

THE VIBRATIONAL PROPERTIES OF CHINESE FIR WOOD DURING MOISTURE SORPTION PROCESS

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The vibrational properties of Chinese fir (*Cunninghamia lanceolata*) wood were investigated in this study as a function of changes in moisture content (MC) and grain direction. The dynamic modulus of elasticity (DMOE) and logarithmic decrement (δ) were examined using a cantilever beam vibration testing apparatus. It was observed that DMOE and δ of wood varied widely during moisture adsorption and desorption. The DMOE of wood conditioned by the adsorption process showed significant increases during the later stages of conditioning when the MC scarcely changed. However, with the desorption process, the DMOE did not increase as much during the later stages of conditioning, though they increased during the early stages of conditioning when the MC greatly decreased. These results suggest that wood in an unstable state, caused via the existing state of moisture, shows different vibrational behaviors. Furthermore, the parallel to grain direction showed much higher DMOE and lower δ when compared to the perpendicular to grain direction. The variation of vibrational properties between parallel and perpendicular to grain direction under constant MC and during moisture adsorption process could be attributed due to the microscopic, macroscopic molecular, as well as chemical constituents of wood.

Keywords: Changing process of moisture; Dynamic modulus of elasticity; Logarithmic decrement; Anisotropic characteristics

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INTRODUCTION

Wood, one of the most important biomaterials, is a complex bio-composite consisting of three structural components: cellulose, hemicellulose, and lignin, which display significantly different properties. Wood exhibits viscoelastic behavior that is associated with both its molecular structure and supramolecular architecture within the cell wall. The viscoelastic properties of wood are relevant for construction of musical instruments, such as violins and pianos. They also play a significant role in heating, drying, and gluing, and thus they affect the quality of the wood and wood-based materials.

One convenient way of studying viscoelastic properties of wood is through vibrational analysis. A damped free vibration test was carried out with a cantilever beam vibration testing apparatus. The dynamic modulus of elastic (DMOE) and internal friction (logarithmic decrement, δ) measurements can be used to study the viscoelastic nature of

wood. The DMOE is related to sound velocity and δ to sound absorption or damping within the wood. Both quantities themselves are important for technological applications.

Since wood is a hygroscopic material, it will take up or release moisture depending on the temperature and relative humidity of the surrounding atmosphere. In general, most physical and mechanical properties of wood vary inversely with the moisture content (MC) of wood below the fiber saturation point. Furthermore, since environmental conditions never remain stable and ambient relative humidity and temperature changes continuously, repeated adsorption and desorption of moisture takes place and MC of wood seldom reaches an equilibrium level with its surroundings. It has been observed by several researchers that wood behaves differently during adsorption and desorption, and some of its physical and mechanical properties are influenced by the state of sorption (Goulet and Hernández 1991; Hernández 1993a,b; Obataya *et al.* 1998; Naderi and Hernández 1999; Chauhan and Aggarwal 2004; Takahashi *et al.* 2006; Lee *et al.* 2011).

In any event, the existence of sorption hysteresis suggests that, in terms of the existing states of moisture, wood moisture conditioned during the adsorption process is different from that during the desorption process. The aim of this study was to investigate the effect of the state of moisture sorption on the vibrational behavior of wood. This was achieved by examining the DMOE and δ of wood during the moisture conditioning process of adsorption and desorption.

MATERIALS AND METHODS

Wood Material

Chinese fir (*Cunninghamia lanceolata*) heartwood was tested in this study. The basic density of the samples based on oven-dried weight and green volume was about 296 kg/m³. Specimens were prepared from air-dried defect-free boards; two main anisotropic directions were considered for this study: parallel to grain and perpendicular to grain (hereafter referred to as “L” and “R” specimens). The dimensions of L specimens were 125 mm × 12 mm × 2 mm (L × R × T), and those of R specimens were 125 mm × 12 mm × 2 mm (R × L × T).

Moisture Conditioning

Samples for the vibration tests at constant MC were divided into five groups, each consisting of five samples. Specimens were moisture-conditioned in three conditioning rooms (20°C, relative humidity (RH) levels: 30%, 65%, 90%) for four weeks, which provided equilibrium moisture contents of approximately 7.6%, 13.3%, and 18.9%, respectively. Saturated samples were prepared by soaking them in water for four weeks at room temperature. Oven-dry samples were dried using a constant temperature drying chamber (24 h at 105°C).

