Sensitivity of Several Selected Mechanical Properties of Moso Bamboo to Moisture Content Change Under Fiber Saturation Point

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The moisture dependence of different mechanical properties of bamboo was not fully understood. In the paper, longitudinal tensile modulus, bending modulus, compressive strength and shearing strength parallel to grain of bamboo with 0.5, 1.5, 2.5 and 4.5 years old were tested under different moisture content (MC) to elucidate the sensitivity of different mechanical properties of bamboo to MC change. The results showed that the four mechanical properties of bamboo respond differently to MC change. Compressive and shearing strength parallel to gain were most sensitive to MC change, then was longitudinal tensile modulus and followed by bending modulus, which can be partially explained by the different response of the three main components in the plant cell wall to MC change. For tensile modulus and bending modulus, the effect of bamboo ages on the sensitivity to MC change was insignificant while young bamboo (0.5 years old) was more sensitive to MC change for shear strength and less sensitive for compression strength than the older ones.

Key words: bamboo; mechanical properties; moisture dependence; specific density

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Introduction

Water exists in plant material during its entire life cycle from growth, processing to application. For wood and wood-based products, the relationship between mechanical properties and moisture content (MC) is rather important for quality control and product application. For the past decades, considerable researches have been performed on water in wood and its relevance to mechanical properties (Green et al. 1986; Kretschmann and Green, 1996; Wang et al. 1999; Kojima and Yamamoto, 2004; Liu and Zhao, 2004; Green et al. 2007). At MC from oven-dry to the so called fiber saturation point (FSP), bound or adsorbed water accumulates in the wood cell wall. Above the FSP, free water accumulates in the cell cavity. It is well known the change of moisture content below FSP significantly influences the mechanical properties of wood, whereas affects very little above FSP. Furthermore, it has been further revealed different mechanical properties of wood showed different sensitivity to the change of MC (Green et al. 1999; Ishimaru et al. 2001; Sudijono et al. 2004).

Specifically, the data in United States wood handbook has declared the longitudinal tensile strength of wood decreased 16.7% from air-dried state (MC 12%) to saturated state, followed by bending modulus (23.7%), shearing strength parallel to gain (30.0%) and compressive strength parallel to gain (42.5%).

Bamboo is one of the most important non-wood forest resources in the world, growing faster than almost all the trees on earth. As a plant material, bamboo is also hygroscopic, gaining or losing water to equilibrate with its environment (Hui and Yang, 1998). Although the effect of MC on the mechanical properties of bamboo might be similar to wood in general (Zhou, 1998), specific relationship might be somewhat different, since significant difference exists in chemical composition and microstructure between bamboo and wood. This study is part of a program aimed to gain a better understanding of the effect of MC on the mechanical properties of bamboo. In this paper, the effect of MC from oven dry to FSP on four selected mechanical properties (namely longitudinal tensile modulus, bending modulus of elasticity, shear strength parallel to gain and longitudinal compression strength) of bamboo with ages of 0.5, 1.5, 2.5 and 4.5 years was investigated in order to reveal the different sensitivity to MC change of the selected mechanical properties of bamboo with different ages under FSP.
Materials And Methods

Sample preparation

Figure 1. The specific shape and size of those two kind of samples
Longitudinal tensile (Left); Shear strength parallel to grain (Right)

Moso bamboo (Phyllostachys pubescens Mazei ex H.de Lebaie) aging with 0.5, 1.5, 2.5 and 4.5 years was taken from a bamboo plantation located in Zhejiang Province, China. 32 bamboo culms were cut down in total with 8 culms for one age. All the samples for mechanical testing were cut from 15-25 internodes and prepared according to a Chinese national standard for bamboo (GB/T 15780-1995). The specific dimensions of the samples were as follows: 20 (L)×20 (T)×t (Thickness of bamboo culm wall) for compression strength parallel to grain; 160 (L)×10 (T)×t (Thickness of culm wall) for three point bending modulus. The specific shape and size of samples for longitudinal tensile modulus and shear strength parallel to grain gain were showed in Figure 1. All the samples were air-dried in the lab environment for more than six months before moisture conditioning.

Moisture conditioning

All the air-dried mechanical samples were randomly divided into 9 groups for moisture conditioning. Each group contained 20 samples for compressive strength, 16 samples for longitudinal tensile modulus, 16 samples for bending modulus, and 12 samples for shear strength with each bamboo age. The samples with MC under FSP were conditioned in desiccators containing different aqueous saturated sale solution listed in Table 1.

Table 1. Relative humidity (RH) levels in the experiments and the corresponding equilibrium moisture contents (EMC).

