

Dynamic viscoelastic properties of Chinese fir under cyclical relative humidity variation

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Abstract The dynamic viscoelastic properties of Chinese fir (*Cunninghamia lanceolata*) with a moisture content of 10.65 % (30 °C, 58 % RH) under cyclical relative humidity (RH) variation (90–10 % RH) were examined. After seven-cycle RH changes, moisture content of specimens decreased. The storage modulus and loss factor increased and decreased, respectively. The occurrences of local maximum or minimum values of the storage modulus and loss factor lagged behind the occurrences of the maximum or minimum values of RH. Both lagged time and changing rate of storage modulus and loss factor decreased with the increasing cyclical times. When RH decreased from 90 to 10 % RH, the increasing rate of the storage modulus decreased with the decreasing of RH, while the loss factor decreased almost linearly. The unsteady effect and its partial recovery were observed during the desorption and the adsorption process, respectively. With the increasing cyclical times, the unsteady effect decreased and wood returned back to the dynamic equilibrium state gradually.

Keywords Chinese fir · Cyclical RH variation · Storage modulus · Loss factor · Unsteady effect

Introduction

The moisture content (MC) influences nearly all the physical and mechanical properties of wood. Wood cell walls are made from polymers which are more or less hydrophilic. Hydroxyl groups of the wood polymers are the main chemical component in terms of attracting water molecules. When entering the cell walls, water absorbs on the microfibril surfaces or into the surrounding matrix of hemicelluloses and lignin. Hydrogen bonds within the polymer network are replaced by the bonds to water molecule. As water plays a role of plasticizer, its entrance into wood cell walls may cause the decrease of wood stiffness.

The dynamic viscoelastic behavior of wood is essential in the wood industry, particularly in the processing and manufacturing operations, such as the drying, wood forming, veneer cutting, and panel pressing. The viscoelasticity of wood is closely related to its anatomy structure and chemical components, as well as ambient temperature and relative humidity (RH). Investigations of influence of the temperature on the dynamic viscoelasticity of wood are helpful in providing insight into mechanical relaxation and thermal degradation of constituents of wood cell walls [1–5]. The viscoelastic properties of wood change also with varying ambient RH. In 1961, Armstrong and Kingston [6] reported the viscoelastic behavior of wood during cyclical RH changing process, and which was referred to as the mechano-sorptive effects [7]. Numerous investigators studied the mechano-sorptive effect experimentally and theoretically [8–14], and some explanations regarding physical mechanisms were proposed. The MC variation caused the breaking and reforming of hydrogen bonds [8], created free volume which provided a destabilized condition [15] and molecular mobility, and the

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internal stress gradients varied with the presence of moisture gradients [11]. The changing of temperature and RH disturbed the equilibrium packing of molecular, which offered a destabilized condition that slowly returned to the equilibrium condition [16–19]. This asymptotic return to equilibrium is known as physical aging [15]. One of the most means of detecting the changes associated with destabilization and aging was the dynamic mechanical test. Ebrahimzadeh and Kubát [20] and Ebrahimzadeh et al. [21] observed the increase in loss factor ($\tan\delta$) at the early stages of the adsorption or desorption process due to the transient moisture effect and close relationship between the rate of adsorption/desorption and the shape of the $\tan\delta$ peak. Furthermore, the $\tan\delta$ was higher in a given moisture content if wood was in adsorption state rather than in desorption.

Studies of the influence of RH to dynamic viscoelastic properties of wood mainly focused on water equilibrium state, namely under different MCs which were conditioned by different RHs [2, 22–24]. However, limited studies describing the responses of viscoelasticity under non-equilibrium moisture states [25, 26] were found in the literature review. With the aim of obtaining findings on the viscoelastic properties of wood with cyclical RH variation, the present study described the time dependence of the dynamic viscoelasticity under non-equilibrium states. The discrepancy of responses of elastic fiber and viscous matrix to cyclic RH variation was also discussed through the wood behaviors of elastic and viscous properties examined by DMA.

Materials and methods

Materials

With the same growth ring ranges, Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook) specimens were cut into a size of 60 mm × 12 mm × 2.5 mm (L × R × T). These specimens were selected without any visible defects and knots. All specimens were conditioned at about 30 °C in a sealed container over a saturated solution of NaBr which gave 58 % RH. The corresponding MC and raw density of specimens used were about 10.65 % and 0.40 g/cm³, respectively.