Five oven-dried specimens were subjected to multistep adsorption in three relative humidity rooms: 30%, 65%, and 90%. During the moisture sorption processes, specimens were taken out from conditioning rooms at different times (2, 5, 10, 16, or 26 hours) to determine their MC and vibrational behavior. After completion of adsorption

experiments, samples were kept in distilled water for a sufficient period to ensure full saturation of the cell walls. These samples were placed in a conditioning room with 90% RH for 2 days (the MC of specimens were about 22%). After this period, the samples were subjected to multistep desorption mode in two relative humidity rooms: 65% and 30%. They were then placed in a desiccator containing P₂O₅ (about 0% RH). The specimens were weighted and measured for the vibrational properties at different times (2, 5, 10, 16, or 26 hours) of each desorption processes.

Measurement of Vibrational Properties

The test samples moisture-conditioned for 2, 5, 10, 16, or 26 hours were sealed with a polyethylene film to avoid changes in MC during the test. At room temperature (20°C, 65% RH), a cantilever beam vibration testing apparatus (Forest Products Laboratory, USA) was used for vibration tests under constant MC and during moisture changes. The specimen was gripped securely at one end and excited near the free end with a sharp flick from a shooting valve. The vibration was detected with a laser displacement transducer and recorded as a function of time. The frequency and amplitude attenuation is then used to calculate the dynamic modulus of elasticity (DMOE) and logarithmic decrement (δ) of the cantilever samples.

The dynamic modulus of elasticity (DMOE) can be calculated by the following equation (Turk et al. 2008),

$$\text{DMOE} = \frac{M}{L} \frac{12}{bt^3} (2\pi f)^2 \left(\frac{l^2}{1.875^2} \right)^2 \quad (1)$$

where M is mass of the specimen (kg), L is complete length of the specimen (m), b is base width of the specimen (m), t is thickness of the specimen (m), f is the detected frequency of the first natural mode of vibration (Hz), and l is the unclamped length of the cantilever beam (m).

As far as the internal damping is concerned, the law governing a damped vibration has the following form,

$$\chi = \chi_0 \exp(-ht) \times \cos(\omega t + \varphi) \quad (2)$$

where h is the damping constant. The amplitude is a function of time and it decreases towards zero.

A typical specimen free vibration response is shown in Fig. 1. In order to determine the logarithmic decrement (δ), the following equation can be used:

$$\delta = \ln \frac{\chi_n}{\chi_{n+1}} \quad (3)$$

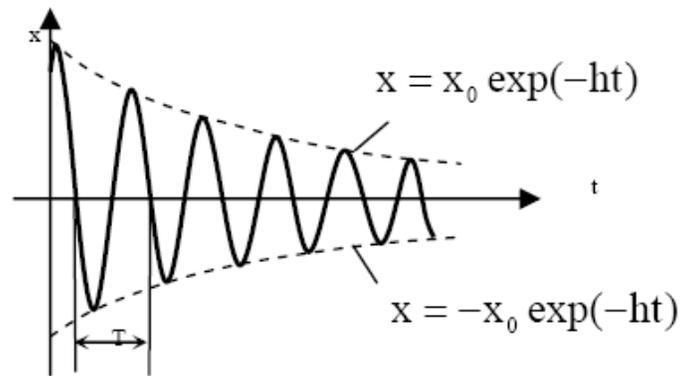


Fig. 1. A typical specimen free vibration response

RESULTS AND DISCUSSION

Vibrational Properties of Wood at Constant Moisture Contents

Figure 2 shows the DMOE and δ values of specimens in both grain orientations as a function of constant MC obtained at various relative humidity levels. Each column represents the averaged values for five samples, and the 95% confidence interval for the plots was less than 0.026 GPa (L specimen) and 0.004 GPa (R specimen). The DMOE of R samples were much lower than that of L samples (Fig. 2a). This result agrees well with findings of the previous studies (Mano 2002; Jiang and Lu 2009). The higher elasticity in the parallel to grain direction may be due to the longitudinal orientation of the cell along the axial direction. Furthermore, the δ values of R specimens were 100 percent higher than those for L specimens (Fig. 2b).