<table>
<thead>
<tr>
<th>NO.</th>
<th>RH, Average (%)</th>
<th>EMC, Average (%)</th>
<th>Chemicals for conditioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.9</td>
<td>0.5</td>
<td>Silica Gel</td>
</tr>
<tr>
<td>B</td>
<td>12.5</td>
<td>4.7</td>
<td>LiCl</td>
</tr>
<tr>
<td>C</td>
<td>37.1</td>
<td>5.5</td>
<td>MgCl2</td>
</tr>
<tr>
<td>D</td>
<td>53.9</td>
<td>7.1</td>
<td>K2CO3</td>
</tr>
<tr>
<td>E</td>
<td>68.7</td>
<td>11.8</td>
<td>NaBr</td>
</tr>
<tr>
<td>F</td>
<td>74.1</td>
<td>12.5</td>
<td>NaCl</td>
</tr>
<tr>
<td>G</td>
<td>88.9</td>
<td>16.3</td>
<td>KCl</td>
</tr>
<tr>
<td>H</td>
<td>100</td>
<td>30.5</td>
<td>Water soaking</td>
</tr>
<tr>
<td>I</td>
<td>100</td>
<td>50.9</td>
<td>Water soaking</td>
</tr>
</tbody>
</table>
The desiccators were put in the lab with a constant temperature of 20 °C for at least one month. Relative humidity (RH) in the desiccators was measured with a hygrothermograph (TESTO 608-H1) placed in the containers. The actual EMC of each sample was measured by weighing after conditioning. The EMC above FSP were achieved by water soaking.

**Measurement of mechanical properties**
Mechanical testing was conducted according to a Chinese National Standard for bamboo (GB/T 15780-1995). A universal mechanical tester (5582, Instron Co. USA) was used for both three point bending and tensile testing. The span for bending test is 120 mm and the loading speed is 4 mm/min. A noncontact video extensometer was used for measuring tensile strain during tensile test. The tensile speed was set at 1.5 mm/min. Compressive strength parallel to grain and shear strength parallel to grain were tested by another mechanical tester (WDW-E100D, JINANSHIJIN Co. China) because the 5582 mechanical tester is not equipped with the standard grips we needed.
Results And Discussion

Mechanical properties of bamboo under different MC

Figure 2A: Longitudinal tensile modulus of four ages bamboo measured under different RH
Although the general relationship between MC and mechanical properties of bamboo should be similar to that of wood to a large extent, some specific differences still exist since the structure and chemical compositions were different. Tensile modulus, bending modulus, shear strength parallel to grain and compressive strength parallel to grain of bamboo plotted against MC are respectively shown in Figure 2A-D. Figure 2A showed the effect of MC on the longitudinal tensile modulus of bamboo with different ages (0.5, 1.5, 2.5, 4.5 years). A general decrease trend with the increase of MC can be easily observed. However, there seemed to have a plateau from MC 10% to 15%, followed by a continuing decrease with rising MC until FSP. For bending modulus, a general decrease trend with MC rising from nearly zero to water saturation was also observed (Figure 2B). However, the bending modulus of 0.5 and 1.5 years bamboo at MC 5%-6% was abnormally higher than the value measured at nearly zero MC, which might be attributed to the inherent sample variation between groups since the bamboo with 2.5 and 4.5 years old did not show similar behavior. The relationship between MC and shear strength parallel to gain of the four ages bamboo are shown in Figure 2C. An initial reduction at the early stage of moisture increasing can be observed, followed by a rising to the maximum value at MC 8%-9%. The shear strength then decreased again with increasing MC to FSP. For compressive strength parallel to gain (Figure 2D), a stable and more linear decrease trend was obtained with MC increasing to 20% for the bamboo of 1.5, 2.5 and 4.5 years old, and 25% for the bamboo of 0.5 years old. However, an unexpected, small but stable increase when MC was about 25% or more was repeatedly observed for the bamboo of all the ages, which has not been reported before and no explanations could be proposed presently.

Sensitivity to MC change of different mechanical properties of bamboo
In order to get a quantitative relationship between the four mechanical properties of bamboo and MC for practical application, a linear fitting was performed on the data involving all the four ages (Figure 3). The value of mechanical properties at FSP is actually the average of the two values measured at water saturation presented in Figure 2. Here oven dry has not been selected as the start point of low MC only because such low MC was seldom to be encountered in the practical application. Therefore, the variation scope of MC of longitudinal tensile modulus, bending modulus, shear strength parallel to grain and compressive strength parallel to gain of bamboo was 5.5%~FSP, 5.5%~FSP, 8%~FSP, 5%~FSP, respectively. In a previous study, we have found the FSP of Moso bamboo was related to its ages (Wang et al. 2010). For the young bamboo with only 0.5 years old, the FSP was about 28%, while the bamboo aging 1.5, 2.5 and 4.5 years has nearly the same FSP 23%. From the obtained four linear equations, it can be inferred per 1% MC change would result in a increase or decrease of 0.21 GPa for tensile modulus, 0.10 GPa for bending modulus, 0.52 MPa for shear strength...
and 2.50 MPa for compression strength. In order to further compare the sensitivity of the four properties to MC change, a reference value must be obtained in advance. Here, the properties at MC 12% were selected as the reference value, which can be calculated according to the above four equations. Then the moisture sensitivity K, namely the change rate of the properties per 1% MC change, can be defined by the ratio between the scopes of the linear equations and the properties at 12% MC (P12) according to formulae (1). The calculation result was showed in Figure 4.