Measurement of dynamic viscoelasticity

The forced-oscillation-type equipment (Q800 by TA Instruments) was used for obtaining the viscoelasticity parameters: storage modulus E' , loss modulus E'' and loss factor $\tan\delta$ ($\tan\delta = E''/E'$). Based on the feasibility of testing the responses of dynamic viscoelasticity to RH

variation, 3-point bending mode (with a span of 50 mm) was selected for the measurements instead of cantilever mode, which was the most common type among the dynamic test. The shrinkage loosed the alignment between the specimen and cantilever clamp during the cyclical variation of RH so that we chose the 3-point bending mode instead of the cantilever mode. The dynamic viscoelastic properties were determined at a frequency of 1 Hz. The displacement amplitude was 15 μm and the force track was 125 %. Force track, the ratio of static to dynamic force, was used to make sure tightly contact between sample and clamp and avoid the overstraining or creep of sample also. The preload force was 0.01 N. This applied force value was so small that the creep or mechano-sorptive creep effects could be negligible. The testing temperature was kept the same with the conditioning temperature at 30 °C to avoid any change of viscoelasticity caused by the heating temperature.

After mounted on the clamp in the testing chamber, the specimens were placed under a constant RH value of 58 % before the actual viscoelastic measurements. The constant RH atmospheres in the equipment were conducted as follows. The air in the chamber was firstly increased to 58 % RH (2 %/min) within 30 min and remained unchanged. After the specimens stabilized for more than 10 min, constant RH and cyclical RH tests were conducted, respectively. During the constant RH test, RH value in the testing chamber was kept 58 % within the whole time duration of 560 min. As for the cyclical RH test: RH increased from 58 to 90 % firstly, and then experienced 7 times of decrease (90–10 % RH) and 6 times of increase (10–90 % RH) alternately, finally RH increased to 58 % to end up. The whole cyclical RH progress took 560 min with a RH changing rate of 2 %/min. The MC changes were determined by weighing the specimens before and after the constant and cyclical RH tests. At least three replicates were carried out and one representative curve is shown here.

Results and discussion

Storage modulus and loss factor during the constant RH test

The values of storage modulus E' and loss factor $\tan\delta$ during the constant RH (58 %) condition were 6038.77 MPa and 0.0599, respectively. Generally, the viscoelasticity values were influenced by the wood species, test method and clamp type. The 3-point bending clamp, as a kind of tensioning clamp, applied a preload force to pretension the sample before the oscillation. The pretension load increased the energy dissipation of wood comparing to

the cantilever clamp (non-tensioning clamp), but the measurement values could be considered to be reasonable comparing to previous studies [27, 28]. The values of coefficient of variation of E' and $\tan\delta$ under constant RH condition were 0.06 and 0.05 %, respectively. The testing temperature (30 °C) was not high enough to provide sufficient energy for wood softening [29]. In addition, no change in MC was found after the test. Therefore, wood dynamic viscoelasticity remained unchanged at the constant environment (30 °C, 58 % RH).

Storage modulus during the cyclical RH test

Figure 1 shows a typical example of E' curves during the cyclical RH variation, and presents the responses of wood to the changes of RH in the surrounding atmospheres. The E' displayed fluctuated with the change of RH. E' decreased with the increase of RH, and increased with the decrease of RH. During the cyclical progress of the increasing and decreasing of imposed RH, 7 times of local minimum or local maximum values of E' (E'_{\min} and E'_{\max} , respectively) alternately occurred. The occurrences of E'_{\min} and E'_{\max} lagged behind the corresponding maximum value or minimum value of RH (RH_{\max} , 90 % RH or RH_{\min} , 10 % RH, respectively). Both values of E'_{\min} and E'_{\max} occurred each time were higher than that of the previous time they occurred. The ultimate value of E' increased compared to the initial value after 560 min RH changing progress.