As for L specimens, the DMOE reached a maximum at 30% RH (about 7.6% MC) and then decreased with an increase in RH while the δ value showed a minimum at 30% RH and then rose with increasing RH. These results agree with those obtained by Kollmann and Krech (1960), James (1961, 1964), Suzuki (1962), Obataya *et al.* (1998), and Takahashi *et al.* (2006). They reported that at about 5 to 8% MC elastic modulus showed a maximum value and δ showed a minimum value. These phenomena can be explained by the hypothesis that in an oven-dry state, molecular chains in the amorphous regions of the cell wall are unnaturally distorted. Also, microvoids exist between the molecular chains.

This unnatural structure of the cell wall in an oven-dry state causes a smaller DMOE and a greater δ value. With increasing MC from oven-dried state, water molecules are embedded in the microvoids and the distorted molecular chains are rearranged. As a result, at about 5 to 8% MC, a more stable state for the cell wall structure is obtained and tends to increase the modulus. Above 8% MC, water acts as a plasticizer that allows more molecular movement, and the cohesive forces between molecules are decreased, resulting in decreasing DMOE and increasing δ values.

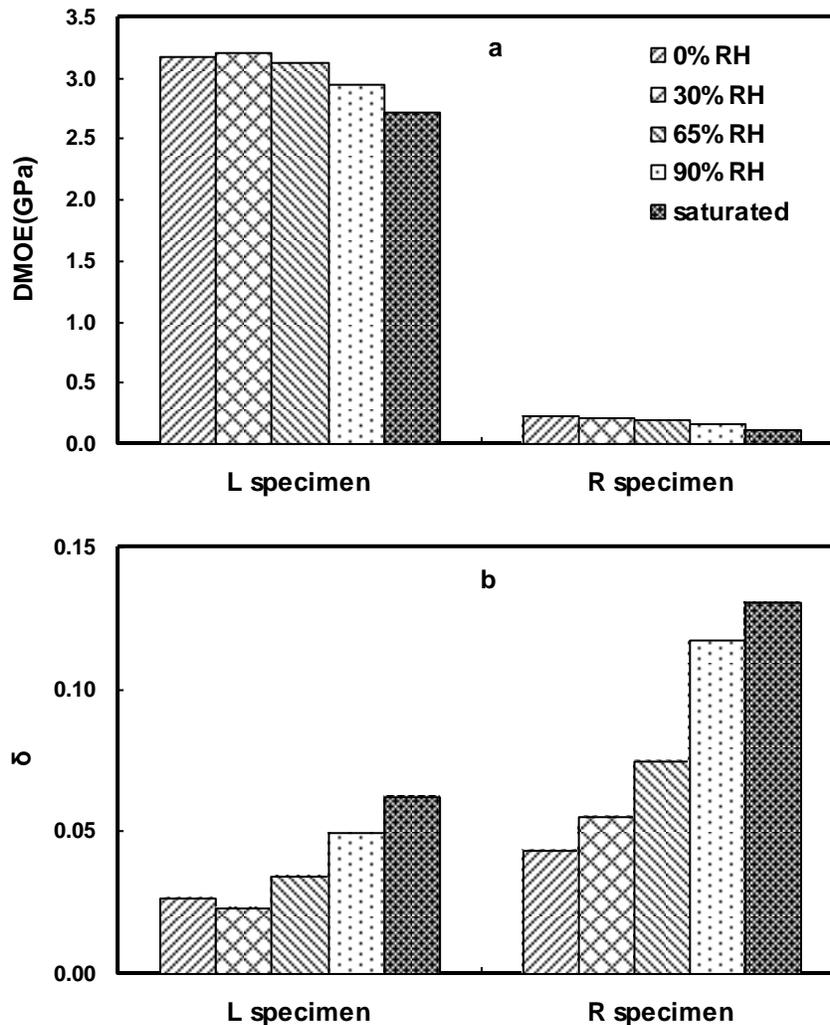


Fig. 2. Changes in the DMOE (a) and δ (b) of L and R specimens at constant moisture content obtained at various relative humidity levels

However, an increase in DMOE with the addition of water could be observed in the L specimen, but it did not appear in the R specimen. This is probably attributable to the stiffness of the molecular chain, a relatively high molecular orientation, and the high crystallinity in wood fibers of L samples.

Changes in Vibrational Properties during Moisture Adsorption Processes

The changes in MC of the samples in both grain directions during adsorption processes are shown in Fig. 3.

Regardless of grain direction, the MC increased with the conditioning period during adsorption process. The MC changes were greater in the samples conditioned at a higher relative humidity during the conditioning period examined. In general, changes in the MC of the samples from 16 to 26 hours of the conditioning period were small.

