Tianyi Zhan, Jiali Jiang, Jianxiong Lu*, Yaoli Zhang and Jianmin Chang

Frequency-dependent viscoelastic properties of Chinese fir (*Cunninghamia lanceolata*) under hygrothermal conditions. Part 1: moisture adsorption

<https://doi.org/10.1515/hf-2018-0208>

Received September 15, 2018; accepted February 21, 2019; previously published online March 30, 2019

Abstract: To elucidate the frequency-dependent viscoelasticity of wood under a moisture non-equilibrium state, changes in stiffness and damping as a function of frequency were investigated during the moisture adsorption process. The moisture adsorption processes were carried out at six temperatures (30–80°C) and three relative humidity levels (30, 60 and 90% RH). During the moisture adsorption process, the wood stiffness decreased, and damping increased with the increment of moisture content (MC). Regardless of the moisture adsorption time, the wood stiffness increased, and damping decreased with the increasing testing frequency. Based on the re-organized Williams-Landel-Ferry (WLF) model, the time-moisture superposition (TMS) relation was assumed to be applicable for developing a master curve of wood stiffness during the moisture adsorption process. The frequency ranges of the stiffness master curves spanned from 16 to 23 orders of magnitude at temperatures ranging from 30 to 80°C. However, the TMS relation was not able to predict the wood damping properties during the moisture adsorption process due to the multi-relaxation system of the wood and the non-proportional relationship between free volume and MC at transient moisture conditions.

Keywords: adsorption, frequency-dependent, hygrothermal conditions, moisture state, polymer relaxation, time-moisture superposition, viscoelasticity

Introduction

In the processing and manufacturing operations in the wood and paper industries, wood and fiber materials are often under the impact of dynamic loadings, such as cutting, pulping and pressing (Marchal et al. 2009; Zhou et al. 2010; Navi and Pizzi 2015; Pichler et al. 2018). Besides these dynamic loadings, ambient temperature and relative humidity (RH) continuously change during these operations. In other words, wood or fiber materials are often subject to combined “thermo-hygro-mechanical (THM)” interactions (Li et al. 2018a; Liu 2018; Liu et al. 2018; Wang et al. 2018).

Under the dynamic loading, wood exhibits both elastic behavior and viscous behavior that is termed as viscoelasticity. The viscoelastic properties of wood are associated with the amplitude and frequency of the dynamic loading, ambient temperature and wood moisture content (MC). Understanding the effect of THM interactions on the viscoelasticity of wood is helpful for optimizing manufacturing operations and improving the quality of wood and its products.

Dynamic mechanical analysis (DMA) is an effective tool for describing the viscoelastic properties of wood (Menard 2002). DMA applies an oscillating force to a wood sample and analyzes the sample's response to the applied force. The most common use of DMA is the temperature-scan technique, which could enhance the understanding of the organization and properties of *in situ* wood polymers (Sun et al. 2007). During the temperature-scan process, several relaxation peaks are observed, in which a major relaxation peak occurs over a range of 70–200°C. This relaxation peak is attributed to the glass transition of lignin in wet or water-saturated state of wood (Salmén 1984; Olsson and Salmén 1997; Laborie et al. 2004; Placet et al. 2007; Guo et al. 2017). The glass transition temperature (T_g) of lignin moves

***Corresponding author: Jianxiong Lu**, Research Institute of Wood Industry of Chinese Academy of Forestry, Hunan Collaborative Innovation Center for Effective Utilizing of Wood and Bamboo Resources, Beijing 100091, P.R. China, e-mail: jianxiong@caf.ac.cn

Tianyi Zhan: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing 210037, P.R. China; and Research Institute of Wood Industry of Chinese Academy of Forestry, Hunan Collaborative Innovation Center for Effective Utilizing of Wood and Bamboo Resources, Beijing 100091, P.R. China

Jiali Jiang: Research Institute of Wood Industry of Chinese Academy of Forestry, Hunan Collaborative Innovation Center for Effective Utilizing of Wood and Bamboo Resources, Beijing 100091, P.R. China

Yaoli Zhang: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing 210037, P.R. China

Jianmin Chang: College of Materials Science and Technology, Beijing Forestry University, Beijing 100083, P.R. China

to lower temperature ranges at higher wood MCs and is related to the testing frequency and the lignin structure (Olsson and Salmén 1997). Regardless of the wood MC (dry, moist or water-saturated state), another relaxation peak could be found due to the motions of methylol groups in amorphous regions of the wood cell wall at around -90°C (Kimura and Nakano 1976; Sugiyama and Norimoto 1996; Obataya et al. 2001).