The movement of water molecular into and out of wood cell walls was probably the main reason that E' fluctuated with the change of ambient RH. When RH increased, water molecular entered into cell walls and were absorbed on the microfibril surfaces or into the surrounding matrix. As water played a role of plasticizer, it formed water–lignin, water–hemicellulose, and water–paracrystalline cellulose

bonds, which replaced hydrogen bonds within the polymer and caused the decrease of wood stiffness [3]. When RH decreased, the vapor pressure in wood was higher than that in air. The difference in vapor pressure caused the desorption at the sample surfaces and the formation of MC gradient and vapor pressure gradient in the samples. The vapor pressure gradient forced the movement of water from sample cores to the surfaces [30]. When the water was out of cell walls, the bonds formed with cellulose, hemicellulose and lignin vanish. The spaced water molecular occupied the cells before diminishing due to the shrinkage of the cells. The polymers became close and formed hydrogen bonds again, resulting in the increase in wood stiffness. After 560 min cyclic RH changed, MC decreased by about 2.35 %. The decrease in MC could be the main reason that giving E' a higher ultimate value than the initial one.

Table 1 lists the changes of E'_{\min} and E'_{\max} during 7 times of RH cycles. It was also illustrated that the lagged time between occurrences of E'_{\min} or E'_{\max} and corresponding RH_{\max} or RH_{\min} decreased with the increasing cycle times. With the increasing occurrences, lagged time of E'_{\min} and E'_{\max} decreased from 4.83 and 4.89 to 3.09 and 3.16 min, respectively. The lagged responses of E' to RH showed a close relationship with anatomy structure of wood. Diffusion rates of water in coniferous wood mainly depended on longitudinal tracheids and transverse bordered pit pairs. The overall diameter of the pit chambers of bordered pits had an approximate range from 6 to 30 μm [30], which provided a large resistance against water diffusion. When RH reached the maximum (minimum) value and began to decrease (increase), water desorbed from (absorbed into) sample surfaces. Since the water diffusion speed was much slower than the RH changing rate, the occurrences of E'_{\min} or E'_{\max} lagged behind RH_{\max} or RH_{\min} . After a transient period of 7 cycles, lagged time of E'_{\min} and E'_{\max} decreased and leveled off with the increasing cyclic time. Chomcham and Skaar [31] believed that the response of wood more nearly followed the humidity changes with the increasing cyclic time and approached constant values as the number of cycles increased.

The E'_{\min} and E'_{\max} values occurred each time were always higher than the previous time they occurred. Although the increasing rate of E'_{\min} was higher than that of E'_{\max} , both the increasing rates decreased with the increasing cyclic time. Their increasing rates decreased from 0.54 and 0.33 to 0.31 and 0.17 %, respectively. These changes were mainly related to the reciprocated diffusion of water into and out of wood cell walls. The water diffusion caused the breaking and reforming of hydrogen bonds [8], increasing the fluidity of polymer molecular [11], creating or vanishing the free volume which gave a destabilized condition to cell walls [15]. The destabilized state of cell wall provided wood a lower stiffness comparing to that under a stabilized state [25]. The changes in

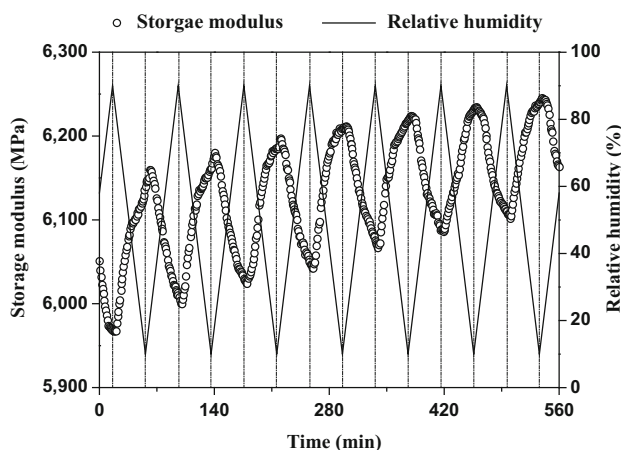


Fig. 1 Changes of storage modulus during the cyclical relative humidity variation

Table 1 Changes in local minimum or maximum value of storage modulus during the cyclical relative humidity variation