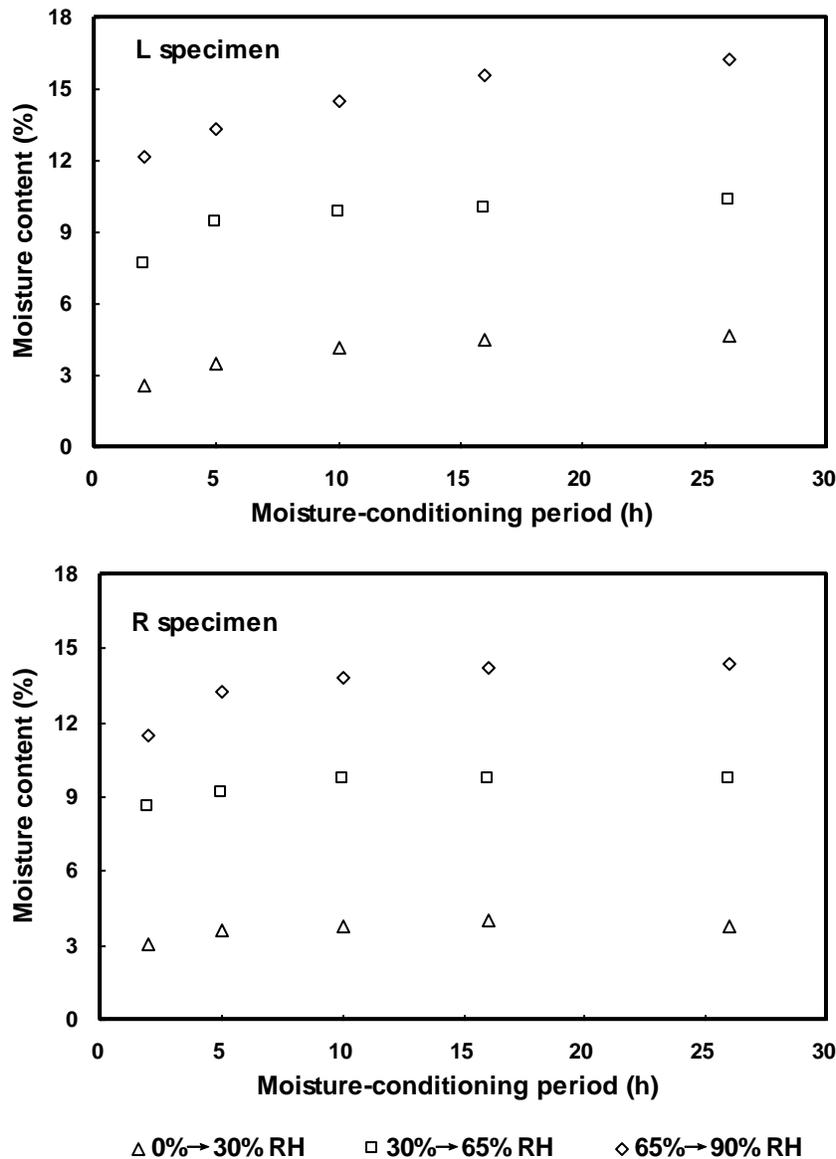


Fig. 3. Changes in the moisture content of L and R specimen during the successive adsorption processes

Figure 4 shows changes in DMOE and δ values for the wood moisture-conditioned by the adsorption process in both grain directions. The tests were carried out five times for each condition. Because the behavior of DMOE and δ with MC change was very alike for all conditions, only one of the results is shown here. Regardless of grain direction, the DMOE decreased with an increase in RH, and a reverse trend was observed clearly for the changes in the δ values.

As for L specimens, in each adsorption condition, DMOE reached a minimum and then increased or flattened out according to the duration of the conditioning period (Fig. 4a). Therefore, considering the changes in MC during the conditioning period, as shown in Fig. 3, the decreases in DMOE during the early stages (0 to 10h) of moisture

conditioning can be mainly attributed to increases in the MC. However, it is notable that the DMOE increased despite slight increases in the MC during the later stage (16 to 26 h) of conditioning. The changing behavior of DMOE from the oven-dry state to approximately 7.6% MC (0 → 30% RH) was compared with that of the other two adsorption processes (30% → 65% RH and 65% → 90% RH). A remarkable decrease in DMOE during the early stages of conditioning was apparently observed at 30% RH. The adsorption rate should affect the decreasing behavior of DMOE because a greater adsorption rate leads to greater destabilization during an adsorption process (Takahashi *et al.* 2005).

