorable and renewable material and has been gaining increased attention.

Bamboo is fast growing, with just 3 years required to be mature enough for harvesting. It has good commercial value and is often used in construction or for making furniture, mats, musical instruments and art crafts. Due to its short growth and renewal cycles and high tensile strength, bamboo has been deemed as one of the most promising alternatives for replacing wood in some applications. However, bamboo is a type of biocomposite material, and its variability in compositional structures, such as different density distributions across bamboo cane thickness and differences in the top and bottom portions of bamboo canes, may lead to various effects in its application.

Previous research has found that the maximum density, tensile strength, elastic modulus and dimensional shrinkage rate are distributed mainly at the outer layer and top part of a bamboo cane [1]. Despite its features of fast growth and high mechanical properties, bamboo is more vulnerable to biodegradation than wood [2], due to the high contents of starch and sugar in the bamboo, making it a nutritious host for insects and fungi [3–4].

To improve its properties, bamboo is treated with preservatives that are also used for wood. However, these preservatives have been posing negative influences on human health and environment. The increasing public attention to the environment and

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restrictions in the use of harmful chemicals has led some European countries to develop and apply environment-friendly thermal modification technologies on wood. Despite deterioration in wood mechanical properties due to heat treatment, thermally modified wood has the distinct advantages of being environmentally friendly, highly effective in anticorrosion, dimensional stable and weathering resistant.

Thermal modification may, therefore, be considered as an effective method for the development of new materials for a broad range of applications. To date, a number of new materials have been designed and developed by using different thermal modification technologies, such as ThermoWood® of Finland, Retification® and Torrefaction® of France, and PLATO-wood® of the Netherlands.

Parameters of concern in heat treatment include temperature, heating speed, medium, duration, cooling down duration and controlling process. Results of heat treatment can vary depending on the material treated. Therefore, the selection of heat treatment parameters according to the material of interest is important in producing thermally modified materials. However, the information in this field for bamboo is limited.

To study the effect of heat treatment on physical properties of bamboo, Nguyen et al. [5] investigated two of the main bamboo species growing in Vietnam and heat treated at various conditions. The mass loss of treated bamboo increased as the treatment temperatures and durations increased. In addition, the values of mass loss also varied depending on both the bamboo species and the culm zones.

Wahab et al. [6] treated Semantan bamboo (*Gigantochloa scortechinii*) under different durations and found that the density of the treated bamboo decreased as the treatment temperature and duration increased. This density decrement was attributed to the mass loss due to bamboo degradation during heating. Moreover, heat treatment at lower temperatures would evaporate water in the bamboo, and this phenomenon is more noticeable when treated at higher temperatures. This water loss can be attributed to bond breakage between hydroxyl groups and water, allowing the unbound water to evaporate. Additionally, the equilibrium moisture content (EMC) of heat-treated bamboo was significantly lower than that of untreated bamboo, mainly due to degradation of bamboo cell wall components during heat treatment. At the same time, lower moisture absorption may lead to better dimensional stability of the bamboo [7]. Moreover, the degradation of bamboo cell wall components during heat treatment can result in dark surface color of bamboo, and the degree of darkening would increase with higher treatment temperatures and/or longer the durations. As well, the surface color became uniform with the rise in treatment temperatures and durations [5].

Some studies have pointed out that heat treatments can result in the decrease of the mechanical properties of the bamboo. Zhao et al. [8] studied the effects of steam treatment under various conditions on the bending properties of moso bamboo. Results showed the steam temperature and treatment time had no significant effect on the bending properties of bamboo culms; however, a significant decrease in bending strength was found at 200 °C. Similar results have also been observed by Zhang et al. [9]. In contrast to the bending strength of heat-treated bamboo, the modulus of elasticity of heat-treated bamboo was affected just slightly, even a small increment was observed when heated below 200 °C.