In addition, Backman and Lindberg (2001), Jiang and Lu (2008) and Li et al. (2018b) reported a small peak at around room temperature or even below ambient temperatures when the wood MC ranged from around 3 to 14.1%. Li et al. (2018b) assumed that this small peak was attributed to the melting of frozen water. Backman and Lindberg (2001) and Jiang and Lu (2008) assumed that the small peak was attributed to the glass transition of hemicellulose. Paiva and Magalhães (2018) reported a similar result in nearly dried cork and assumed that the damping change between 10 and 25°C might be associated with the melting of suberin in cork.

The viscoelastic changes during temperature scan could also be observed over a sufficiently wide frequency range when the temperature remains constant. Plot of viscoelastic parameter vs. frequency appears as a reverse-like temperature scan (Menard 2002). The collections of frequency-dependent viscoelastic data as a function of temperature are also commonly obtained for exploring the effect of frequency on temperature-driven changes in the material (Amada and Lakes 1997; Jiang et al. 2010; Zhang et al. 2012; Li et al. 2015). From the viewpoint of molecular chain movement, smaller-scale molecular movements are involved at higher testing frequencies. Specifically, high stiffness could be obtained at high frequencies, while it could also be found at low temperatures. Hence, the changes in stiffness by altering the temperature are somewhat similar to those caused by frequency changes. The time-temperature superposition principle (TTSP) is widely applied to predict the rheological properties of polymers at wide ranges of frequency or time (Chevali et al. 2009; Townsend et al. 2011; Chowdhury and Frazier 2013; Sirk et al. 2013; Tan and Guo 2013; Arbe et al. 2016). According to TTSP, a master curve is obtained by shifting a series of multiplexed frequency scans relative to a reference curve. Various models have been developed for the shift. The most commonly used models are the Williams-Landel-Ferry (WLF) model and the Arrhenius equation (Ferry 1980; Menard 2002). The constructed master curve covers a range much greater than that of the original data. Based on the constructed master curve, the mechanical properties at long-term

or extreme-temperature conditions could be predicted. Salmén (1984) firstly demonstrated that TTSP was applicable to the water-saturated wood around T_g of lignin. Numerous wood-TTSP studies have been carried out using both static and dynamic methods (Samarasinghe et al. 1994; Lenth and Kamke 2001; Laborie et al. 2004; López-Suevos and Frazier 2005, 2006; Placet et al. 2007; Sun and Frazier 2007; Dlouhá et al. 2009; Peng et al. 2017; Wang et al. 2017; Hsieh and Chang 2018). TTSP is effective for analyzing the *in situ* softening of lignin and for improving the understanding of structure/property relationships in plasticized lignocellulose (Salmén 1984; Laborie et al. 2004; Chowdhury and Frazier 2013). However, the applicability of TTSP to wood is still controversial, and some researchers stated that it was applicable only under limited conditions (Salmén 1984; Kelley et al. 1987; Nakano 1995, 2013). Salmén (1984) stated that the WLF model was applicable for water-saturated wood when the temperature was within T_g to $T_g + 30^{\circ}\text{C}$. Sun and Frazier (2007) found that TTSP was valid in the range of $100\text{--}170^{\circ}\text{C}$ for dry wood that received a prior 30-min thermal treatment. For the ethyl formamide- or ethylene glycol-treated wood, the applicable temperature was from T_g to $T_g + 85^{\circ}\text{C}$ (Kelley et al. 1987) or T_g to $T_g + 40^{\circ}\text{C}$ (Laborie et al. 2004), respectively. The limited conditions of applicability of TTSP to wood viscoelasticity were because wood is a polymer blend with multiple transition zones, and different components have different temperature-dependent performances. On the other hand, wood MC changes as a result of the temperature change. The increase of both MC and temperature is known to reduce the stiffness of wood and other polymers. Using an analogous approach to TTSP, several authors suggested that viscoelastic measurements of polymers at different MCs (or RH levels) can be rationalized on the basis of a time-moisture superposition (TMS) relation (Chu and Robertson 1994; Zhou et al. 2001; Ishisaka and Kawagoe 2004; Mano 2008; Patankar et al. 2008; Fabre et al. 2018).

