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RESEARCH ARTICLE

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Hygrothermal effect of bamboo by dynamic mechanical analysis

Abstract Dynamic properties of bamboo, *Phyllostachys pubescens*, with moisture content (MC) ranging from –130 to 130°C, were studied by dynamic mechanical analysis (DMA). The results showed that the hygrothermal effect on dynamic mechanical properties was negative. The storage modulus decreases with increasing temperature and MC, and glass transition temperature decreases with increasing MC. The glass transition temperature and tan delta of bamboo were 30.5°C, 0.02 and 10.61°C, 0.04, when MC was 10% and 34%, respectively.

Keywords bamboo, dynamic mechanical analysis (DMA), hygrothermal effect

1 Introduction

Bamboo is a natural macromolecule and is widely used as an engineering material for its specially orientated fiber structure and excellent mechanical properties. It is usually loaded by periodic stress; therefore, the dynamic properties of bamboo are critical for its use as an important engineering material. Yu (2002) and Zhang (2003) researched dynamic shear modulus and dynamic Young's modulus of bamboo and relative factors. Bamboo's chemical content comprises cellulose, hemicellulose, and lignin (Zhang et al., 2002). As framework content, cellulose includes crystalline and noncrystalline zones, so that bamboo is nonhomogeneous and viscoelastic in its mechanical nature. The viscoelastic properties of polymer are relatively close to time, temperature, and moisture content (MC), but the relation between MC and dynamic properties of bamboo has not been studied. Bamboo is hygroscopic, and moisture absorption not only makes dimension change but also has an effect on the static mechanical properties of bamboo. Increasing attention has been paid on the hygrothermal effect on properties of bamboo.

Dynamic mechanical analysis (DMA) is widely used for testing and analyzing viscoelasticity of polymers to get a series of viscoelastic parameters of polymers, such as modulus and shear modulus, when time or temperature changes (Guo, 2002). In this study the hygrothermal effect of bamboo is observed by testing its viscoelasticity in different MCs in certain temperature zones using DMA.

2 Materials and methods

2.1 Materials

A 5-year-old *Phyllostachys pubescens* was taken as sample from Anji, Zhejiang Province, China. The sample was made according to the Chinese Standard Test Method for Measuring the Dynamic Mechanical Properties of Plastics and Composite — Nonresonance Method (Chinese Aviation Industry Group, 1999). The dimensions of the sample were 40 mm×6 mm×2.5 mm. The sample was divided into groups 1, 2, and 3 for treatment in three different environmental conditions. Each group consisted of three samples, of which one was used as the control when testing MC, and the other two were prepared for DMA testing.

2.2 Methods

2.2.1 MC treatment of bamboo sample

Main equipment：GDJS-100 high-low temperature adjuster.

Treatment conditions: group 1—100°C drying; group 2—20ºC, 65%; and group 3—30ºC, 95%.

The three samples of each group were treated to balance quality in the respective environment. Then the MC of one sample was tested while the other two samples were prepared for DMA testing.

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2.2.2 Test methods of DMA

Equipment: MA Q800, V7.0 Build 113, TA Co., U.S.A.

Test method: Dynamic Temperature Ramp Test, in which, given a certain frequency and strain, the changes in the dynamic properties of the sample are tested with varying temperature in a certain scale to attain a special temperature. The parameters of the test are:

Frequency: 3 Hz.

Temperature scale: –130–130°C.

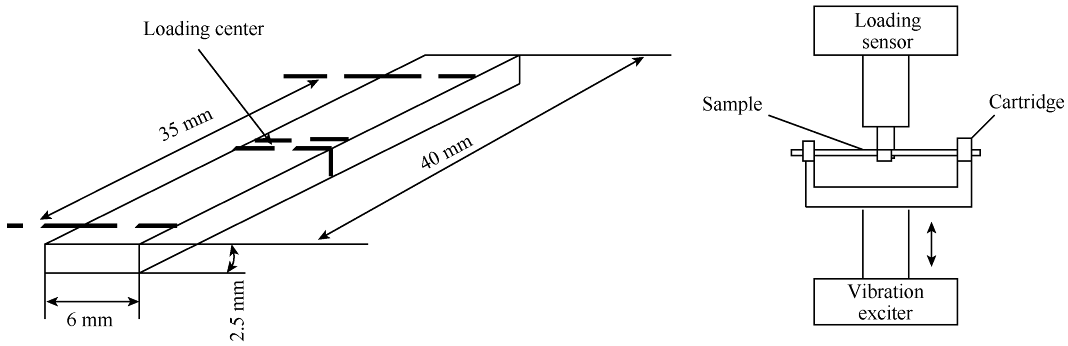
Rate of increasing temperature: 5°C/min.

Nonresonance method: single cantilever beam.

Size of bamboo sample and loading type: as shown in Fig. 1.

3 Results and discussion

For the results of dynamic mechanical thermal analysis of bamboo see Fig. 2a–c.



