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Effect of thermal expansion at low temperature on mechanical properties of Birch wood

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ABSTRACT

Thermal expansion phenomenon would occur in woody materials in terms of temperature change as well as moisture content (MC), which will influence the mechanical properties in extreme low temperature condition. In this study, thermal expansion of birch (*Betula platyphylla*) wood with three levels of MC (water-saturated specimen with a MC of 149.7%, air-dried one with a MC of 9.7% and oven-dried one with a theoretical MC of 0%), was analyzed for temperature ranging from −150 to +20 °C. Furthermore, the dimension changes of the birch specimens were measured and the effect of thermal expansion on the mechanical properties in low temperature condition was investigated. The crystallinity of the wood at low temperatures was examined by the X-ray diffraction (XRD). The results showed that all specimens shrank from +20 to −150 °C. Water-saturated wood showed more dramatic shrinkage as compared to the other two groups (air/oven-dried). The value of the linear thermal expansion coefficient λ increased with the increasing temperature. At any temperature, λ of the water-saturated specimen was the greatest one among the three groups. The increase of MOR, i.e., the variation between the corrected MOR adjusted according to the λ at low temperature and the uncorrected one, had a linear relationship with temperature, which would provide a method for the forecast of actual MOR at low temperature according to the value at room temperature. XRD analysis indicated that the crystalline structure of wood polymers was not influenced by temperature. Stability and mechanical property offer insight of the performance of wood product used for low temperature applications.

1. Introduction

Woody biomass is one of the most abundant lignocellulosic materials on earth (Carlmark et al., 2012; Esteves and Pereira, 2008; Ma et al., 2014; Wei et al., 2015a). However, wood is always subjected to suitable modification/treatment to prolong its service life in field. To improve the performances of wood this can be achieved by physical (e.g. mechanical, heat, and cold treatment) (Bledzki and Gassan, 1999; Korkut et al., 2008) and chemical (e.g. maleic anhydride, organosilanes, isocyanates, etherification and esterification) modifications (Gassan and Bledzki, 1999; Joseph et al., 1996; Lu et al., 2000; Wei et al., 2013). Temperature changes can cause the variation of internal binding energy and further influence the average distance between molecules, resulting in the expansion or contraction of wood (Li, 2002). However, most researches on wood thermal expansion are majorly focused on the effect of high temperature (above +150 °C) and their anisotropic properties (Esteves and Pereira, 2008; Korkut et al., 2008; Pelaez-Samaniego et al., 2013). Fewer studies have been conducted at temperature below room temperature, especially below −50 °C (Ayrilmis et al., 2010; Zhao et al., 2015a, b).

The thermal expansion coefficient (λ) is an important parameter to characterize the stability, which plays a significant role in the application of materials (Zeisig et al., 2002). For example, the influence of the thermal stability of silicon should be fully considered when used in aircraft for the analysis of aviation structure and life (Wang et al., 2009). The thermal expansion of various wood species in the radial, tangential and longitudinal directions was studied by Stamm (1935). Results showed that the λ value is anisotropic. The λ in the longitudinal direction is very small, which is only about 1/10 compared to that in the transverse direction, while that in the radial direction is slightly less than that in the tangential direction (Cheng, 1985). This is mainly contributed to the cellulose in the wood cell wall. The changes of the macromolecules in each direction varied due to crystal structure/morphology and the arrangement of the S2 layer as well. The λ in the transverse direction is significantly larger than that in the longitudinal direction because the vertical direction of the long chain should obtain maximum amplitude. While the difference of λ between the radial and tangential direction mainly depends upon the restriction of the wood structure and cell morphology (Li, 2002). Hori and Wada (2005) investigated the thermal expansion of tension wood cellulose obtained from poplar (*Populus maximowiczii*) using X-ray diffraction (XRD) in the

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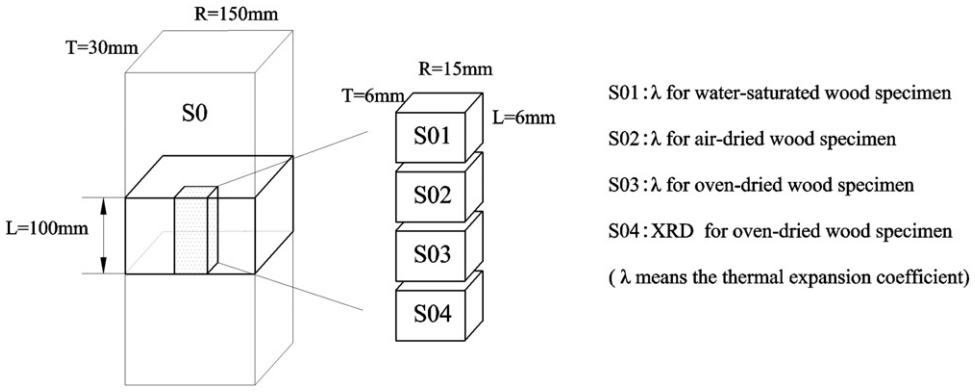

Fig. 1. Sample preparation.

temperature ranging from room temperature to +250 °C, which reported that wood thermal expansion in three coordinate directions was anisotropic. This phenomenon was closely dependent on the cellulose crystal structure which determined the macroscopic thermal behavior of solid wood. Ramiah and Goring (1965) reported that the thermal expansion of wood constituents in the water-saturated state was several times greater than that measured in the dry state in the temperature range of −30 to +30 °C.