In actual manufacturing and processing operations, wood undergoes varieties of MC (i.e. moisture adsorption or desorption). Hence, exploring the TMS relations on wood viscoelasticity during the moisture variation process is necessary for further explaining the effect of THM interactions on the rheological response of wood. The present study set out to evaluate the frequency-dependent viscoelasticity of Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook.) during the moisture adsorption process. The influences of ambient temperature and RH on stiffness/damping as a function of frequency were investigated. Furthermore, the applicability of TMS on

wood stiffness and damping was evaluated during the moisture adsorption process.

Materials and methods

Materials: Specimens were prepared from Chinese fir heartwood with a dimension of $60 \times 12 \times 2.5$ mm³ (L × R × T). Before testing, all specimens were conditioned in a sealed container over P₂O₅, which provided a RH of 0%. The corresponding MC of the conditioned specimens was 0.6%.

Viscoelasticity measurement: A DMA Q800 (TA Instruments, New Castle, DE, USA) was used to automatically examine the elastic (storage modulus E') and viscoelastic (loss modulus E'') responses. The DMA was equipped with a humidity accessory which controlled the RH precisely by modulating the mixture of dry nitrogen and saturated moisture. A dual-cantilever bending mode with a span of 35 mm was selected. The specimens were clamped on the radial surfaces and the bending occurred in the tangential direction. The sinusoidal bending displacement was 15 μm in a series of frequencies scanned from 50 to 1 Hz, and the corresponding strain was 0.032–0.034% in the temperature ranging from 30 to 80°C. All tests were carried out within the linear viscoelastic region, where the strain response was directly proportional to the mechanical input (stress), and the reproducible data were expected to accurately reflect the relationships between molecular structure and viscoelastic behavior (Sun et al. 2007; Kaboorani and Blanchet 2014).

The specimens were mounted in the testing chamber and pre-heated at 0% RH for 30 min at six constant temperatures (30, 40, 50, 60, 70 and 80°C). After the pre-heating period, the RH was ramped up from 0 to 30 (Figure 1a), 60 (Figure 1b) or 90% RH (Figure 1c), respectively, with a ramping rate of 2% RH min⁻¹. The RH was then kept isohume for 240 min. MC was measured on a dry basis by weighing specimens before and after the moisture adsorption. To monitor the MC changing trend, some separate specimens were also tested under the same hygrothermal conditions, but only until the time points marked with the frequency scan symbols in Figure 1 (i.e. termination of RH_{ramp}, 60 min under RH_{isohume} and 120 min under RH_{isohume}). The viscoelastic data are presented for the 240 min isohume period for the three RH levels. Three measurements were performed for each condition.

Figure 1: Experimental setup for the frequency scan tests. a: 30% RH, b: 60% RH, c: 90% RH.

Results and discussion

Storage modulus

Figure 2 shows the typical changes in frequency-dependent E' during the moisture adsorption process when the temperatures were 30 and 80°C. The viscoelastic values at the other temperatures are shown in Supplementary Table S1. Regardless of temperature or adsorption time, an increase in E' was observed with the increment of frequency. The wood exhibited more elastic-like behavior as the testing frequency increased, and E' tended to slope upward as frequency increased (Menard 2002). At higher temperatures, larger amounts of moisture adsorption were found under these conditions (Figure 3). As in our previous study (Zhan et al. 2018), none of the specimens reached the equilibrium MC, and not even at the end of the 240-min RH_{isohume} period. With the extension of adsorption time, E' decreased as a consequence of increasing MC. The reduction in wood stiffness was attributed to the plasticization effect of moisture (Li et al. 2018c). At higher temperatures or humidity levels, greater decrements of E' could be found because the plasticization effect was intensified at hygrothermal conditions.