\[ K = 100\% \times \frac{\text{Scope}}{P_{12}} \]  

(1)

Figure 3 The Relation Model of Moisture Content and Mechanical Properties

Figure 4 The change rate of mechanical properties per 1% MC change
L: Longitudinal tensile modulus; B: Bending modulus; S: Shear strength parallel to gain; C: Compression strength parallel to gain
Figure 4 indicates bending modulus exhibits the smallest sensitivity to MC change by a K value of 1.09%, followed by 1.93% for longitudinal tensile modulus, 3.08% for shear strength parallel to gain and 3.76% for compression strength parallel to gain. Bending modulus and tensile modulus showed much less sensitivity to MC change than shear strength and compression strength, which can be partially explained by the different response to MC change of the three main components (cellulose, hemicelluloses and lignin) in the plant cell wall. The mechanical properties of lignin/hemicelluloses matrix have been experimentally (Cousins, 1976, 1978) and theoretically (Sakurada et al. 1962; Koponen et al. 1989) proved to be much more sensitive to MC change than cellulose. In the process of shear and compression testing, hemicellulose/lignin matrix gives considerable contribution to the final failure, while for the stiffness measurement both in the tensile and bending modes, cellulose undoubtedly dominates the whole process. Although bamboo also belongs to lignocellulosic materials, their mechanical responses to MC change show some differences from wood. The sensitivity of bending modulus to MC change of bamboo is significantly less than that of tensile modulus, while the former is higher than the latter for wood. That seems to be incapable of being explained by the chemical differences between them, while should be more attributable to the two phase composite structure of bamboo with much softer parenchymal cells embedded in much stiffer fiber bundles. We assumed the MC increase tended to weaken the interfacial bonding between parenchymal cells and fibers, resulting in extra internal slipping and reduced stiffness. Compared with wood, bamboo was lower sensitive to MC change than wood in bending modulus and compression strength, but had higher sensitivity in tensile modulus and comparable sensitivity in shear strength. This suggests that some mechanical properties of bamboo are better than wood in resisting the change of environment humidity.
Figure 5 Correlation between the four mechanical properties and moisture content. 
A: longitudinal tensile modulus; B: bending modulus; C: shear strength; D: compressive strength.
The effect of ages on the sensitivity to MC change of different mechanical properties of bamboo

In order to further investigate the effect of ages on the moisture dependence of different mechanical properties of bamboo, a linear fitting was performed for the range from MC 5.5% (or 8% for shear strength) to FSP (Figure 5). From the obtained linear equations, it could be inferred the mechanical properties of bamboo with 0.5 years old normally changed smaller in absolute value than that with older ages for per 1% MC change. However, no significant difference was found among the bamboo with 1.5, 2.5 and 4.5 years old in general. Similarly, for further comparing the different sensitivity to MC change of bamboo with different ages, the K value of bamboo with different ages was calculated according to the approach adopted in the last section. The results were plotted in Figure 6.

![Figure 6. The change rate of different mechanical properties per 1% MC change under different ages](image)

L: Longitudinal tensile modulus; B: Bending modulus; S: Shear strength parallel to gain; C: Compression strength parallel to gain

It seemed bamboo ages affected little on the K value of tensile modulus and bending modulus. However, the K value of shear strength of bamboo with 0.5 years old was a little higher than that of mature bamboo with 1.5 to 4.5 years old, which means young bamboo may be more sensitive to MC change in shear strength. For compression strength, the K value of bamboo with 0.5 years old was significantly lower than that of bamboo with 1.5 to 4.5 years old, which indicates young bamboo may be less sensitive to MC change in compression strength. Why different mechanical properties of bamboo with different ages responded differently to MC change need to be further explored from both microstructure and chemical compositions.

Conclusions

The results of combined investigation of four mechanical properties of bamboo under different MC permit the following conclusions:
Four mechanical properties of bamboo exhibited different sensitivity to MC change. Compressive and shearing strength parallel to gain were most significantly affected by MC, then was longitudinal tensile modulus and followed by bending modulus. The sensitivity of
tensile modulus and bending modulus was little affected by bamboo ages, while young bamboo was more sensitive to MC change than mature one in shear strength parallel to grain and less sensitive in compression strength parallel to grain.

Acknowledgement

We are grateful to the National Natural and Science Foundation of China (31070491) and National Natural and Science Foundation of China (30730076) for financial support.

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