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Variation of Drying Strains between Tangential and Radial Directions in Asian White Birch

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Academic Editor: Phillip G. Comeau

Received: 19 January 2016; Accepted: 29 February 2016; Published: 7 March 2016

Abstract: In this study, wood disks of 30 mm in thickness cut from white birch (*Betula platyphylla* Suk) logs were dried at a constant temperature (40 °C). The drying strains including practical shrinkage strain, elastic strain, viscoelastic creep strain and mechano-sorptive creep were measured both tangentially and radially. The effects of moisture content and radial position on each strain were also discussed qualitatively. Overall, the difference of the practical shrinkage strain between the tangential and radial directions was proportional to the distance from the pith. The tangential elastic strain and viscoelastic creep strain were higher than these strains in a radial direction, and they all decreased with the decrease of moisture content. Additionally, there were opposite mechano-sorptive creep between tangential and radial directions.

Keywords: drying stresses; drying strains; wood rheological behavior; white birch disk

1. Introduction

Cutting wood logs into thin disks is advantageous to better understand the evolution of drying stresses because of the possibility to control the moisture content gradient longitudinally and compare drying strains between the tangential and radial directions. It also provides a better method for using small-diameter or crooked logs than when lumber is cut lengthwise; this occurs because waste is much less when logs are cut into cross sections during the logging and sawing processes [1]. However, with wood as an anisotropic material, drying defects emerge more readily in wood disks than in lumber. There are a variety of reasons, such as the difference of the shrinkage ratios in the tangential and radial directions, and material heterogeneity that wood cross sections always include both heartwood and sapwood or perhaps both juvenile and mature wood.

Drying defects are often linked to drying stresses which can be approximated by measuring drying strains. From wood rheological theory, the components of drying strains comprise free shrinkage strain, elastic strain, viscoelastic creep strain and mechano-sorptive (MS) creep. The survey of these strains will provide an effective foundation for forecasting and analyzing drying stresses. Extensive studies on this topic have been carried out. The MS creep phenomenon of wood was first proposed reported by Armstrong [2]. Rice and Youngs found that MS creep is the major component of strain and it is a function of moisture change during drying of red oak [3]. Wu and Milota investigated the tangential MS deformations of Douglas fir in both desorption and absorption processes [4,5]. Takahashi *et al.* found that the creep behaviors of Japanese cypress are different during the drying process, immediately after drying, and after a long period of conditioning under constant humidity and temperature [6]. Perre and Passard proposed a comprehensive model to predict drying stress evolution based on MS creep at different temperature levels [7]. Lazarescu and Avramidis investigated elastic, viscoelastic, MS and plastic strains developed in a perpendicular direction to the grain of restrained wood [8].

The tangential, radial and longitudinal shrinkage strain in jack pine were measured by Peng *et al.* [9,10]. Zhan and Avramidis separated MS creep from viscoelastic creep strain and determined the relative magnitude of each drying strain under different drying temperatures [11,12]. Larsen and Ormarsson reported on the moisture-induced strains and tensile strength in a tangential direction under different climatic conditions based on finite element modeling [13,14]. That is the most written about topic for a long time, but no research has been published on the difference of drying strains between the tangential and radial directions.

The present study was conducted to investigate the variation of practical shrinkage strain, elastic strain, viscoelastic creep strain and MS creep between the tangential and radial directions in white birch (*Betula platyphylla* Suk). The effects of moisture content and radial position on each strain were also discussed.

2. Materials and Methods

Wood for this study was obtained from forests in the region of the Lesser Khingan Mountains, located in northeastern China. The density of wood was 495–607 kg/m^3 with moisture content higher than 60% and a diameter at breast height of 250 mm. One plantation white birch (*Betula platyphylla* Suk) tree was first sawn into one hundred wood disks of 30 mm in thickness starting at a distance of 0.3 m from the roots and then numbered, wrapped with plastic film, and stored in a freezer to prevent water loss and decay. Ten wood disks without visual defects were randomly selected from the prepared wood disks for drying experiment, of which one was used to determine the green moisture content, three were for determining target moisture content (26%, 18% and 10% moisture content for wood disks during drying), and the remaining six were for strain studies. Two replications were carried out.