(a) Loading span (b) Cantilever bending

Fig. 1 The specimen dimension and cantilever bending sketch map

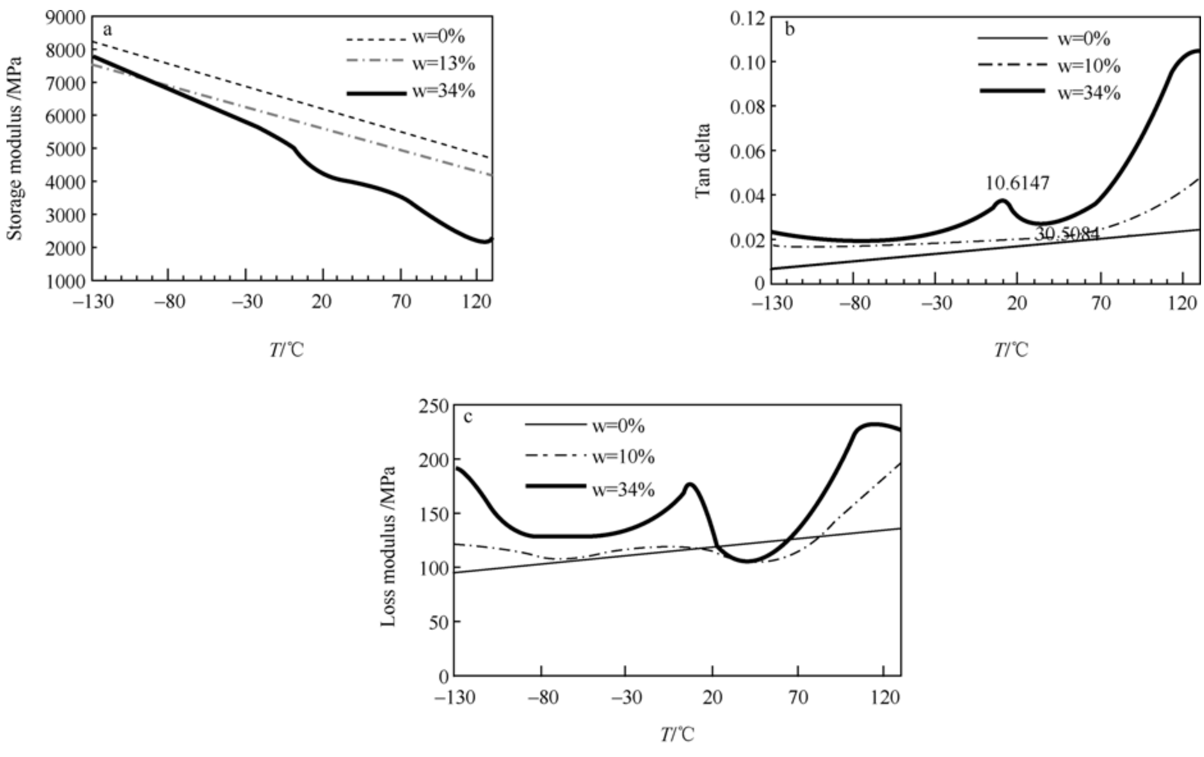


Fig. 2 The dynamic mechanical thermal analysis of bamboo in different MCs

3.1 Relationship between storage modulus and temperature of bamboo in different MCs

As shown in Fig. 2a, the storage modulus of bamboo in different MCs decreases as temperature increases; furthermore, the higher the MC is, the more obvious is the decline of the storage modulus, whereas lower temperatures can enhance the storage modulus of bamboo. Comparing the sample of 10% MC with that of 34% MC, the former had a sharp drop near 20ºC; accordingly, increasing the MC of bamboo can reduce storage modulus within a normal temperature scale. Therefore, bamboo with a low MC is better in view of the security limit of bamboo in application.

The data of Fig. 2a were regressed in line, and equations of storage modulus and temperature in different MCs were:

$$y_0 = -13.512x + 6{,}449.9 \qquad R^2 = 0.999{,}9 \qquad (1)$$

$$y_{10\%} = -13.724x + 6{,}006.6 \qquad R^2 = 0.995{,}6 \qquad (2)$$

$$y_{34\%} = -22.569x + 4{,}971.7 \qquad R^2 = 0.992{,}7 \qquad (3)$$

where y_0, $y_{10\%}$ and $y_{34\%}$ are storage modulus of 0, 10%, and 34% MC bamboo, respectively; x is temperature.

The slopes in Eqs. 1, 2, and 3 explain the declining speed of storage modulus with temperature. It is obvious that the declining speed of storage modulus in 34% MC bamboo (–22.569) is nearly two times higher than that in 10% MC bamboo (–13.724). Increase in MC accelerates the decrease of storage modulus with temperature.