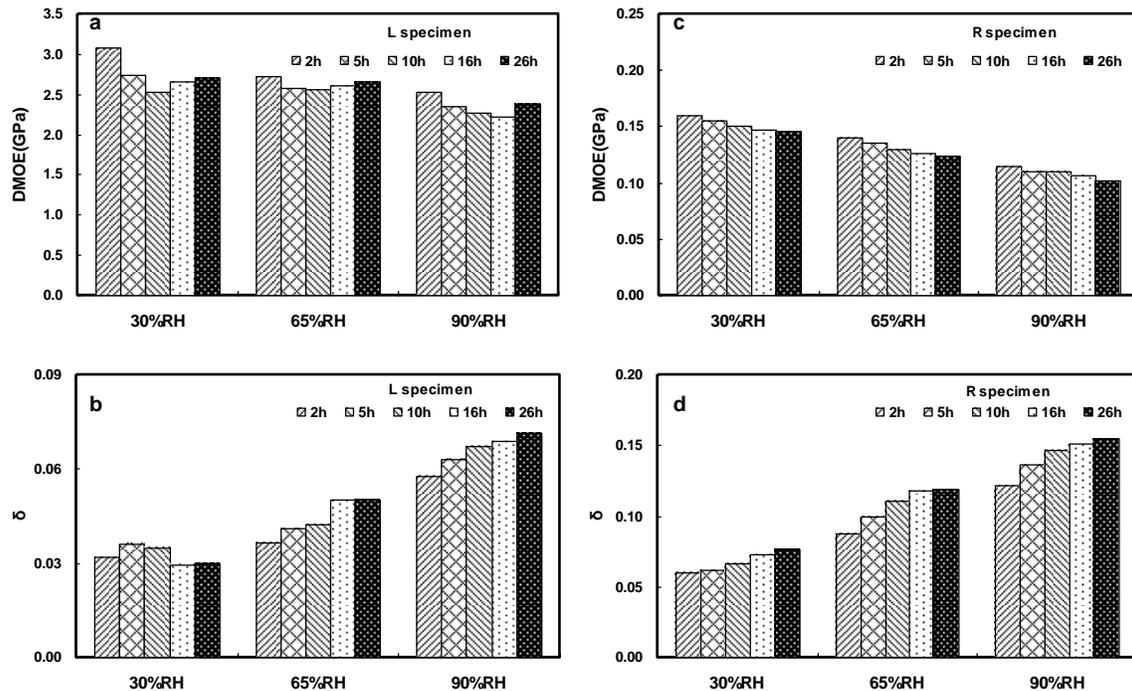


Fig. 4. Changes in the DMOE and δ of L specimen (a, b) and R specimen (c, d) during the successive adsorption processes

According to Fig. 4b, the L specimen conditioned at 30% RH showed a maximum in δ and then decreased during the MC adsorption processes. The δ value of the wood conditioned at 65% RH and 90% RH both increased from 2 hours to 26 hours of conditioning. In oven-dry state, the hydroxyl groups of the cellulose cell wall became close together, allowing the formation of weak cellulose-to-cellulose hydrogen bonds. Adsorption of water then occurred in lower MC and a part of these weak bonds were broken down by the entering of water molecules, and some hydroxyl groups were released (Bowyer *et al.* 2003). Therefore, the reorientation of molecular chains may cause energy dissipation during the initial adsorption processes, resulting in increasing δ values.

With respect to the R specimen (Fig. 4 c, d), in each adsorption condition, the DMOE and δ values were gradually decreased and increased with prolonging of moisture-conditioning periods, respectively. It is possible to think that the variation of vibrational properties between L and R samples is due to the difference in the

arrangement of cell wall and lumen in addition to the anisotropy of cell wall substances. Furthermore, according to some researchers (Norimoto and Yamada 1972; Kabir *et al.* 1998), the properties of wood may be influenced by cellulose in parallel to grain direction, whereas in perpendicular to grain direction, the behaviors are influenced by lignin.

Changes in Vibrational Properties during Moisture Desorption Processes

Figure 5 shows the changes in MC of the samples in both grain directions during the desorption processes. In each RH condition, the MC decreased during desorption process for both the L and R specimens. In general, changes in the MC were small from 16 to 26 hours of the conditioning period.