Local minimum or maximum value of E'	Occurred sequency	Lagged time ^a (min)	Value (MPa)	Changing rate ^b (%)
E'_{\min}	1	4.85	5966.97	/
	2	4.83	5999.41	0.54
	3	3.48	6023.64	0.40
	4	2.96	6045.35	0.36
	5	2.97	6066.34	0.35
	6	3.03	6085.27	0.32
	7	3.09	6104.27	0.31
E'_{\max}	1	4.89	6159.25	/
	2	4.85	6179.78	0.33
	3	4.68	6196.91	0.28
	4	4.10	6211.35	0.23
	5	3.17	6223.76	0.20
	6	3.22	6234.35	0.17
	7	3.16	6245.16	0.17

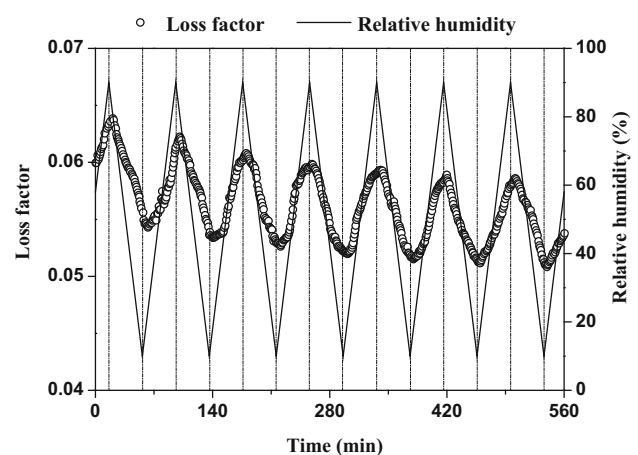
$$^a \text{Lagged time} = t_{E'_{\min/\max}} - t_{RH_{\max/\min}}$$

$$^b \text{Increasing rate} = (E'_{\min/\max}{}^i - E'_{\min/\max}{}^{i-1}) / E'_{\min/\max}{}^{i-1} \times 100 \%$$

wood stiffness during the changing of RH were attributed to two aspects. The first factor was the MC-caused changing of stiffness. Another factor was the destabilized-caused changing of stiffness resulted from the changes in RH, no matter increment or decrement of RH. During the increasing period of RH, destabilized-dependent effect to stiffness aggravated the decrease in stiffness caused by MC. In reverse, the increase in stiffness during the decreasing period of RH was the multi-effects of MC and the destabilized state. Before the test, the samples were conditioned at 58 % RH for over 8 weeks. When RH increased to 90 %, E'_{\min} occurred at the first time with the most destabilized state comparing to other E'_{\min} and E'_{\max} occurred subsequently. With the cyclic changes of RH, polymers asymptotically returned to the dynamic equilibrium state. The progress that polymers returning to equilibrium manifested as the increasing rate of E'_{\min} was more than E'_{\max} and both the increasing rates decreased with the increasing cyclic time.

Loss factor during the cyclical RH test

Figure 2 presents the response of $\tan\delta$ to cyclical RH changes. Similar to the responses of E' , $\tan\delta$ fluctuated with the change of RH also. $\tan\delta$ increased with the increasing RH and decreased with the decreasing RH. Changes of $\tan\delta$ lagged behind the changing of humidity and occurred $\tan\delta_{\max}$ and $\tan\delta_{\min}$. The occurred times of $\tan\delta_{\max}$ and $\tan\delta_{\min}$ corresponded with E'_{\min} and E'_{\max} , respectively. The ultimate value of $\tan\delta$ decreased by about 10.31 % compared to the initial value.

**Fig. 2** Changes of loss factor during the cyclical relative humidity variation

Generally, adsorbed water molecular increased interactions within wood substance and between water and wood substance. When polymolecular adsorbed water within wood cell walls, the mechanical relaxation could be mainly due to the orientation of water molecular in wood cells [2]. The increasing RH led to both increases in MC and $\tan\delta$. When RH decreased, the decreasing trend of both MC and $\tan\delta$ could be observed.