It was found that the increasing temperature and MC had similar effects on the stiffness reduction of Chinese fir (Zhan et al. 2018). According to TTSP, E' at a given temperature (T) is the same as that of another reference temperature (T_r), providing that the frequency (f) axis is shifted as (Menard 2002):

$$E'(T, \log f) = E'(T_r, \log a_{T/T_r} + \log f) \quad (1)$$

where $\log a_{T/T_r}$ is the horizontal shift factor. The most commonly used WLF model for the shifting is given as (Williams et al. 1957):

Figure 2: Influence of frequency on storage modulus at five moisture adsorption time points: $\diamond$, experimental initiation; $\square$, termination of RH_{ramp} ; Δ , 60 min under RH_{ishume} ; $\times$, 120 min under RH_{ishume} ; $\circ$, 240 min under RH_{ishume} (storage modulus scaling varied at 30 and 80°C).

Figure 3: Changes in the moisture content at five moisture adsorption time points: $\diamond$, experimental initiation; $\square$, termination of RH_{ramp} ; Δ , 60 min under RH_{ishume} ; $\times$, 120 min under RH_{ishume} ; $\circ$, 240 min under RH_{ishume} .

$$\log a_{T/T_r} = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \quad (2)$$

where C_1 and C_2 are material constants, fitted by the relationship between T and T_r . Sometimes, the vertical shift should also be considered for obtaining a smooth master curve. The vertical shift factor may be associated with the temperature dependency of the wood density (Wang et al. 2017). Taking into account that moisture has a similar implication as temperature during the change in wood stiffness, it was rationalized to display a TMS relationship based on TTSP. Hence, Equation (1) may be rewritten as:

$$E'(MC, \log f) = E'(MC_r, \log a_{MC/MC_r} + \log f) \quad (3)$$

where $\log a_{MC/MC_r}$ is the horizontal shift factor with respect to a reference value of the MC (MC_r). $\log a_{MC/MC_r}$ is calculated by a re-organized WLF model:

$$\log a_{MC/MC_r} = \frac{-C'_1(MC - MC_r)}{C'_2 + (MC - MC_r)} \quad (4)$$

where C'_1 and C'_2 are material constants, fitted by the relationship between MC and MC_r . In addition, the vertical shift is associated with the moisture dependency of the wood density, which is not discussed in this study.

To investigate the possibility of TMS, the evolution of E' at all the three RH levels is displayed together as a function of frequency in the left side of Figure 4. In total, there were 13 frequency sweeps at each given temperature. At each RH level, four frequency sweeps were obtained corresponding to four time points (termination of RH_{ramp} , 60 min under RH_{isohume} , 120 min under RH_{isohume} and 240 min under RH_{isohume}). Additionally, one more frequency sweep was obtained based on the average value of the frequency-dependent E' at the experimental initiation, and this frequency sweep was regarded as the reference curve with the MC of 0.6%. Equation (3) was used to horizontally shift a series of MC-dependent E' to the reference curve for constructing the superposition master curve. The master curve was established and is presented in the right side of Figure 4. Smooth master curves could be developed at all hygrothermal temperatures. From 30 to 80°C, the frequency ranges of the master curves spanned from 16 to 23 orders of magnitude. With the increasing temperature, the plasticization effect was accelerated and intensified (Dlouhá et al. 2009), which was seen as a broadened frequency range.

The TMS relation of viscoelasticity has also been demonstrated for other materials, including cement (Chu and Robertson 1994), glass-fiber reinforced epoxy pipe (Yao and Ziegmann 2006), chitosan (Mano 2008), proton exchange membrane (Patankar et al. 2008) and polyamide 6,6 (Fabre et al. 2018). The shift factors of the amorphous thermoplastics commonly exhibited non-linear temperature (or moisture) dependencies, while the experimental value of $\log a_{MC/MC_r}$, as a function of MC, was highly linear in this study (Figure 5). The Arrhenius (linear) behavior has also been reported for ethylene glycol and N,N-dimethylformamide plasticized wood (Laborie et al. 2004; Chowdhury and Frazier 2013), and attributed to inter-molecular cooperativity within polymeric materials. When the wood MC is around 0.6%, a slight relaxation occurs at 30–80°C (Sun et al. 2007; Jiang et al. 2008), which may explain why $\log a_{MC/MC_r}$ and MC exhibited linear relationships in Figure 5. Decreasing $\log a_{MC/MC_r}$ could be observed with increasing MC. The shift factor represents the ratio of relaxation time at a given MC to that at the reference MC (0.6%). The greater absolute value of $\log a_{MC/MC_r}$ means less relaxation time of molecular movement. At the end of the 240-min RH_{isohume} period (90%) when the temperature was 30 or 80°C, the absolute value of $\log a_{MC/MC_r}$ was 11.7 or 15.8, respectively. The increment of water molecules speeded up the movement pace of amorphous polymers within the wood cell walls, and shortened the relaxation times.