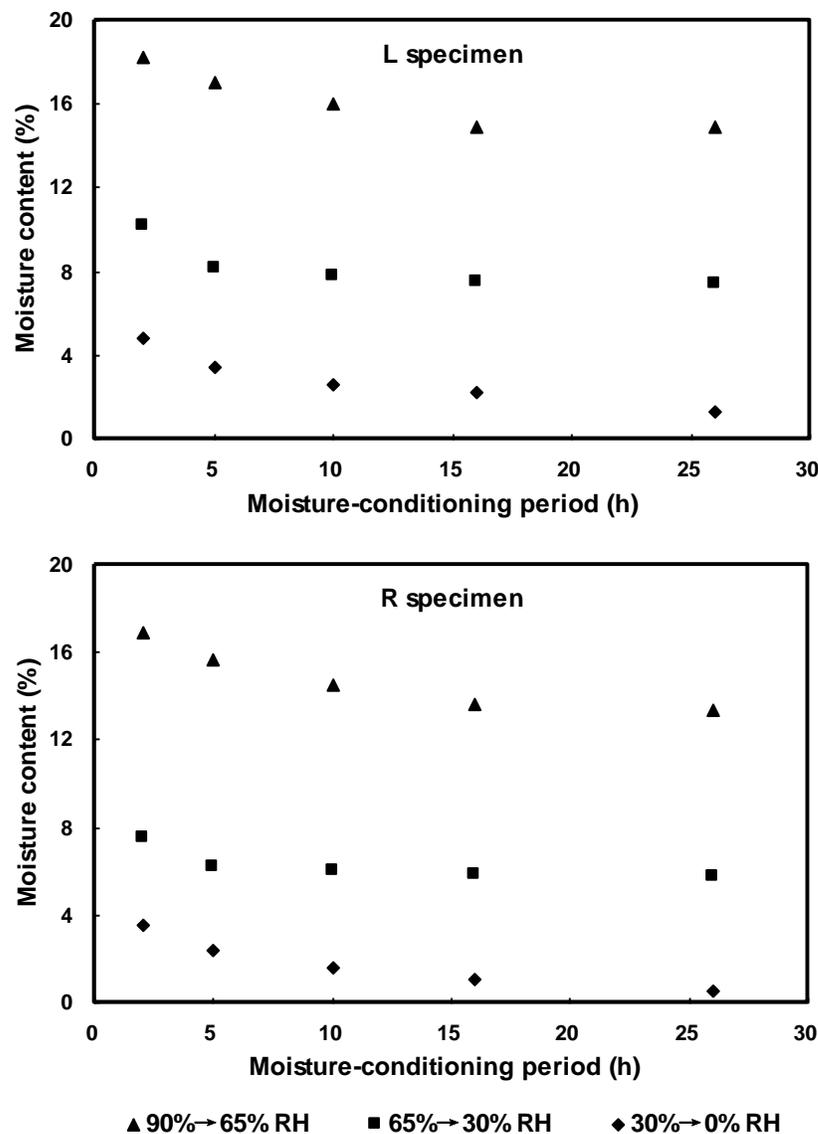


Fig. 5. Changes in the moisture content of L and R specimen during the successive desorption processes

A representative result of DMOE and δ values for samples during moisture desorption processes in two grain directions are shown in Fig. 6. Regardless of the grain direction, the DMOE increased with decreasing RH, and a reverse trend was observed clearly for the changes in the δ , without showing a maximum value. In each desorption process, DMOE showed extensive increases during the early stages (0 to 10h) of moisture-conditioning, and then the rate of increase diminished throughout the duration of the conditioning period (Fig. 6a,c). However, the δ decreased almost linearly according to the duration of the conditioning period (Fig. 6b, d).

