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Evidence of mechano-sorptive effect during moisture adsorption process under hygrothermal conditions: Characterized by static and dynamic loadings

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ABSTRACT

The viscoelasticity of Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook.) was examined during moisture adsorption at a relative humidity step (RH_{step}) mode (made up of RH_{ramp} and $RH_{isohume}$ periods) from 0 to 90% RH and temperatures ranging from 30 to 80 °C. The viscoelastic tests were carried out by static and dynamic loadings. The moisture adsorption resulted in an increase in compliance or damping. The phenomena that more pronounced mechano-sorptive (MS) effect during RH_{ramp} periods than $RH_{isohume}$ periods were observed, indicating that the MS effect could be detected by both static and dynamic loading tests. At 70 or 80 °C dynamic loading tests, the lignin transition was observed. Before the occurrence of the lignin transition, or when temperature at or below 60 °C, a smooth master curve of E'' vs. E' was formed and indicated that during the adsorption process the temperature not only accelerated the viscoelastic processes, but also increased their intensity.

1. Introduction

Dynamic mechanical analysis (DMA) is an accessible and usable rheological test to offer an insight into the viscoelastic behavior of wood [37,10,29]. As most hygroscopic polymers, wood exhibits complex viscoelastic behavior depending on both temperature and moisture content (MC). Elevation of temperature provides wood cell wall polymers with heating energy for segmental motions, leading to the decreasing stiffness and increasing damping [20,17]. When water is introduced into wood cell walls, dissociative hydroxyl groups attract water molecules. Some internal hydrogen bonds (HBs) within amorphous regions are broken and new HBs between water and amorphous components (hemicellulose, lignin and para-crystalline cellulose) are formed, causing the enhancement of wood flexibility [34,12,28]. Engelund and Salmén [8] investigated the double-effects of both temperature and MC on wood viscoelasticity, revealing that temperature had the equal effect on elastic and damping properties, and MC affected damping property in a greater degree.

When water molecules adsorbs, an increase in polymer molecular mobility was observed [1,30,8]. The increase in molecular mobility destabilized the condition of molecular packing degree, resulting in free volume in wood cell walls [18]. The MC changing behaves as mechano-sorptive (MS) effect when wood is subject to loading, no matter static or dynamic one [7,24,33,39].

The MS deformation might be affected by different variables: wood species [16], specimen geometry [14], grain direction [16,35], heating history [16], cultivation condition [2], etc. The MS deformation, which causes large deflections of beams; large movements of wood-based sheeting in walls, floors, and ceilings; and distortion of wood-based floor boards, is fundamental topic for both the serviceability and safety of engineering used timber structures [27]. In order to minimize the variation of MC and MS deformation, some modification methods are proposed such as heat treatment, acetylation, maleic acid impregnation, etc. [32,9]. These methods either reduces the hydroxyl groups in the three polymers via the decomposition of hygroscopic constituents (mostly hemicelluloses) or forms the cross-linking at the molecular level [32,19].

Concerning the MC changing is associated with the ambient temperature [31], the hygrothermal effect, i.e., the double-effects of temperature and MC on wood viscoelastic properties during the MC change process are complicated. On the one hand, temperature elevates the MC changing rate, which aggravates the MS effect. On the other hand, temperature provides heating energy for the