Manalo and Acda [10] conducted heat treatment for three species of Philippine bamboo in the medium of virgin coconut oil at different temperatures and for different durations. The decreased bending and impact strengths observed in the research verified the destruction of bamboo microstructures due to heat treatment. The results also indicated that the acidic substances produced during hemicellulose degradation may have caused further hydrolysis of bamboo cell wall compositions, thereby decreasing bamboo mechanical strength.

This study aims at evaluating various properties of moso bamboo heat treated in three media: air, nitrogen and linseed oil. The effects of heat treatment parameters were investigated. Particularly, comparing with previous studies that just usually applied one medium, the effects of different treatment media on various properties were discussed in the present study. The outcome of this study will help establish fundamental knowledge for heat-treated bamboo and provide information for future industrial applications of thermally modified bamboo.

2. Materials and methods

2.1. Material and specimen preparation

In order to investigate the effects of different heat treatments on basic properties of bamboo, this study collected bamboo samples from 4-year-old moso bamboo, the average dimension of the bamboo was 12 cm, that was harvested from Chushang, Nantou, Taiwan. In the preparation of the testing specimens, cylindrical bamboo was split longitudinally into 3–6 strips with approximate widths of 2 cm, lengths of 180 cm, and thicknesses of 0.8 cm. These strips were then soaked in hot water for 60 min. Afterwards, the strips were air dried, and then planed and sanded to obtain flat and smooth surfaces before being stacked and stored in a room conditioned at 20 °C and 65% relative humidity (RH) for 4 weeks.

The center portion of the conditioned bamboo strips were cut into two sizes of specimens, measuring 20 (width) × 5 (thickness) × 150 mm (length) and 20 × 5 × 50 mm. Thirty clean specimens of each size were selected, with the density ranging from 750 to 800 kg/m^3.

2.2. Heat treatment processes

Different heating media were investigated: air, nitrogen and linseed oil. The heat treatments were conducted at 150, 170, 190 and 210 °C for durations of 1, 2, and 4 h. The processes of heating bamboo specimens in the three different media are described in the following subsections.

2.2.1. Heat treatment in a medium of air or nitrogen

The bamboo specimens were first placed in an oven, and nitrogen (N_2) was then injected into the oven at a speed of 500 mL/min for 10 min and switched to 50 mL/min when the oven started to heat up. The heating stage involved the oven being heated to 100 °C in 6 h; and, in the drying phase, the oven was further heated to 130 °C in the following 12 h. The target temperature of 150, 170, 190 or 210 °C was then reached with an additional 6 h of heating. Subsequently, the temperature was kept constant for the designed time duration, and the specimens were then cooled in the oven to room temperature.

The heat treatment in air follows the same procedure, but without the injection of N_2.

2.2.2. Heat treatment in an oil medium

Commercial linseed oil was also used as a medium for heat treatment. The conditioned bamboo specimens were fully soaked into a linseed oil bath, which was heated up from room temperature at a rate of 5 °C/min to the target temperature and then kept constant. The specimens were kept in the oil bath for 4 h to cool down. The cooled specimens were then wiped dry before conditioning.

All the specimens treated under the different heat treatments were conditioned at 20 °C and 65% RH for 4 weeks prior to a series of experiments.

2.3. Properties of heat-treated specimens

2.3.1. Physical properties

2.3.1.1. Equilibrium moisture content. The heat-treated bamboo specimens were kept in a room at 20 °C and 65% RH for 4 weeks to reach equilibrium moisture content (EMC). EMC of treated specimens was calculated as:

$$EMC(\%) = \frac{m_u - m_o}{m_o} \times 100$$

where m_u is the mass of the heat-treated specimen after conditioning, and m_o is the oven-dried mass of the specimen.

2.3.1.2. Mass loss. Mass loss (ML) was calculated as follows:

$$ML(\%) = \frac{W_o - W_1}{W_o} \times 100$$

where W_o and W_1 are the oven-dried mass of untreated and heat-treated specimens, respectively.