Table 2 lists the changes of $\tan\delta_{\min}$ and $\tan\delta_{\max}$ during 7 times of the RH cycles. Occurrences of $\tan\delta_{\min}$ and $\tan\delta_{\max}$ matched with that of E'_{\max} and E'_{\min} , respectively. When RH reached the RH_{\max} (RH_{\min}), MC_{\max} (MC_{\min}) lagged behind. Then, the amount of the created hydrogen bonds water–polymers increased (decreased). Subsequently, the

Table 2 Changes in local minimum or maximum value of loss factor during the cyclical relative humidity variation

Local maximum or minimum value of $\tan\delta$	Occurred sequency	Lagged time ^a (min)	Value	Changing rate ^b (%)
$\tan\delta_{\max}$	1	4.85	0.0639	/
	2	4.83	0.0622	-1.88
	3	3.48	0.0607	-1.44
	4	2.96	0.0594	-1.29
	5	2.97	0.0582	-0.82
	6	3.03	0.0574	-0.66
	7	3.09	0.0573	-0.66
$\tan\delta_{\min}$	1	4.89	0.0544	/
	2	4.85	0.0533	-2.59
	3	4.68	0.0526	-2.32
	4	4.10	0.0519	-2.24
	5	3.17	0.0515	-1.98
	6	3.22	0.0511	-1.41
	7	3.16	0.0508	-0.20

^a Lagged time = $t_{\tan\delta_{\min/\max}} - t_{RH_{\min/\max}}$

^b Increasing rate = $(\tan\delta_{\min/\max}^{i-1} - \tan\delta_{\min/\max}^i) / \tan\delta_{\min/\max}^{i-1} \times 100\%$

wood stiffness decreased (increased) to E'_{\min} (E'_{\max}). Meanwhile, interactions between water and polymers increased (decreased) to $\tan\delta_{\max}$ ($\tan\delta_{\min}$).

During the cyclic RH changing process, the values of $\tan\delta_{\min}$ and $\tan\delta_{\max}$ occurred each time were always higher than that of the previous time they occurred. Although the decreasing rate of $\tan\delta_{\min}$ was lower than that of $\tan\delta_{\max}$, both the decreasing rates decreased with the increasing of cyclic time. Their decreasing rates decreased from -1.88 and -2.59 to -0.66 and -0.20 %, respectively. These results matched with the changes of E'_{\min} and E'_{\max} . The decreasing changing rates of both E' and $\tan\delta$ were attributed to the returning of the dynamic equilibrium state from a destabilized state of cell wall. The changes of E' and $\tan\delta$ may also be related to the swelling/shrinkage properties of microfibril and matrix under changing RH [32]. The different responses of microfibril and matrix to the varying RH caused a phase lag of dimensional changing between these two parts. The dissipated energy increased with the existing dimensional phase lag. With the increase in cyclic time, the phase lag between microfibril and matrix gradually decreased and was corresponding to less energy dissipation.

Storage modulus vs RH

It is possible to transform the time x axis of Fig. 1 to a RH axis based on the RH time setting program. The results of 7 times of cyclic RH changes are shown in Fig. 3 where E' is plotted versus the RH values. The whole RH changing region was divided into 3 parts for further discussion: (1) 58 % RH → 90 % RH (Fig. 3a), (2) 90 % RH → 10 %

RH (Fig. 3b), (3) 10 % RH → 58 % RH (Fig. 3c). Based on E' vs RH curves, one cycle was proposed as RH changed from 58 % RH and back to 58 % RH again (58 % RH → 90 % RH → 10 % RH → 58 % RH). As seen in the whole RH changing regions, E' decreased with the increased RH and increased with the decreased RH. These trends were consistent with the results in Fig. 1. Regardless of RH value, E' increased with cyclic time. During the RH changing process from 58 to 90 % RH (Fig. 3a), the changing rate of E' at the second cycle compared to the first one was significantly higher than subsequent cyclic times. At the beginning of RH change, polymers of cell wall had the most destabilized state. The effect of physical aging of polymer molecular on the decreasing wood stiffness was observed most obviously at this period [15]. With the subsequently RH changing process, polymers were back to the dynamic equilibrium state gradually. When RH varied from 90 % RH to 10 % RH (Fig. 3b), E'_{\min} occurred at about 80 to 85 % RH. The RH value that E'_{\min} occurred increased and leveled off with the increasing cyclic time. The RH lag phase between E'_{\min} and RH_{\max} (90 % RH) is presented as time lag phase in Fig. 1. When E' reached E'_{\min} and went through the increasing progress, its increasing rate decreased with the decreasing RH. These phenomena were probably related to the sorption properties of wood. Like other polymers, typical of the moisture sorption isotherms of wood was the type II isotherm [33]. During the decreasing period of RH, the wood MC decreasing rate decreased also, which led to the similar changing trends of E' . When RH increased from 10 to 58 % RH, E'_{\max} occurred at the ranges from 15 to 20 % RH.

