EFFECTS OF STEAM TREATMENT ON BENDING PROPERTIES AND CHEMICAL COMPOSITION OF MOSO BAMBOO (*PHYLLOSTACHYS PUBESCENS*)

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Received April 2009

ZHAO RJ, JIANG ZH, HSE CY & SHUPE TF. 2010. Effects of steam treatment on bending properties and chemical composition of moso bamboo (*Phyllostachys pubescens*). Effects of temperature (25, 160 and 200 °C) and time (15 and 30 min) of steam treatment on the mechanical and chemical characteristics of moso bamboo were studied. The modulus of rupture (MOR) and modulus of elasticity (MOE) of the outer culm were at least 2.4 and 2.2 times respectively greater than those of the inner culm. Temperature and time had no effect on bending properties of the outer and inner culms. A significant decrease in MOR occurred after the specimens were subjected to 200 °C. The per cent MOR reduction after 30 min treatment at 200 °C was more than 33 and 29% respectively, as compared with that of 25 and 160 °C, but steam treatment had no effect on MOE. Of the three major chemical constituents of bamboo, alpha-cellulose was very stable to temperature and time, but lignin content increased slightly when temperature was increased to 200 °C. However, the hemicellulose content decreased substantially as temperature increased. The similar decreases for hemicellulose content and MOR of bamboo suggested that hemicellulose loss in thermally-degraded bamboo was correlated with MOR strength loss. At 200 °C, there were significant decreases in MOR, hemicellulose content and pH, and increases in hot water extractives, ethanol–benzene extractives, 1% NaOH extractives and lignin content.

Keywords: Modulus of elasticity, modulus of rupture, cellulose, lignin, hemicellulose, cutin layer

ZHAO RJ, JIANG ZH, HSE CY & SHUPE TF. 2010. Kesan pengewapan terhadap ciri-ciri lentur dan komposisi kimia buluh *Phyllostachys pubescens*. Kesan suhu (25 °C, 160 °C dan 200 °C) dan masa (15 min dan 30 min) rawatan wap terhadap ciri-ciri mekanik dan kimia buluh *Phllostachys pubescens* dikaji. Nilai-nilai modulus kepecahan (MOR) dan modulus keanjalan (MOE) lapisan luar kulma masing-masing 2.4 kali dan 2.2 kali lebih tinggi daripada lapisan dalam kulma. Suhu dan masa tidak mempunyai kesan terhadap ciri-ciri lentur di bahagian luar dan dalam kulma. Nilai MOR berkurangan secara signifikan apabila spesimen dirawat pada 200 °C. Penurunan nilai MOR selepas rawatan wap selama 30 min pada 200 °C adalah masing-masing 33% dan 29% berbanding dengan rawatan pada suhu 25 °C dan 160 °C. Namun, pengewapan tidak mempunyai kesan terhadap MOE. Antara tiga komponen kimia yang utama dalam buluh, alfa-selulosa sangat stabil terhadap suhu dan masa rawatan tetapi kandungan lignin bertambah sedikit apabila suhu rawatan meningkat ke 200 °C. Namun, kandungan hemiselulosa berkurangan dengan banyak apabila suhu bertambah. Pengurangan kandungan selulosa dan MOR mencadangkan bahawa kehilangan hemiselulosa dalam buluh yang menjalani pengewapan berkorelasi dengan kehilangan kekuatan MOR. Pada 200 °C, MOR, kandungan hemiselulosa dan pH berkurangan dengan signifikan manakala ekstrakan air panas, ekstrakan etanol–benzene, ekstrakan 1% NaOH dan kandungan lignin bertambah dengan signifikan.

INTRODUCTION

Bamboo has a maturation period of three to eight years, which makes it the fastest growing plant known (Farrelly 1984). In China, bamboo is considered a very promising alternative to wood because of its higher growth rate, shorter rotation age and higher tensile strength. Moreover, with the decreasing quantity and quality of forest resources, global interest in bamboo utilisation has increased considerably. The recent successful commercialisation of bamboo plywood

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and bamboo flooring has stimulated bamboo research for structural applications, including preservation and dimensional stability.

There are many methods of modification to improve the properties of wood and other bio-based materials, including heat treatment (Stamm *et al.* 1946, Hill 2006). Depending on the temperature used, heat treatment can degrade hemicelluloses, soften lignin and modify cellulose groups (Bekhta & Niemz 2003). Wood treated at high temperature loses its ability to absorb water. It is well known that most wood decay problems occur at a moisture content of over 20%. Therefore, if wood loses its ability to absorb water, it can remain naturally durable and accordingly heat treatment has been considered as an environmental-friendly alternative to metal-based wood preservatives (Inoue *et al.* 1993, Kamdem *et al.* 2002, Gündüz *et al.* 2008). Many studies have shown improved mechanical properties of wood after heat treatment (Kim *et al.* 1998, Bengtsson *et al.* 2002, Poncsak *et al.* 2006, Boonstra *et al.* 2007, Esteves *et al.* 2007, Mburu *et al.* 2008, Esteves & Pereira 2009). Moreover, heat-treated wood may have more favourable in-service mechanical properties than wood at a constant moisture content due to its reduced hygroscopicity (Borrega & Karenlampi 2008).