In Fig. 2a, if we draw a line parallel to the x axis upon 5,000 MPa, the line will meet the three curves at three different points. The same bending value of bamboo can be attained not only in high MC with low temperature, but also in mild MC with moderate temperature, as well as in low MC with high temperature. Therefore, properties of bamboo can be adjusted by MC and temperature. Bamboo is naturally a functional gradient material, whose bending properties go up with the height of culm from bottom to top (Nogata and Takahashi, 1995; Yu et al., 2003; Tommy et al., 2004). Chinese researchers say that the MC of bamboo decreases along the height of bamboo culm (Zhou, 1998). Considering that environmental temperature gradually increases from the bottom to the top of bamboo, the MC of culm decreases along the height. Therefore, bamboo can keep a certain amount elastic and tenacity when environmental temperature and loading change, ensuring bending properties in a certain safe zone.

Bamboo can also adjust its properties by hygrothermal effect, though this happens too long after its life cycle is terminated. As a case in point, the strength and flexibility of a 34% MC bamboo is good in a storage modulus range of 5,000–4,000 MPa, as temperature varies from 0 to 35ºC.

3.2 Tan delta (loss factor) and loss modulus

As showed in Fig. 2b, tan delta of drying bamboo declined in linearity with temperature from –130 to 130ºC, while loss modulus of drying bamboo increased slowly (Fig. 2c). Generally, the bending behavior of bamboo changed with the variety of moisture in the range of normal temperature. There is an obvious peak of tan delta in the curve (see Fig. 2b), and loss modulus of bamboo increased (see Fig. 2c).

Glass transition temperature point of bamboo in different MCs can be found in Fig. 2. Glass transition temperatures and tan delta of 10% and 34% MC bamboo are 30.5ºC, 0.04 and 10.61ºC, 0.02, respectively. Therefore, glass transition temperature of bamboo descends as MC goes up in the same temperature and loading, and tan delta drops in a similar fashion. When the temperature is nearly 130ºC, tan delta of bamboo goes up as MC increases from 0.02 (0 MC) to 0.05 (10% MC), then up to 0.15 (34% MC). The maximum value of tan delta is 2–7 times higher than that of drying bamboo. Bamboo is elastic when it is in the glass transition zone. This zone is critical for bamboo to survive in different environmental conditions because it can hold "elasticity" by adjusting its MC to respond to the loading change and temperature in the natural environment. Bamboo is easy to bend when it is young as its ability in adjusting the MC of culm generally allows it to "bend, not break". However, this ability diminishes when bamboo grows old, and then the property shows "breaking, not bending".

Bamboo, a kind of heterogeneous polymer, mainly consists of natural macromolecules, such as cellulose, hemicellulose, and lignin, which contain many hydroxyls. The molecular chain of these macromolecules is long and flexible, as one little part called a segment moves against the other main part of the macromolecule. This kind of segment in bamboo contains massive hydroxyls. When temperature is lower than glass transition point, these segments are frozen, so that the bamboo becomes rigid and has a high modulus and small deformation. When MC of bamboo changes to below fiber saturation point, most of the water molecules exist as hydrogen bonds, which easily bond to the hydroxyl of a segment. Hydrogens and hydroxyls of segments freeze together, and there is no relative displacement among segments. Then the internal friction has to be overcome when the bamboo is loaded. Therefore, the value of tan delta and loss modulus of bamboo is accordingly small. As MC increases, free water exists in bamboo cells and more free water is retained in the cell wall. When temperature is below freezing point, water in the cell wall crystallizes into a kind of solid snow or ice; this kind of crystal product produces more internal friction in the bamboo when it is loaded. So bamboo in 34% MC shows a bigger peak of loss modulus in –130ºC (see Fig. 2b).

Figure 2b shows that tan delta peak immerges above 130ºC when MC is high, because the bending properties of bamboo move to low temperature with increasing MC, so that the environmental temperature of bamboo becomes low. Considering this phenomenon, it is critical to improve the water-retaining capacity of bamboo so as to keep its properties within the elasticity scale and not in the glass scale when bamboo is transplanted in the arctic zone. The low-temperature resistance of bamboo can be enhanced by increasing its water-retaining capacity in low temperatures. Meanwhile, this mechanism of hygrothermal effect can be applied to adjust the properties of bamboo.

4 Conclusion

Bamboo samples in different MCs were tested by dynamic thermal analysis when temperature changed from –130 to 130ºC. The result showed that storage modulus of bamboo decreased with increasing temperature, and that the higher the MC is, the lower is the storage modulus. Generally, the hygrothermal effect of storage modulus of bamboo under different hygrothermal conditions is negative.

Glass transition temperature is lower when MC is higher. The values of transition temperature and tan delta of bamboo in different MCs are 30.5ºC, 0.02 (10% MC) and 10.61ºC, 0.04 (34% MC), respectively. Tan delta and loss modulus of drying bamboo are minimum at the same temperature. So tan delta value of bamboo in glass transition zone increases as MC of bamboo increases. Tan delta of bamboo in high MC is 2 to 7 times higher than that in low MC.

Bamboo can change from glassy state to elastomeric state under the function of hydrothermal effect by controlling MC and/or temperature, increasing bamboo flexibility and strength in the natural environment. This state transition under the function of hygrothermal effect is a critical theory, based on which we can conduct research on cold endurance and hygrothermal modification of bamboo.

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