Our previous work indicated that wood mechanical strength was increased with higher moisture content (MC) at low temperature (−196 to +20 °C) (Zhao et al., 2015a, b). Considering the importance of thermal expansion/shrinkage, opportunities can be sought for exploring its impact on wood mechanical properties at low temperature.

Limited by the testing sample sizes only one year-ring can be included if specimens are cut in the tangential direction, therefore only thermal expansion in the radial direction was investigated in this study. The overall objective of this research was to investigate the thermal expansion in the radial direction and mechanical property changes when birch wood was treated at low temperature (−150 to +20 °C). The effect of three MC levels (water-saturated, air-dried, and oven-dried) was studied as well. Crystallinity of wood at different temperatures was examined by XRD. In this study, a more accurate description of the wood properties at low temperature was obtained, which would provide a theoretical/practical guidance to the wood products potentially utilized in cold environments.

2. Experimental

2.1. Materials

Green birch (*Betula platyphylla*) lumber with an average MC of 67.0% and a density of 0.57 g/cm^3 was sourced locally.

Block specimens (radial × tangential, 15 × 6 mm^2) without knots and defects were cut from lumber. Specimens (radial × tangential × thickness, 15 × 6 × 6 mm^3) were cut continuously from the block sample. Three water-saturated, air-dried, and oven-dried specimens were selected randomly, as well as the specimen for XRD analysis. Sample preparation was showed in Fig. 1. The water-saturated specimen was prepared by immersing the sample in water until constant weight was achieved, and MC was 149.7%. The oven-dried wood specimen was prepared by placing samples in an oven set at 103 °C for above 48 h, with a theoretical MC of 0%. The MC for the air-dried samples is 9.7%. Specimens for XRD analysis were milled to powder to pass through a 100 mesh screen, and then placed in a desiccator with phosphorous pentoxide (P_2O_5) as a drying absorbent until reaching a constant weight. The whole test of XRD was carried out under vacuum, thus, only oven-dried wood powder was analyzed in the XRD study.

2.2. Thermal expansion test

The thermal expansion of wood samples was characterized by a dilatometers (Linseis, L75 Platinum Series, Germany) installed with an electric heater. Specimens were cooled with liquid N_2 to with a speed of 5 °C/min and being kept for 15 min at −150 °C, then heated up to +20 °C at 3 °C/min. Sample dimensional changes were recorded. Sample size at +20 °C was considered to be zero as the reference point. Hence, the shrinkage occurred below +20 °C was negative, while the swelling occurred above +20 °C was positive.

According to the relationship between sample temperature and elongation, the linear thermal expansion coefficient, λ, was calculated as follow (Hori and Wada, 2005):

$$\lambda = \frac{\Delta L}{L} \times \frac{1}{\Delta T} \quad (1)$$

where L, ΔL and ΔT are the original sample length, sample length changes, and temperature changes, respectively.

2.3. Crystallinity characterized by XRD

The crystalline structure of samples treated at different temperatures (+20, 0, −30, −70, −110, −160, and −196 °C) was characterized by XRD (Bruker D8 Discover diffractometer, Germany). Scanning was performed over 2θ ranging from 10 to 40° with steps of 0.01°. The whole test was carried out under vacuum. The degree of crystallinity (Cr) of wood cellulose was calculated using Eq. 2 (Wei et al., 2015b; Wei et al., 2015c):

$$C_r = \frac{I_{002} - I_{am}}{I_{002}} \times 100\% \quad (2)$$

where I_{am} is the intensity of the crystalline peak at 2θ = 18°, I_{002} is the maximum intensity of the (002) plane diffraction.

3. Results and discussion

3.1. Thermal expansion

The degree of shrinkage of samples dried under different conditions was investigated and the absolute linear changes, ΔL/L, as a function of temperature are shown in Fig. 2. All samples experienced contraction from +20 to −150 °C. This may be because the mobility of macrochains in the amorphous part (e.g., cellulose amorphous region, hemicellulose, and lignin) of the wood complex was restricted and the energy of sample was significantly diminished at low temperatures, i.e. below 10 °C especially. Therefore, the macro shrinkage of wood samples was brought about due to the reduced spaces between molecules (Li,