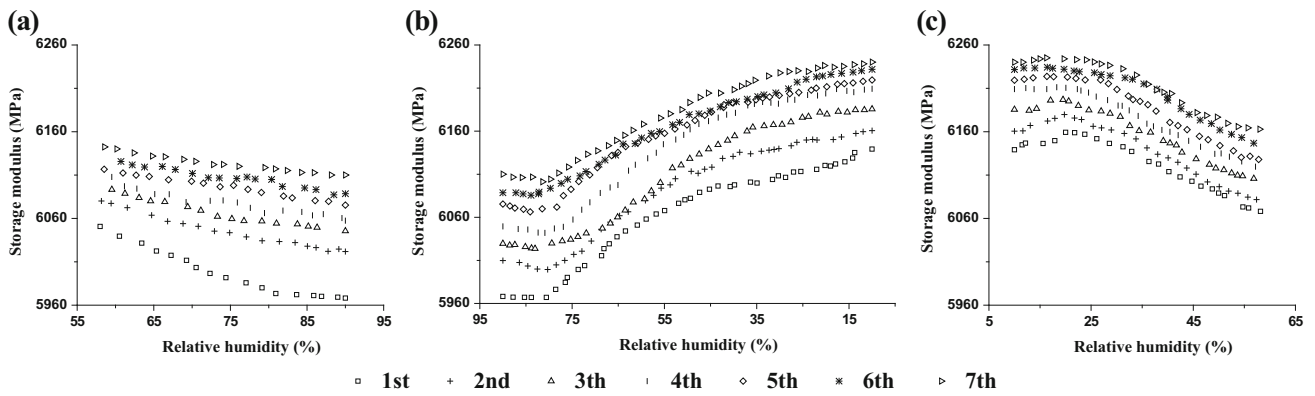


Fig. 3 Influence of relative humidity on storage modulus during the cyclical relative humidity variation **a** 58 % RH → 90 % RH, **b** 90 % RH → 10 % RH, **c** 10 % RH → 58 % RH

Loss factor vs RH

When transforming the time x axis of Fig. 2 to a RH axis, curves of $\tan\delta$ versus RH are obtained in Fig. 4. The same as E' , discussions in $\tan\delta$ as a function of RH were also based on 3 parts of RH regions: (1) 58 % RH → 90 % RH (Fig. 4a), (2) 90 % RH → 10 % RH (Fig. 4b), (3) 10 % RH → 58 % RH (Fig. 4c). Consistent with the trends of E' , $\tan\delta$ increased with the increasing RH and decreased with the decreasing RH at the whole RH region. $\tan\delta$ decreased with the increased cyclic time at the any same RH value. In Fig. 4a, the changing rate of $\tan\delta$ at the second cycle was significantly higher than subsequent cyclic times compared to the first one. When RH decreased from 90 to 10 % RH (Fig. 4b) and increased from 10 to 90 % RH (Fig. 4c), difference values between the occurrence RH value of $\tan\delta_{\min}$ or $\tan\delta_{\max}$ and RH_{\min} or RH_{\max} decreased and leveled off with the increased cyclic time. The decreasing rate of $\tan\delta$ presented as almost the same during the RH decreasing period (90–10 % RH). It was probably related to the phase lag of the dimensional change between the

microfibril and matrix. The chemical properties of the microfibril and matrix mainly determined the dynamic mechanical properties of wood, but also their volume fractions [22].

Loss factor vs storage modulus

As discussed before, E' was inversely proportional to the variation of RH, while $\tan\delta$ was proportional to the variation of RH. These two parameters revealed the influence of MC and the unsteady effect on wood. Basically, E' was likely affected by the direct effect of MC, and $\tan\delta$ exhibited the unsteady effect as well. To investigate how the $\tan\delta$ varies with E' (MC), the curves of $\tan\delta$ as a function of E' in the first 90 % RH → 10 % RH process and the first 10 % RH → 90 % RH process are presented in Fig. 5.