Steam treatment is a commonly used practice in bamboo production to facilitate bending of bamboo into desired shapes. Heat from the steam can also improve the resistance of bamboo to insect attack (Liese 1987). In particular, it has been shown that temperatures above 200 °C clearly enhanced the durability of bamboo against basidiomycete fungi and soft rot attack but significantly reduced shock resistance (Leithoff & Peek 2001).

There are few reports on the effects of steam treatment on bamboo properties. Therefore, the objective of this work was to obtain basic data on the effects of steam treatment on mechanical properties and chemical composition of moso bamboo *(Phyllostachys pubescens)*. This study was performed in two experiments to determine bending properties of: (1) inner and outer layers of bamboo culms and (2) whole layer of bamboo culms.

MATERIALS AND METHODS

Six 3-year-old moso bamboo culms were cut at ground level. They were obtained from the Kisatchie National Forest near Bentley, LA USA. The bamboo culms were more than 7.6 m in length with base ranging from 13.5 to 15.5 cm diameter. The culms were sawn into 17.8 cm sections. The culm sections were divided into two groups based on culm wall thickness: wall thickness ≥ 9.5 mm (group 1) and < 9.5 mm (group 2). Group 2 samples were not used in this study.

One section was selected from the base of each of the six culms and cut into 12.7 mm wide specimens. The specimens were sanded lightly in order to make them more rectangular in shape. Thirty specimens were randomly selected, then split evenly in halves along the tangential direction into two layers: outer layer (near the cutin) and inner layer. After sanding the split surfaces, the specimen thickness of the outer and inner layers was approximately 3.2 mm. Thus, a total of 60 specimens (15.24 cm long, 12.7 mm wide and 3.2 mm thick) were obtained for evaluation. The variables included three temperatures (25, 160 and 200 °C), two heating times (15 and 30 min), two bamboo culm layers (outer and inner) and five replications.

Steam treatment was conducted in a stainless steel cylinder (38.1 cm long and 12.7 cm in diameter). To start steam treatment, the temperature of the heating jacket was pre-heated to 160 or 200 °C. The cylinder, with the specimens in place and the cover closed, was placed into the temperature-controlled heating jacket for steam treatment. The steam was introduced through one of two valves on the cover and maintained throughout the duration of the treatment.

The modulus of rupture (MOR) and modulus of elasticity (MOE) in bending were carried out at 23 °C and 65% relative humidity based on ASTM D1037-99 (ASTM 1999) with a cross head speed of 2.54 mm min^{-1}. The test spans were 8.9 cm (span to depth ratio of 28) and 11.4 cm (span to depth ratio of 12) for experiments 1 and 2 respectively. All outer layer specimens in experiment 1 were tested with the cutin surface on the compression side, while the inner layer specimens were tested with inner surface on the compression side. For experiment 2, the treated specimens were equally divided, with half tested with the cutin surface on the compression side and the other half tested with the cutin surface on the tension side.

Untreated (control) and treated specimens were used for chemical analyses. Bamboo from each experiment was ground to pass a 40-mesh screen. The ground bamboo meal was measured for acid-insoluble lignin using ASTM D1106-96 (ASTM 1996), holocellulose content using ASTM D1104-56 (ASTM 1956), alpha-cellulose content in accordance with ASTM D1103-60 (ASTM 1960), ash content based on ASTM D1102-84 (ASTM 1984a), 1% sodium hydroxide solubility using ASTM D1109-84 (ASTM 1984b), alcohol–benzene solubility using ASTM D1107-84 (ASTM 1984c), hot water solubility based on ASTM D1110-84 (ASTM 1984d) and pH using Chinese National Standard (CNS) GB/T 6043-1999 (CNS 1999).

Statistical analysis

For mechanical properties, all multiple comparisons were first subjected to an analysis of variance (ANOVA) and significant differences between mean values of control and steam-treated samples were determined using the Duncan's multiple range test. For chemical analyses, only mean values and standard deviations were reported.

RESULTS AND DISCUSSION

On average, samples tested with the cutin layer in compression (facing upwards) yielded consistently higher MOR and MOE than those with the cutin later tested in tension (facing downwards) (Table 1). However, the ANOVA results indicated that these differences were not statistically significant (Table 2). The effects of temperature on strength properties were only significant for MOR but not for MOE (Table 2).

