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Flexural property of wood in low temperature environment

Liyuan Zhao [1], Jinghui Jiang [1], Jianxiong Lu *, Tianyi Zhan

State Key Laboratory of Tree Genetics and Breeding, Research Institute of Wood Industry, Chinese Academy of Forestry, Beijing, 100091, China

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ABSTRACT

The effect of low temperatures (<0 °C) on the mechanical properties of wood materials was investigated in this study. The modulus of rupture (MOR) and modulus of elasticity (MOE) of birch (*Betula platyphylla*) with five different levels of moisture content (MC) (water-saturated, green, fiber-saturated, air-dried and oven-dried), were analyzed for temperature from 0 °C to −196 °C. The morphological characteristics at low temperatures were explored by means of the cryogenic scanning electron microscopy (Cryo-SEM). The results showed that when the temperature was below 0 °C, MOR and MOE of specimens increased with decreasing temperature. Significant differences ($p < 0.05$) in MOR and MOE of the specimens at four out of five MC levels (water-saturated, green, fiber-saturated, and air-dried) were observed between +20 °C and −196 °C. However, the effects of low temperatures on MOR and MOE of the oven-dried wood specimens were not significant. The higher the MC, the greater and faster was the increase in MOR and MOE. The ductility ratio decreased with decreasing temperature for all MC levels, which means increasing flexibility below 0 °C. The findings suggest that extremely low temperatures have an important influence on the performance of wood with various MC.

1. Introduction

Environmental temperatures (high and low) play an important role as they affect the mechanical properties of wood. The wood property at high temperatures, such as in fire, was evaluated by Moraes et al. (2005), Schaffer (1973) and Zhou et al. (2012). There are numerous applications of wood in low temperature environment. When the timber is used for the body of liquefied natural gas (LNG) ship to contain LNG, it requires adequate strength to endure the pressure from LNG at −163 °C (Kim and Lee, 2009). When it is used for the roof of wooden-structural housing, it needs to withstand the pressure from the massive snow and low temperature (Ayrilmis et al., 2010). Also, when wood is stored in an open yard in winter, its mechanical properties are influenced by negative temperatures (Szmutku et al., 2013). However, there is no systematic study evaluating the effect of low temperatures (<0 °C) on the mechanical properties of wood materials.

The modulus of rupture (MOR) and modulus of elasticity (MOE) are two important properties of wood as a structural material. Previous research showed that wood mechanical properties tended to increase when wood was cooled below room temperature (Jiang et al., 2014; Kollmann and Cote, 1968). It was found that MOE increased monotonically with the decreasing temperature from 66 °C to −18 °C for the lumber at 12% moisture content (MC) (Green et al., 1999). The finding was confirmed by DeGeer and Bach (1995), which showed that MOE and MOR of spruce–pine–fir (*Picea glauca–Pinus cembra–Abies lasiocarpa*) increased by 0.13% and 0.34%, respectively, as the temperature decreased by 1 °C. The above mentioned studies were aimed at the study of mechanical properties of air-dried wood. In terms of the effect of MC, Xu et al. (2014) examined MOE and MOR of *Pinus koraiensis* and *Populus ussuriensis* timber from 20 °C to −20 °C, indicating that wood with higher MC was more sensitive to temperature than the air-dried one. Similar results were reported by Gao et al. (2015). Zhao et al. (2015) studied MOE of water-saturated, green, air-dried, and oven-dried wood specimens after low temperature treatment, which confirmed the effect of MC. Ice strength increased with decreasing temperature (Merkel, 2004), which may partially explain the increase of wood strength when below 0 °C.

MC and temperature are two important factors affecting the wood strength. However, in previous research, wood strength was rarely determined at ultra-low temperatures, such as −100 °C to −196 °C. In the present study, MOR and MOE of wood specimens with five different levels of MC, i.e. water-saturated, green, fiber-saturated, air-dried and oven-dried, were investigated at temperatures between +20 °C and −196 °C, with the aim to comprehensively examine the flexural property of wood under low temperatures. The flexural property was determined in a temperature-controlled chamber with a precise temperature, which was different from the previous studies where specimens were tested at room temperature after storing them for a period of time at low temperatures (Ayrilmis et al., 2010; Bekhta and Marutzky, 2007; Kendra and Cortez, 2010; Szmutku et al., 2013). The

* Corresponding author. Tel.: +86 10 62889482.
E-mail addresses: zhao_li_yuan@126.com (L. Zhao), jiangjh@caf.ac.cn (J. Jiang), jianxiong@caf.ac.cn (J. Lu), tianyizhan_caf@126.com (T. Zhan).

[1] These authors contributed equally to this work and should be considered co-first authors.

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cryogenic scanning electron microscopy (Cryo-SEM) was used for the observation of wood morphology in low temperature environment, ensuring that the initial MC and morphology of wood specimens remained unchanged.

2. Experimental

2.1. Materials

Green birch (*Betula platyphylla*) with an average MC of 67% and a basic density of 570 kg/m^3 was used in this study. Specimens without knots and defects were cut to a size of 300 mm (length) × 20 mm (radial) × 20 mm (tangential) for the determination of MOR and MOE.