The curves' shapes of $\tan\delta$ against E' were presented as arcs (A). When the points (E' , $\tan\delta$) at 10 and 90 % RH during each RH variation process were linked by a line (L), $\tan\delta$ on A was lower than on L with a same value of E'

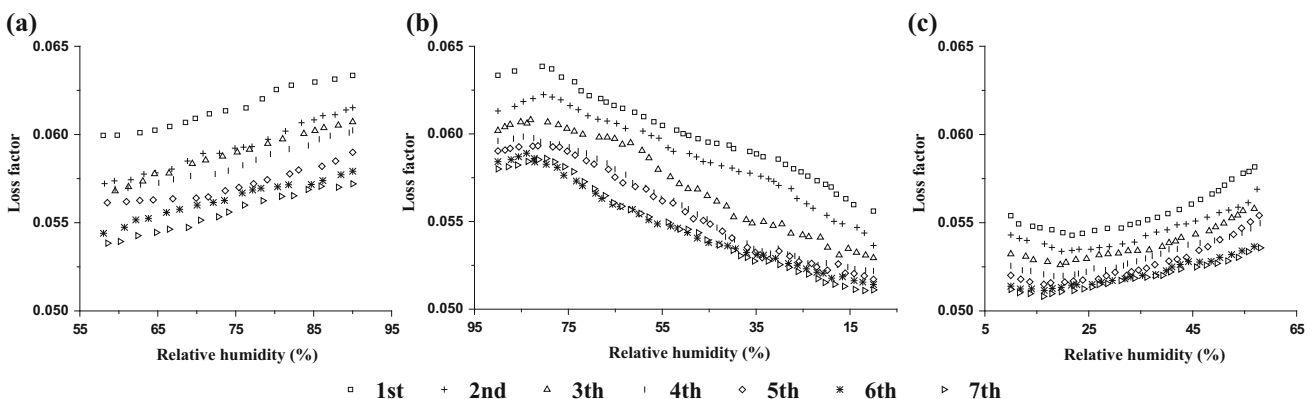


Fig. 4 Influence of relative humidity on loss factor during the cyclical relative humidity variation **a** 58 % RH → 90 % RH, **b** 90 % RH → 10 % RH, **c** 10 % RH → 58 % RH

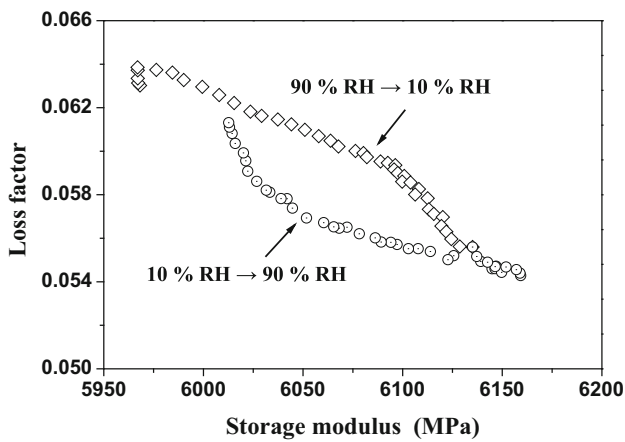


Fig. 5 Changes of loss factor as a function of storage modulus at the first 90 % RH → 10 % RH process and the first 10 % RH → 90 % RH

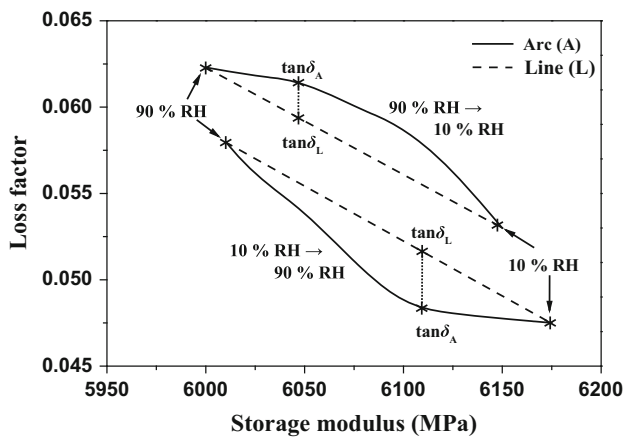


Fig. 6 Schematic diagram of $\tan\delta_A$ and $\tan\delta_L$ during typical relative humidity increasing and decreasing processes

Table 3 Changes in $\tan\delta_A/\tan\delta_L$ during the relative humidity variation processes

