Construction and Building Materials 178 (2018) 59–71

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of thermal modification on the surface and chemical properties of moso bamboo

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HIGHLIGHTS

- Heat treatment imposed a significant effect on the surface color of the bamboo.
- The compositional properties of the heat-treated bamboo are investigated.
- Microstructure of heat-treated bamboo are inspected.
- Chemical structural changes are verified by FTIR analysis.

ARTICLE INFO

Article history:
Received 18 October 2017
Received in revised form 2 May 2018
Accepted 9 May 2018

Keywords:
Thermal modification
Moso bamboo
Chemical properties
Surface properties
Microstructure

ABSTRACT

Fast growth and high mechanical properties are the key commercial value of bamboo used in various applications. However, the high contents of starch and sugar in the bamboo may cause issues of biodegradation. Heat treatment provides the effective method to modify the chemical properties of bamboo. This study here investigated the effects of heat treatment technology on modifying the surface and chemical properties of moso bamboo (*Phyllostachys edulis*). The bamboo heat treatment was conducted in different conditions; specifically, three treatment media (i.e., air, nitrogen, and linseed oil), four treatment temperatures (i.e., 150, 170, 190, and 210 °C), and three durations (i.e., 1, 2, and 4 h) were explored. The results revealed that the treatment temperature and duration imposed a significant effect on the surface color and contact angle of the bamboo. In other words, higher treatment temperatures induced darker surface colors and larger contact angles, which ensure favorable hydrophobicity of the bamboo. Moreover, by inspecting the microstructure of the bamboo, this study discovered that the bamboo treated at high temperatures were prone to intense damage to its tissue structures, particularly the parenchyma cells. In addition, Fourier-transform infrared (FTIR) spectroscopy was conducted to examine heat-induced changes in the chemical components of the bamboo. The results of the FTIR spectroscopy revealed that the intensity of the characteristic absorption peaks of polysaccharides decreased with increasing treatment temperatures, whereas the intensity of lignin peaks demonstrated an opposite changing trend. Through a quantitative analysis of the chemical components of the treated bamboo, the content of holocelluloses, hemicelluloses, and α-celluloses of the treated bamboo was determined. The analytical results were highly consistent with that of the FTIR spectroscopy.

1. Introduction

Bamboo belongs to the *Gramineae* family, the worldwide bamboo plants are more than 90 genera with over 1200 species, and the total area of about 22 million hectares. In addition, bamboo is distributed throughout the world and naturally distributed in the tropical and subtropical regions between approximately 46° north and 47° south latitude. Most of them are commonly found in Asia, Africa and Latin America [1]. Compared to wood, bamboo is considered a favorable and renewable material and has been gaining increased attention due to increasing demand but limited availability of forest resources. Particularly, bamboo has short growth and renewal cycles and could be used in structural applications in various scales such as constructions, furniture, mats, musical instruments and engineering applications [2]. Some studies also

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https://doi.org/10.1016/j.conbuildmat.2018.05.099
0950-0618/

demonstrated bamboo is widely used to produce bamboo based composites, such as bamboo plywood [3], laminated bamboo lumber [4], oriented strand board [5], bamboo particleboard [6] and bamboo plastic composites [7].

However, due to the natural hygroscopicity of bamboo, some undesirable properties such a dimensional instability caused by water or humidity absorption and desorption limited its application [8]. In addition, low durability of bamboo against mold, fungal and insect attack is also associated strongly with its chemical composition [9,10]. To improve its properties, bamboo used to be treated with preservatives that are also used for wood. However, these preservatives have been posing negative influences on human health and environment.

In recent years, thermal modification technology exhibits significant advantages in modifying the properties of wood; therefore, numerous studies have been contributed to investigating wood heat treatment [11–17]. However, the information in this field for bamboo is relatively limited [18]. Therefore, intense research attention focused on bamboo heat treatment for developing superior bamboo-based green structural materials should be needed. Notably, heat treatment induces microstructural and chemical changes in materials, and such changes may alter the macro features of the materials, thereby possibly restricting their commercial applications.

Parameters of concern in heat treatment include medium, 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. On the other hand, bamboo and wood have similar chemical compositions; namely, primarily composed of celluloses, hemicelluloses, and lignin. In bamboo, the three components together account for more than 90% of the total dry weight, whereas the content of other chemical components varies depending on the age and provenance of the bamboo. Based on previous successful experience, heat treatment is supposed to improve various properties of bamboo. In terms of physical and mechanical properties of heat-treated bamboo, several related studies have been conducted in the past [8,18–24].