It is generally recognised that heat treatment of wood can result in strength reductions by hydrolytic cellulose depolymerisation (Ifju 1964) or hydrolisation of hemicellulose, causing cleavage of covalent bonds (Sweet & Winandy 1999). Studies have shown that hemicellulose is the most thermal-chemically sensitive component of wood and that changes in the hemicellulose content and structure are primarily responsible for initial strength loss (Levan *et al.* 1990, Winandy 1995). Therefore, one possible cause for the similar MOR and MOE values at low and high temperatures is the chemical composition of bamboo.

Of the three major chemical compositions of bamboo (cellulose, lignin and hemicellulose), alpha-cellulose content was largely unaffected by the steam temperature, but the lignin content increased slightly when temperature was increased to 200 °C (Table 3). The increased lignin content might be due in part to condensation of products as shown in a previous study on steaming of red oak (*Quercus* sp.) (Kubinsky & Ifju 1972).

Hemicellulose decreased slightly as the temperature increased from 25 to 160°C (4% reduction) but decreased substantially from 160 to 200 °C (23.8% reduction). These changes closely paralleled with the per cent MOR reduction of 5 and 29.8% respectively as temperature increased from 25 to 160 °C and from 160 to 200 °C. The parallel similarity between per cent decrease in hemicellulose content and per cent reduction in MOR strength of bamboo suggests that hemicellulose loss in thermally-degraded bamboo is correlated with MOR strength loss, which agrees with previous studies on fire-retardant-treated wood (Levan *et al.* 1990, Winandy 1995).

Steam temperature at 200 °C had an interesting effect on bending properties and chemical compositions. It appeared that the temperature 200 °C was a critical point that could cause significant decreases in MOR,

Table 1 Effects of temperature and test method on MOR and MOE

Property	Test method	Temperature (°C)		
		25	160	200
MOR (MPa)	Cutin layer faced upwards	213 (16.2)	200 (15.8)	142 (33.3)
	Cutin layer faced downwards	196 (15.1)	189 (8.8)	131 (18.9)
MOE (KPa)	Cutin layer faced upwards	13.84 (1270.2)	13.13 (988.3)	13.36 (1562.6)
	Cutin layer faced downwards	12.59 (1315.6)	12.76 (1231.4)	13.16 (978.7)

Values in parentheses are standard deviations.

Table 2 ANOVA results of the effects of steam heat treatment and sample orientation during testing (test method) on the bending strength of whole bamboo strips

Source	df	Type I SS	Mean square	F value	Pr > F
1. Dependent variable: modulus of rupture (MOR)					
Temperature	2	672334247.7	336167123.9	41.90	< 0.0001
Test method	1	30595648.4	30595648.4	3.81	0.0602
Temp × test	2	1607457.1	803728.5	0.10	0.9050
2. Dependent variable: modulus of elasticity (MOE)					
Temperature	2	14400256154	7200128077	0.22	0.8019
Test method	1	70823491420	70823491420	2.19	0.1495
Temp × test	2	40394866702	20197433351	0.62	0.5426

Table 3 Chemical composition of steam-treated bamboo

Chemical composition (%)	Steam treatment temperature (°C)		
	25	160	200
Hot-water extractives	7.0 (0.11)	7.9 (1.55)	12.7 (0.27)
Alcohol–benzene extractives	5.2 (0.05)	6.6 (0.12)	9.1 (2.56)
1% NaOH extractives	24.5 (0.33)	28.5 (0.23)	40.5 (0.60)
pH	5.06 (0.02)	4.65 (0.00)	4.04 (0.01)
Holocellulose	62.4 (0.27)	61.6 (0.34)	55.7 (0.83)
Alpha-cellulose	37.9 (0.52)	38.1 (0.63)	37.8 (0.50)
Hemicellulose	24.5 (0.34)	23.5 (0.31)	17.9 (1.022)
Lignin	25.2 (0.94)	25.2 (0.54)	27.8 (0.27)
Ash	1.54 (0.01)	1.54 (0.02)	1.55 (0.03)

Values in parentheses are standard deviations.

hemicellulose and pH, and increases in hot-water extractives, alcohol–benzene extractives, 1% NaOH extractives and lignin content.

CONCLUSIONS

The MOR and MOE of the outer layer of bamboo were both substantially higher than those of the inner layer. The steam temperature and treatment time had no significant effects on the strengths of the outer and inner culm layers. There was a significant decrease in MOR, but not in MOE, after the specimens were subjected to steam at high temperature. Alpha-cellulose was very stable and the lignin content increased slightly when temperature was increased to 200 °C. However, hemicellulose content substantially decreased as temperature increased. At 200 °C there were decreases in MOR, hemicellulose and pH but increases in hot water extractives, benzene–ethanol extractives, 1% NaOH extractives and lignin content.

ACKNOWLEDGEMENT

The authors acknowledge the financial support of the Ministry of Science and Technology of China (Grant No. 2006BAD19B04).

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