2.2. Conditioning moisture content

Five MCs of birch wood specimens, i.e., water-saturated, green, fiber-saturated, air-dried, and oven-dried, were prepared as follows. The specimens directly cut from the fresh felled timber were defined as green samples (GW). The water-saturated wood specimens (WS) were prepared by immersing the green wood specimens in water for 2 months. The fiber-saturated wood specimens (FSP) were prepared by placing the green wood specimens in an air-drying shed for 2 months followed by being conditioned at a room temperature in a sealed container over distilled water which provided the 100 % relative humidity (RH) for at least 2 months. The air-dried wood specimens (AD) were prepared by placing the green wood specimens in an air-drying shed for 2 months followed by equilibration in a temperature-humidity chamber at 20 °C and 65% RH for 2 months. The oven-dried wood specimens (OD) were prepared by placing the green wood specimens in an air-drying shed for 2 months, and then in an oven at 103 °C for at least 48 h.

After the conditioning, the average MCs of specimens were as follows: 67% for the green wood, 136% for the water-saturated wood, 29% for the fiber-saturated wood, 12% for the air-dried wood, and approximately 0% for the oven-dried wood.

2.3. Static bending at low temperatures

Seven temperature levels, i.e., 20 °C, 0 °C, −30 °C, −70 °C, −110 °C, −160 °C and −196 °C, were selected for the experiments. Ten specimens were prepared for each temperature level.

A 3-mm diameter end hole was drilled in the specimen sized of 50 mm (length) × 20 mm (radial) × 20 mm (tangential) for the insert of a thermocouple to determine the temperature of the geometrical center. A liquid nitrogen cylinder served as a cooling source whereby temperature was slowly lowered at an hour period, while −196 °C was soaked in the liquid nitrogen. Half an hour was taken to stabilize the temperature after the internal temperature of the specimen reached the target one.

The measuring instrument was the Universal Mechanical Testing Machine (Instron 5582, USA) with a temperature-controlled chamber. The experimental device was placed inside the chamber for determining the properties at a precisely desired temperature. The bending load in the tangential direction of birch wood was applied at a rate of 5.0 mm/min until the failure of the specimen according to GB/T 1936.1 (2009). Specimens were sealed with plastic bags in order to prevent the change of moisture content.

2.4. Mechanical property parameters

MOR and MOE of the specimens were calculated using Eqs. (1) and (2). Due to the viscoelasticity of wood, the specimens could be loaded after reaching the maximum load in the failure. The ductility ratio (μ) is a parameter characterizing the deformation ability of specimens (Chopra, 2009; Zhong et al., 2013), which was calculated using Eq. (3).

$$MOR = \frac{3F_{max}L}{2bh^2} \tag{1}$$

$$MOE = \frac{FL^3}{4bh^3s} \tag{2}$$

$$\mu = \frac{\Delta u}{s} \tag{3}$$

where: F_{max} is the maximum load (N), L is the length of span (mm), b is the width of the specimen (mm), h is the thickness of the specimen (mm), F is the load increment on the straight line portion of the load-deformation curve (N), s is the deformation corresponding to F (mm), and Δu is the limit displacement corresponding to $0.85F_{max}$ (mm).

2.5. Morphological characteristics at low temperatures

Cryo-SEM has several advantages including easy and rapid specimen preparation, elimination of chemical fixation and dehydration which may alter the specimen properties, and can be performed in a frozen hydrated state which minimizes the incidence of shrinkage and collapse (Allan-Wojtas and Yang, 1987). It is especially important that samples in a highly hydrated state can be examined, such as water-saturated wood in the low temperature environment.

In this experiment, water-saturated wood specimens and oven-dried wood specimens were analyzed by means of Cryo-SEM. Specimens were frozen in liquid nitrogen (−196 °C) and then fractured manually to obtain a fresh section for the morphology observation. The temperature was heated up to nearly −90 °C to remove water vapor of the fracture surface. Samples were then examined in the Cryo-SEM after sputter-coating with gold (10 mA, 60 s).

2.6. Data analysis

The SPSS statistical software, version 17.0 (SPSS Inc, Chicago, IL, USA), was used for the data analysis. Duncan multiple comparison tests were carried out to analyze whether the effect of the low temperatures was significant.

3. Results and discussion

3.1. Influence of low temperature on MOR and MOE

Figs. 1 and 2 show MOR and MOE of wood specimens in low temperature environment (0 °C, −30 °C, −70 °C, −110 °C, −160 °C, −196 °C) compared with that at room temperatures (+20 °C). MOR and MOE of the specimens increased with decreasing temperature. When the temperature decreased from +20 °C to −196 °C, the largest increases in MOR of wood-saturated, green, fiber-saturated, air-dried and oven-dried wood specimens were 463.8%, 328.9%, 188.8%, 92.2%, and 18.6%, while that in MOE were 273.7%, 170.7%, 126.0%, 65.6%, and 24.4%, respectively. The higher the MC of a specimen, the greater and faster increase in MOR and MOE was observed at low temperatures. For example, at 0 °C, MOR and MOE of water-saturated wood specimens were 0.30 and 0.29 times larger than that at 20 °C, but rapidly increased to 4.6 and 2.7 times at −196 °C. While for the air-dried specimen, MOR and MOE at 0 °C were 0.25 and 0.05 times larger than that at 20 °C, and they were 0.90 and 0.66 times larger at −196 °C with a slighter and slower increment. Increases in MOR and MOE of the oven-dried specimen were the least and slowest one.

According to the statistical analysis, significant differences ($p < 0.05$) were observed in MOR and MOE of the specimens at the four MC levels (water-saturated, green, fiber-saturated, and air-dried) from +20 °C to