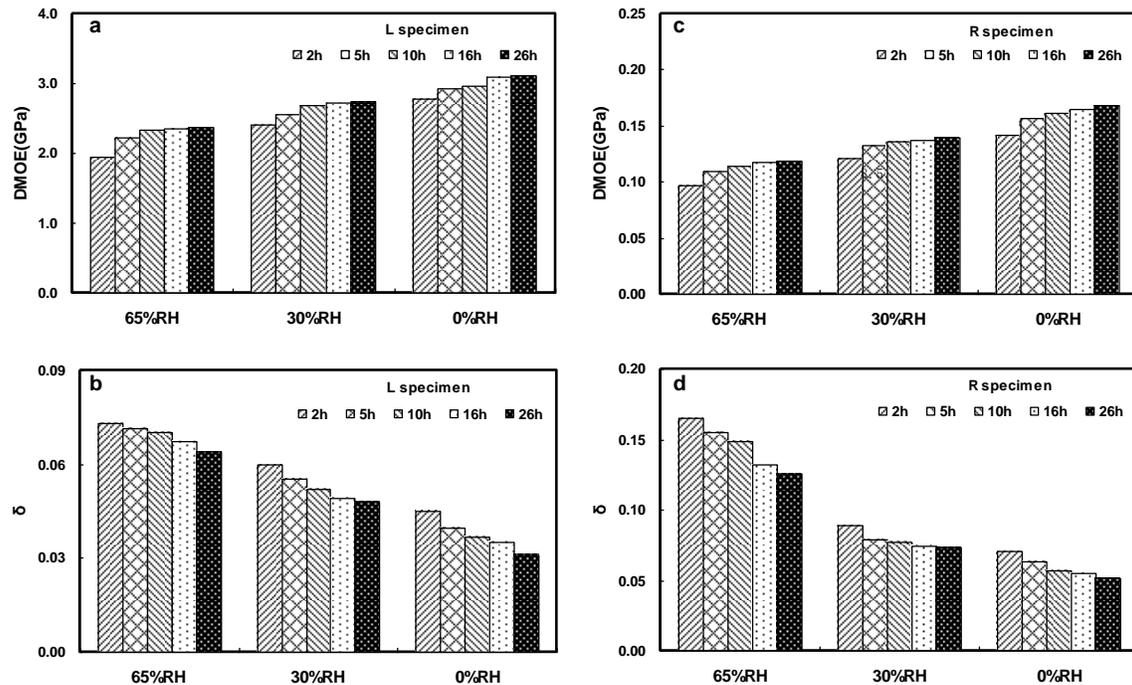


Fig. 6. Changes in the DMOE and δ of L specimen (a, b) and R specimen (c, d) during the successive desorption processes

Relative to the results of the adsorption process shown in Fig. 4, there was a significant increase in DMOE during the later stage of conditioning, whereas the MC scarcely increased (Fig. 3). This can be interpreted as a phenomenon that occurs during a stabilizing process, such as the reorientation of molecular chains of wood constituents toward a stable state by adsorption of moisture. On the other hand, in regards to the results of the desorption process shown in Fig. 6, there was only a slight increase in DMOE during the later stage of conditioning, whereas the MC scarcely decreased (Fig. 5). These observations can be explained by the following points: 1) The stabilization caused by reorientation of molecular chains is more difficult during the desorption process than during the adsorption process; 2) In an unstable state, such disorder of the molecular chains is also induced during the later stage of the desorption of moisture (Ishimaru *et al.* 2001).

CONCLUSIONS

Vibrational properties of Chinese fir wood were measured in both parallel and perpendicular to grain directions under constant MCs and during moisture changing processes. The results of the tests led to the following conclusions:

1. Under constant MC conditions, the DMOE showed a maximum at 30% RH (about 7.6% MC) and then decreased with an increase in RH for L samples, while the DMOE gradually decreased with increasing RH without showing a maximum for R samples. In each adsorption conditions, the DMOE of L specimens increased significantly during the later stages (16 to 26h) of conditioning, though the MC of the wood scarcely changed. During the desorption processes, the DMOE did not increase so much in the later stages of conditioning, though it increased during the early stages (0 to 10h) of conditioning when the moisture content markedly decreased.
2. Under constant MC conditions, L samples showed a minimum δ at 30% RH (approximately 7.6% MC) and then rose with increasing RH, while R samples exhibited an increased trend in δ with an increase in RH. During moisture adsorption process, L specimens conditioned at 30% RH showed a maximum in δ and then decreased during the MC adsorption processes, while the δ values of R specimens were gradually increased during the moisture-conditioned periods. In each desorption conditions, the δ values in both grain directions were decreased throughout the duration of the conditioning period.
3. The grain direction plays an important role for measuring the vibrational properties as a function of MC or moisture sorption state. The parallel to grain direction showed much higher DMOE and lower δ when compared to that of the perpendicular to grain direction. The anisotropy of wood vibrational properties may be attributed to the microscopic, macroscopic molecular, as well as chemical constituents of wood.

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