Loss modulus

Figure 6 shows the typical changes in frequency-dependent E'' during the moisture adsorption processes when the temperatures were 30 and 80°C. The E'' values at the other temperatures are shown in Supplementary Table S1. During the moisture adsorption process, the increment of E'' was found with the increment of adsorption time regardless of the testing frequency. Similar to Equation (3), E'' may be re-organized as:

$$E''(MC, \log f) = E''(MC_r, \log a_{MC/MC_r} + \log f) \quad (5)$$

In the left side of Figure 7, 13 frequency sweeps of E'' are displayed as well as the frequency-dependent E' in Figure 4. Based on Equation (5), master curves of E'' in the right side of Figure 7 were constructed. Master curves of E'' with scattered plots are shown at all the hygrothermal temperatures. The non-smooth behavior of E'' might

Figure 4: Relations of wood storage modulus and frequency (left column) at different adsorption times and master curve as a function of frequency (right column) (storage modulus scaling varied from 30 to 80°C).

illustrate the non-applicability of the TMS relation to wood damping. From the point of view of composite materials, the wood cell wall is a multi-phase composite of elastic fibrils of cellulose and a viscoelastic matrix of amorphous

lignin and hemicelluloses. The TMS relation did not apply for this multi-phase system because different components did not have the same moisture-dependent relaxation behavior (Nakano 1995, 2013).

Figure 5: Shift factor $\log a_{MC/MC_r}$ relationships with moisture content from the master curves and fit of the shift factor $\log a_{MC/MC_r}$ to the re-organized WLF model.

Figure 6: Influence of frequency on loss modulus at five moisture adsorption time points: $\diamond$, experimental initiation; $\square$, termination of RH_{ramp} ; Δ , 60 min under $RH_{isohume}$; $\times$, 120 min under $RH_{isohume}$; $\circ$, 240 min under $RH_{isohume}$ (loss modulus scaling varied at 30 and 80°C).

According to Ferry (1980), the WLF model can be applied when the free volume within a polymer increases proportionally to its MC. While, during the moisture

adsorption process, the free volume is not only influenced by the amount of moisture, but also associated with the transient state of the moisture within the wood

Figure 7: Relations of wood loss modulus and frequency at different adsorption times (left column) and master curve as a function of frequency (right column) (loss modulus scaling varied from 30 to 80°C).

cell wall (Zhan et al. 2016). The free volume within the wood cell wall forms localized stresses that unequally disturbed the equilibrium packing of polymer molecules, resulting in more energy dissipation (Takahashi

et al. 2004). The non-proportional relationship between free volume and MC may be another reason for explaining why the TMS relation failed to predict the wood damping properties.

Conclusions

- (1) The stiffness decreased and the damping increased with increasing time of moisture adsorption under all testing frequencies of Chinese fir wood. An increase in stiffness was observed with the increase of frequency, irrespective of MC.
- (2) Based on the re-organized WLF model, the TMS relation was applicable for developing master curves of wood stiffness. The frequency ranges of the stiffness master curves spanned from 16 to 23 orders of magnitude at temperatures ranging from 30 to 80°C.
- (3) The TMS relation was not able to predict the wood damping properties during the moisture adsorption process due to the multi-relaxation system of the wood. The non-proportional relationship between free volume and MC at transient moisture conditions could also explain why the TMS relation failed to predict the wood damping properties.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: This work was financially supported by the National Natural Science Foundation of China (Funder Id: <http://dx.doi.org/10.13039/501100001809>, no. 31700487), the Natural Science Foundation of Jiangsu Province (CN) (Funder Id: <http://dx.doi.org/10.13039/501100004608>, no. BK20170926), the Innovation Fund for Young Scholars of Nanjing Forestry University (CX2017002) and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD). Tianyi Zhan would like to gratefully acknowledge the financial support from the Jiangsu Provincial Government Scholarship Program.