Studies on wood heat treatment have indicated that thermal degradation of cell wall components such as hemicelluloses and lignin leads to formation of oxidation products such as quinones and chromophores onto wood surfaces, which thus display dark brown colors [25,26]. Moreover, heat treatment can also alter the interfacial properties and contact angle of wood by reducing hydrophilic hydroxyl groups and increasing wood hydrophobicity [27–31]. Besides, heat-treated wood often exhibits intensely darkened colors [24]. This discoloration feature is attributable to the fact that wood lignin and organic components contain chromophores (e.g., carbonyl groups, conjugated double bonds, and benzene ring) and auxochromes (e.g., hydroxyls). Additionally, degradation of wood celluloses and hemicelluloses induced by heat treatment yields additional chromophores, such as furfural generated from hemicellulose degradation, further intensifying wood discoloration. Many studies have discovered that pyrolysis of lignin and hemicelluloses yields oxidation products (e.g., quinones) and chromophores, which spontaneously move to the wood surface, developing dark colors [25,26,32–35]. Wood extractives are also degradable in heat treatment processes, and such degradation produces small-molecule carbohydrates at wood surfaces, consequently changing wood surface colors [36].

As to the effect of heat treatment on chemical components of wood and bamboo, Li et al. [37] reported that the content of α-celluloses and holocelluloses gradually increases from the bottom to the top of bamboo culms and that in a particular bamboo radial section, the outer surface layers have higher α-cellulose, holocellulose, and lignin content but lower ash and extractive content than the inner surface layers do. In contrast to softwood and hardwood hemicelluloses, bamboo hemicelluloses consist predominantly of xylan [38,39]. Therefore, bamboo hemicelluloses are susceptible to thermal degradation when exposed to high temperatures between 200 and 260 °C. Acidic substances such as acetic acids, formic acid, and phenol are yielded as a result of hemicellulose degradation. These acidic substances in turn prompt acid hydrolysis of hemicelluloses and amorphous celluloses, thereby incurring production of furfural and methylfurfural. Because celluloses have higher heat resistance than hemicelluloses do, heat treatment triggers incomplete acid hydrolysis of amorphous celluloses; consequently, the cellulose crystallinity and hydrophobicity of wood were only moderately improved [40].

In heat treatment processes, hemicellulose pyrolysis reduces the amount of free hydroxyl groups, thereby lowering the hygroscopicity and volume swelling of wood. Heat treatment can also be used to enhance the biodegradation resistance of wood by decreasing the equilibrium moisture content (EMC). Yildiza et al. [41] investigated the effect of the treatment temperature on wood chemical components and suggested that higher treatment temperatures lead to lower cellulose content. Zhao et al. [22] applied vapor heat treatment on moso bamboo and confirmed that heat treatment induces decrease in the hemicellulose content and subtle increase in the lignin content of bamboo. Tang et al. [42] indicated that as the heat treatment temperature and time increased, the Klason-lignin content of moso bamboo increased, whereas holo-cellulose and α-cellulose content decreased.

In summary, heat treatment can be used to effectively modify wood properties, particularly the dimensional stability, weathering resistance, color uniformity, and hydrophobicity [43–44]. In our past research, we have also demonstrated that heat treatment could enhance the dimensional stability and moisture excluding efficiencies of bamboo [18]. These modifications are considered highly correlated with changes in wood chemical components, particularly thermal degradation of amorphous carbohydrates [40,44–46].

Because of the similarity between the chemical composition of wood and bamboo, and the effects of heat treatment on the physical and mechanical properties of the bamboo were demonstrated in our previous study [18], this study here applied heat treatment technology to treat bamboo and further investigated the effects of distinct heat treatment procedures on color changes in the inner and outer surfaces of the bamboo. To enrich the knowledge related to the anatomical structure of heat-treated bamboo, this study explored the effects of the treatment temperature and duration on the microscopic properties of bamboo and attempted to determine treatment-induced damages to the microstructure of bamboo. Furthermore, chemical alterations were assessed to determine the relationship between such alterations and particular bamboo properties.

2. Materials and methods

2.1. Materials

To investigate the effects of different heat treatment processes on selected bamboo properties, this study collected bamboo culms from 4-year-old moso bamboo (*Phyllostachys edulis*) harvested from Chushang, Nantou, Taiwan. Fig. 1 illustrates the preparation process of bamboo specimens. Firstly, Bamboo specimens were prepared by first splitting single bamboo culms into 3–6 pieces of 20 (width) × 1800 (length) × 8 mm (thickness) strips. The wax surface layers of these strips were removed before the strips were cooked in hot water for 60 min. Subsequently, the strips were air-dried, planed, and sanded to attain flat and smooth surfaces prior to being conditioned at 20 °C and 65% relative humidity (RH) for 2 weeks to reach an EMC.

The mid-height parts of the conditioned bamboo strips were selected and tailored into 20 (tangential) × 5 (radial) × 150 mm (longitudinal) and 20 × 5 × 50 mm specimens. A total of thirty clean specimens with a density of 750–800 kg/m^3 were selected from each size group.