RH variation process	Changing sequency	Minimum (or maximum) value of $\tan\delta_A/\tan\delta_L$
RH increasing process	1 (58 % RH → 90 % RH)	0.9805
	2 (10 % RH → 90 % RH)	0.9847
	3 (10 % RH → 90 % RH)	0.9866
	4 (10 % RH → 90 % RH)	0.9870
	5 (10 % RH → 90 % RH)	0.9878
	6 (10 % RH → 90 % RH)	0.9888
	7 (10 % RH → 90 % RH)	0.9891
	8 (10 % RH → 58 % RH)	0.9927
RH decreasing process	1 (90 % RH → 10 % RH)	1.0523
	2 (90 % RH → 10 % RH)	1.0459
	3 (90 % RH → 10 % RH)	1.0434
	4 (90 % RH → 10 % RH)	1.0324
	5 (90 % RH → 10 % RH)	1.0248
	6 (90 % RH → 10 % RH)	1.0205
	7 (90 % RH → 10 % RH)	1.0201

during the RH increasing process, and higher during the RH decreasing process. Namely, the ratio $\tan\delta_A/\tan\delta_L$ was lower or higher than 1 during adsorption or desorption process, and was equal to 1 at each 10 or 90 % RH time-point. The arc A, line L and according $\tan\delta_A$, $\tan\delta_L$ of a typical adsorption and desorption processes are shown in Fig. 6. The value of $\tan\delta_A/\tan\delta_L$ manifested the unsteady effect of polymer molecular in wood cell walls during the desorption processes, while some degrees of unsteady recovery were observed during the adsorption processes. Compared to adsorption process, much unsteady effect of wood polymer during desorption process was investigated by other researchers. Takemura believed that during the desorption process additional space produced and provided more room for movements of the surrounding adsorption sites of wood polymer or other units [34]. Mukudai suggested that the loose area would take place between the S_1 layer and S_2 layer in secondary cell wall during the desorption process, resulting in the stress on I (intercellular layer) + P (primary wall) + S_1 increased rapidly [35, 36]. Based on the Eyring’s hole theory and Doolittle’s free volume theory, Nakano proposed that part of additional entropy decrease was the reason for the recovery during adsorption process [37].

The minimum or maximum value of $\tan\delta_A/\tan\delta_L$ during each RH increasing or decreasing process is listed in Table 3. The value of $\tan\delta_A/\tan\delta_L$ increased and decreased with the increasing cyclical RH time at RH increasing and decreasing process, respectively. With the increasing cyclical RH time, unsteady effect of wood polymer diminished due to the dynamic equilibrium state being back gradually. This result was consistent with the gradual reduction of lagged time and the changing rate of extreme E' and $\tan\delta$.

Conclusions

The time-dependent and RH-dependent viscoelasticity of Chinese fir was examined under cyclical RH changes and the conclusions were drawn as follows:

1. Both MC and dynamic viscoelasticity remained unchanged during the constant RH test at 30 °C, 58 % RH. After 7 times of cyclical RH variation, MC of specimens decreased by about 2.35 %. The ultimate values of storage modulus and loss factor increased and decreased, respectively.
2. The occurrences of E'_{\min} (E'_{\max}) and $\tan\delta_{\max}$ ($\tan\delta_{\min}$) lagged behind RH_{\max} (RH_{\min}). The lagged time decreased with the increasing cyclic time.
3. The values of E'_{\min} (E'_{\max}) or $\tan\delta_{\max}$ ($\tan\delta_{\min}$) were always higher or lower than the previous time they occurred. Both the changing rates decreased with the increasing cyclic time. The increasing (decreasing) rate of E'_{\min} ($\tan\delta_{\max}$) was higher than E'_{\max} ($\tan\delta_{\min}$).
4. When RH increased from 58 to 90 % RH, the changing rates of E' and $\tan\delta$ at the second cycle were significantly higher than the subsequent cyclic times compared to the first ones. During RH decreased from 90 to 10 % RH, the increasing rate of storage modulus decreased with the decreasing RH, while loss factor decreased almost linearly.
5. The unsteady effect and its partial recovery were observed during the desorption and the adsorption process. With the increasing cyclical times, the unsteady effect decreased and wood returned to the dynamic equilibrium state gradually.

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