Employment or leadership: None declared.

Honorarium: None declared.

References

- Amada, S., Lakes, R.S. (1997) Viscoelastic properties of bamboo. *J. Mater. Sci.* 32:2693–2697.
- Arbe, A., Moreno, A.J., Allgaier, J., Ivanova, O., Fouquet, P., Colmenero, J., Richter, D. (2016) Role of dynamic asymmetry on the collective dynamics of comblike polymers: insights from neutron spin-echo experiments and coarse-grained molecular dynamics simulations. *Macromolecules* 49:4989–5000.
- Backman, A.C., Lindberg, K.A.H. (2001) Difference in wood material responses for radial and tangential direction as measured by dynamic mechanical thermal analysis. *J. Mater. Sci.* 36:3777–3783.
- Chevali, V.S., Dean, D.R., Janowski, G.M. (2009) Flexural creep behavior of discontinuous thermoplastic composites: non-linear viscoelastic modeling and time-temperature-stress superposition. *Compos. A: Appl. Sci. Manuf.* 40:870–877.
- Chowdhury, S., Frazier, C.E. (2013) Thermorheological complexity and fragility in plasticized lignocellulose. *Biomacromolecules* 14:1166–1173.
- Chu, T., Robertson, R.E. (1994) Viscoelastic behaviour of macro-defect-free cement. *J. Mater. Sci.* 29:2683–2690.
- Dlouhá, J., Clair, B., Arnould, O., Horáček, P., Gril, J. (2009) On the time-temperature equivalency in green wood: characterisation of viscoelastic properties in longitudinal direction. *Holz-forschung* 63:327–333.
- Fabre, V., Quandalle, G., Billon, N., Cantournet, S. (2018) Time-temperature-water content equivalence on dynamic mechanical response of polyamide 6,6. *Polymer* 137:22–29.
- Ferry, J.D. (1980) *Viscoelastic Properties of Polymers*. 3rd ed. Wiley, New York.
- Guo, J., Yin, J., Zhang, Y., Salmén, L., Yin, Y. (2017) Effects of thermo-hygro-mechanical (THM) treatment of the viscoelasticity of in-situ lignin. *Holzforschung* 71:455–460.
- Hsieh, T., Chang, F. (2018) Effects of moisture content and temperature on wood creep. *Holzforschung* 72:1071–1078.
- Ishisaka, A., Kawagoe, M. (2004) Examination of the time–water content superposition on the dynamic viscoelasticity of moistened polyamide 6 and epoxy. *J. Appl. Polym. Sci.* 93:560–567.
- Jiang, J., Lu, J. (2008) Dynamic viscoelasticity of wood after various drying processes. *Drying Technol.* 26:537–543.
- Jiang, J., Lu, J., Yan, H. (2008) Dynamic viscoelastic properties of wood treated by three drying methods measured at high-temperature range. *Wood Fiber Sci.* 40:72–79.
- Jiang, J., Lu, J., Zhao, Y., Wu, Y. (2010) Influence of frequency on wood viscoelasticity under two types of heating conditions. *Drying Technol.* 28:823–829.
- Kaboorani, A., Blanchet, P. (2014) Determining the linear viscoelastic region of sugar maple wood by dynamic mechanical analysis. *BioResources* 9:4392–4409.
- Kelley, S.S., Rilas, T.G., Glasser, W.G. (1987) Relaxation behavior of amorphous components of wood. *J. Mater. Sci.* 22:617–624.
- Kimura, M., Nakano, J. (1976) Mechanical relaxation of cellulose at low temperatures. *J. Polym. Sci. Polym. Lett. Ed.* 14:741–745.
- Laborie, M.P.G., Salmén, L., Frazier, C.E. (2004) Cooperativity analysis of the in situ lignin glass transition. *Holzforschung* 58:129–133.
- Lenth, C.A., Kamke, F.A. (2001) Moisture dependent softening behavior of wood. *Wood Fiber Sci.* 33:492–507.
- Li, Y., Yin, L., Huang, C., Meng, Y., Fu, F., Wang, S., Wu, Q. (2015) Quasi-static and dynamic nanoindentation to determine the influence of thermal treatment on the mechanical properties of bamboo cell walls. *Holzforschung* 69:909–914.
- Li, R., Cao, P., Xu, W., Ekevad, M., Wang, X. (2018a) Experimental and numerical study of moisture-induced stress formation in hexagonal glucan using X-ray computed tomography and finite-element analysis. *BioResources* 13:7395–7403.
- Li, Z., Jiang, J., Lu, J. (2018b) Moisture-dependent orthotropic viscoelastic properties of Chinese fir wood in low temperature environment. *J. Wood Sci.* 64:515–525.
- Li, W., Van den Bulcke, J., Dhaene, J., Zhan, X., Mei, C., Van Acker, J. (2018c) Investigating the interaction between internal structural changes and water sorption of MDF and OSB using X-ray computed tomography. *Wood Sci. Technol.* 52:701–716.