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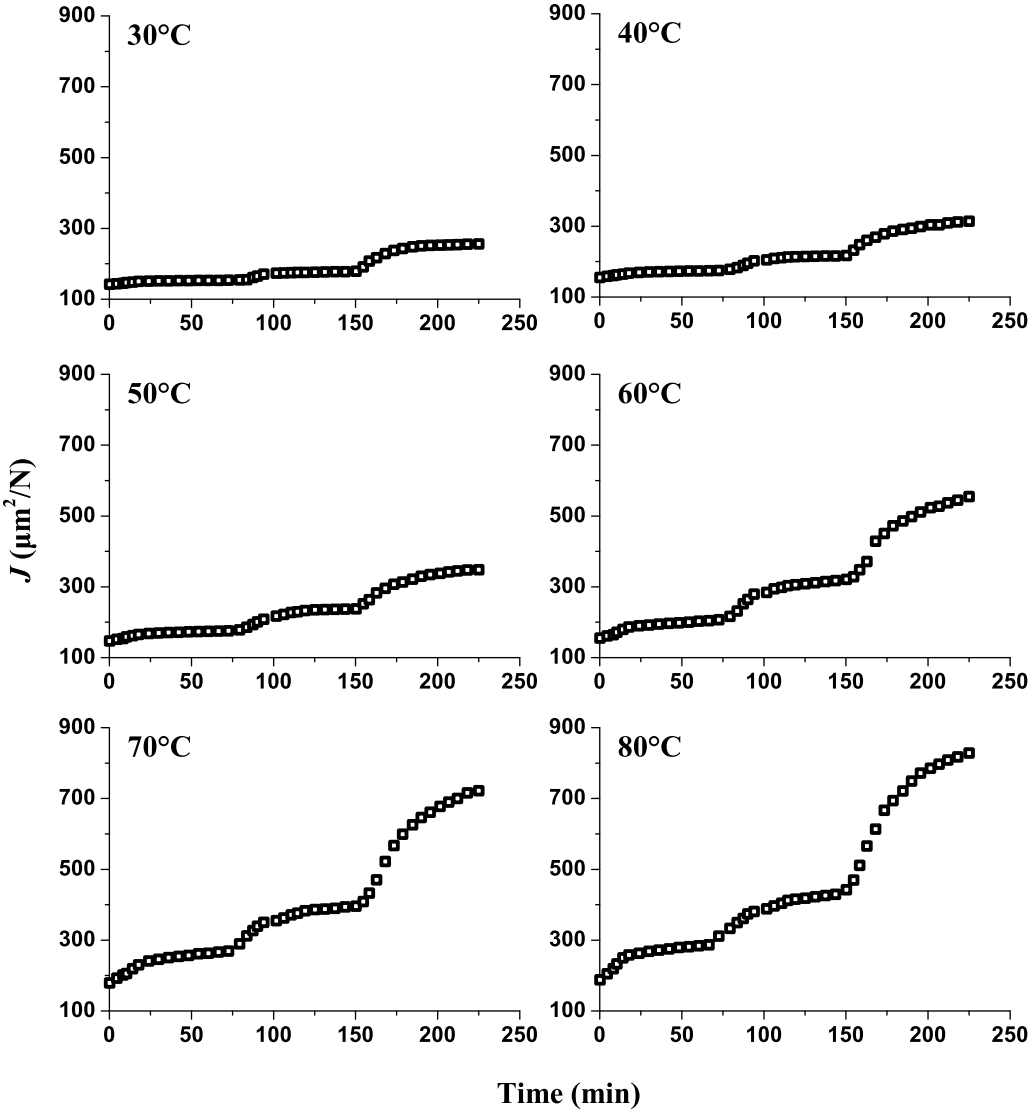

Fig. 1. Changes of J under the RH_{step} mode ($0 \rightarrow 90\%$ RH).

reduction of wood stiffness. Accordingly, there is a need to explore the hygrothermal effect on viscoelastic properties under moisture non-equilibrium state.

In an attempt to understand the hygrothermal effect, this study was conducted an investigation of the viscoelastic behaviors by both static and dynamic loadings during adsorption processes. Adsorption experiments were performed at an RH_{step} mode (made up of RH_{ramp} and $RH_{isohume}$ periods) under isothermal temperatures. The MS effect was discussed by evaluating the changing extent of viscoelastic parameters during the RH conditions (varied or constant) and the influence of temperature on the viscoelasticity was illustrated by the viscoelastic data in a complex plane.

2. Materials and methods

2.1. Materials

Without any visual defects, the Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook.) heartwood specimens with a dimension of $60 \times 12 \times 2.5\,mm^3$ ($L \times R \times T$) were cut within same growth ring ranges. All specimens were dried in a sealed container with P_2O_5 at room temperature until the constant mass was achieved. The corresponding MC and raw density of specimens used were about 0.6% and $0.37\,g/cm^3$, respectively.

2.2. Viscoelastic measurement

The viscoelastic measurement was performed on the TA Instrument DMA Q800 equipped with a RH accessory. Between 5 and 90 °C, the accessory control the RH precisely in the range of 0–90% by modulating the flow rates of dry nitrogen and saturated moisture. A dual-cantilever bending clamp with a distance of 35 mm was used. Specimens were secured with a clamping torque of 80 N cm.

2.2.1. Static loading mode

To ensure that all the tests were carried out within the linear viscoelastic region, the applied stress was selected as 3 MPa [22]. Six constant target temperatures (30, 40, 50, 60, 70 and 80 °C) were used for the hygrothermal environments. Prior to the actual creep tests, specimens were firstly equilibrated at each temperature with a ramping rate of 5 °C/min, and kept isothermal (0% RH) for 30 min. Then RH was adjusted by a ramping rate of 2% RH/min from 0 to 30, 60 and 90% RH, successively. After reached each predefined RH, kept isohume for 60 min. The experimental setup of RH_{step} mode is illustrated in Fig. 2a. Three replicates at each temperature were