- Liu, X. (2018) The main factors affecting temperature change of mat during the manufacturing process of thermoplastic resin plywood. *J. For. Eng.* 3:35–39.
- Liu, J., Yu, J., Wang, X., Li, Y. (2018) Heat and mass transfer multi-scale unit characterization model in the drying process of *Pinus sylvestris*. *J. For. Eng.* 3:26–31.
- López-Suevos, F., Frazier, C.E. (2005) Parallel-plate rheology of latex films bonded to wood. *Holzforschung* 59:435–440.
- López-Suevos, F., Frazier, C.E. (2006) Rheology of latex films bonded to wood: influence of cross-linking. *Holzforschung* 60:47–52.
- Mano, F.J. (2008) Viscoelastic properties of chitosan with different hydration degrees as studied by dynamic mechanical analysis. *Macromol. Biosci.* 8:69–76.
- Marchal, R., Mothe, F., Denaud, L-E, Thibaut, B., Bleron, L. (2009) Cutting forces in wood machining – basics and applications in industrial processes. A review COST action E35 2004–2008: wood machining – micromechanics and fracture. *Holz-forschung* 63:157–167.
- Menard, K.P. (2002) *Dynamic Mechanical Analysis: A Practical Introduction*. CRC Press, Boca Raton, FL, USA.
- Nakano, T. (1995) Time-temperature superposition principle on relaxation behavior of wood as a multi-phase material. *Holz Roh-Werkst.* 53:39–42.
- Nakano, T. (2013) Applicability condition of time-temperature superposition principle (TTSP) to a multi-phase system. *Mech. Time-Depend. Mater.* 17:439–447.
- Navi, P., Pizzi, A. (2015) Property changes in thermo-hydro-mechanical processing COST Action FP0904 2010–2014: thermo-hydro-mechanical wood behavior and processing. *Holzforschung* 69:863–873.
- Obataya, E., Norimoto, M., Tomita, B. (2001) Mechanical relaxation process of wood in the low-temperature range. *J. Appl. Polym. Sci.* 81:3338–3347.
- Olsson, A., Salmén, L. (1997) The effect of lignin composition on the viscoelastic properties of wood. *Nord. Pulp Pap. Res. J.* 12:140–144.
- Paiva, D., Magalhães, F.D. (2018) Dynamic mechanical analysis and creep-recovery behavior of agglomerated cork. *Eur. J. Wood Prod.* 76:133–141.
- Patankar, K.A., Dillard, D.A., Case, S.W., Ellis, M.W., Lai, Y., Budinski, M.K., Gittleman, C.S. (2008) Hygrothermal characterization of the viscoelastic properties of Gore-Select® 57 proton exchange membrane. *Mech. Time-Depend. Mater.* 12:221–236.
- Peng, H., Jiang, J., Lu, J., Cao, J. (2017) Application of time–temperature superposition principle to Chinese fir orthotropic creep. *J. Wood Sci.* 63:455–463.
- Pichler, P., Leitner, M., Grün, F., Guster, C. (2018) Evaluation of wood material models for the numerical assessment of cutting forces in chipping processes. *Wood Sci. Technol.* 52:281–294.
- Placet, V., Passard, J., Perré, P. (2007) Viscoelastic properties of green wood across the grain measured by harmonic tests in the range 0–95°C: hardwood vs. softwood and normal wood vs. reaction wood. *Holzforschung* 61:548–557.
- Salmén, L. (1984) Viscoelastic properties of *in situ* lignin under water-saturated conditions. *J. Mater. Sci.* 19:3090–3096.
- Samarasinghe, S., Loferski, J.R., Holzer, S.M. (1994) Creep modeling of wood using time-temperature superposition. *Wood Fiber Sci.* 26:122–130.
- Sirk, T.W., Khare, K.S., Karim, M., Lenhart, J.L., Andzelm, J.W., McKenna, G.B., Khare, R. (2013) High strain rate mechanical properties of a cross-linked epoxy across the glass transition. *Polymer* 54:7048–7057.
- Sugiyama, M., Norimoto, M. (1996) Temperature dependence of dynamic viscoelasticities of chemically treated woods. *Mokuzai Gakkaishi* 42:1049–1056.
- Sun, N., Frazier, C.E. (2007) Time/temperature equivalence in the dry wood creep response. *Holzforschung* 61:702–706.
- Sun, N., Das, S., Frazier, C.E. (2007) Dynamic mechanical analysis of dry wood: linear viscoelastic response region and effects of minor moisture changes. *Holzforschung* 61:28–33.
- Takahashi, C., Ishimaru, Y., Iida, I., Furuta, Y. (2004) The creep of wood destabilized by change in moisture content. Part 1: the creep behaviours of wood during and immediately after drying. *Holzforschung* 58:261–267.
- Tan, Y., Guo, M. (2013) Study on the phase behavior of asphalt mastic. *Constr. Build. Mater.* 47:311–317.
- Townsend, B.W., Ohanehi, D.C., Dillard, D.A., Austin, S.R., Salmon, F., Gagnon, D.R. (2011) Characterizing acrylic foam pressure sensitive adhesive tapes for structural glazing applications – part I: DMA and ramp-to-fail results. *Int. J. Adhes. Adhes.* 31:650–659.
- Wang, F., Huang, T., Shao, Z. (2017) Application of TTSP to wood-development of a vertical shift factor. *Holzforschung* 71:51–55.
- Wang, X., Chen, X., Xie, X., Wu, Y., Zhao, L., Li, Y., Wang, S. (2018) Effects of thermal modification on the physical, chemical and micromechanical properties of Masson pine wood (*Pinus massoniana* Lamb.). *Holzforschung*, 72:1063–1070.
- Williams, M.L., Landel, R.F., Ferry, J.D. (1957) The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids. *J. Am. Chem. Soc.* 77:3701–3707.
- Yao, J., Ziegmann, G. (2006) Equivalence of moisture and temperature in accelerated test method and its application in prediction of long-term properties of glass-fiber reinforced epoxy pipe specimen. *Polym. Test.* 25:149–157.
- Zhan, T., Lu, J., Jiang, J., Peng, H., Li, A., Chang, J. (2016) Viscoelastic properties of the Chinese fir (*Cunninghamia lanceolata*) during moisture sorption processes determined by harmonic tests. *Materials*. 9:1020.
- Zhan, T., Jiang, J., Lu, J., Zhang, Y., Chang, J. (2018) Influence of hygrothermal condition on dynamic viscoelasticity of Chinese fir (*Cunninghamia lanceolata*). Part 1: moisture adsorption. *Holzforschung* 72:567–578.
- Zhang, T., Bai, S., Zhang, Y., Thibaut, B. (2012) Viscoelastic properties of wood materials characterized by nanoindentation experiments. *Wood Sci. Technol.* 46:1003–1016.
- Zhou, S., Tashiro, K., Li, T. (2001) Confirmation of universality of time–humidity superposition principle for various water-absorbable polymers through dynamic viscoelastic measurements under controlled conditions of relative humidity and temperature. *J. Polym. Sci. B: Polym. Phys.* 39 1638–1650.
- Zhou, C., Dai, C., Smith, G.D. (2010) Viscoelasticity of aspen wood strands during hot pressing: Experimentation and modeling. *Holzforschung* 64:713–723.

Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/hf-2018-0208>).