The drying experiment was conducted in a GDS-100 conditioning chamber (Shanghai Scientific Instruments Yiheng Co., Ltd., Shanghai, China). Table 1 illustrates the detailed drying conditions. The temperature was held constant at 40 °C and the relative humidity slowly decreased. The relative humidity was adjusted and corrected by changing wet-bulb depression and a RS-13H dry-wet bulb thermometer (Espec Techno Corp Co., Ltd., Osaka, Japan,), respectively. The target moisture contents were determined using the oven-dry method with a temperature of 103 ± 2 °C for 24 h. The drying strains including practical shrinkage strain, elastic strain, viscoelastic creep strain and MS creep were measured and distinguished by image analysis, which is a noncontact method based on dot pitches. The camera lens (1628 × 1236 resolution) was fixed on a perpendicularly placed tripod and kept 200 mm from the test plane. Before drying, red stains were sprayed on the polished surface of the disks, using oil-based pike (Figure 1). While drying to the target moisture content of 26%, 18%, and 10%, taken two of the wood disks out from conditioning chamber and cut each one into 18 test specimens along the grid lines, and also the images of the disks (including a scale-plate) were taken before and after cutting. Thereafter, the images were imported into specialized software Image J (National Institute of Mental Health, Bethesda, MD, USA.) for measuring and analyzing the actual length of the two red stains. By comparing the changes of dot pitches, the strain values can be obtained.

Table 1. Drying schedule for white birch disks.

Moisture Content (%)	Dry Bulb Temperature (°C)	Wet Bulb Temperature (°C)	Relative Humidity (%)	Equilibrium Moisturecontent (%)
MC > 50	40	38	88	18.3
40	40	37	82	16
35	40	36	76	14.1
30	40	35	71	12.7
25	40	34	66	11.5
20	40	32	57	9.6
15	40	30	48	8.2
10	40	29	44	7.6

MC indicates moisture content.

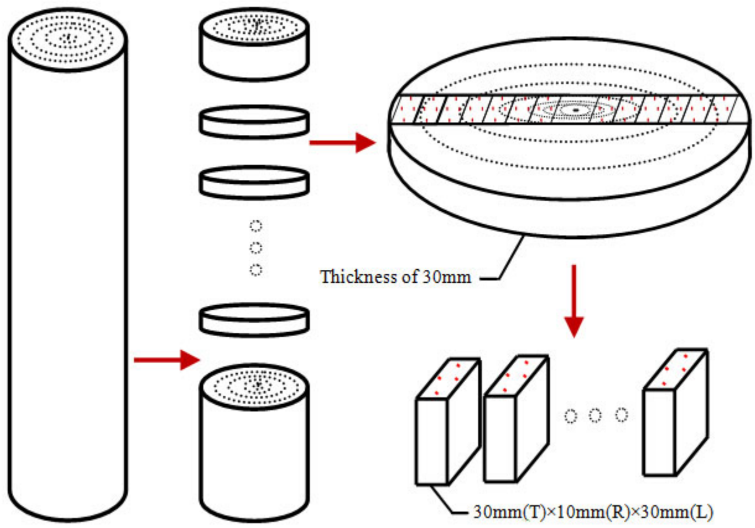

Figure 1. Cutting diagram of moisture content and strain slices. T indicates a tangential measurement; R, radial; L, longitudinal.

Fu *et al.* provide the schematics and calculation formula related to the method [15,16]. The details are as follows:

$$\text{Practical shrinkage strain}: \ \varepsilon_{ps} = (L_0 - L_1)/L_0 \tag{1}$$

$$\text{Elastic strain}: \ \varepsilon_{es} = (L_1 - L_2)/L_0 \tag{2}$$

$$\text{Viscoelastic creep strain}: \ \varepsilon_{ve} = (L_2 - L_3)/L_0 \tag{3}$$

$$\text{Mechano} - \text{sorptive creep}: \ \varepsilon_{ms} = (L_3 - L_4)/L_0 \tag{4}$$

where L_0 is the distance of two measuring dots on the strain slices under green conditions;

L_1 is the distance of two measuring dots on the strain slices before cutting at 26%, 18%, and 10% moisture content;

L_2 is the distance of two measuring dots on the strain slices when the wood disk is split along the grid line;

L_3 is the distance of two measuring dots under stable moisture conditions, achieved by placing the strain slices in a conditioning chamber with equilibrium moisture content equal to moisture content when the slice is split;

L_4 is the distance of two measuring dots with the strain slices soaked in water for 24 h, steamed for 10 h, and placed in a conditioning chamber to maintain the temperature and humidity conditions in L_3.

To analyze the strains in different radial positions, the following regions were observed separately: heartwood *i.e.*, 10 to 20 mm from the pith, mixed wood (transition between heartwood and sapwood) 30 to 60 mm, and sapwood 70 to 90 mm.

The shrinkage radio in tangential and radial directions are calculated with the following formulas:

$$\mathrm{T_{shrinkage\ \ radio}} = [(\mathrm{T_{green\ \ dimension}} - \mathrm{T_{dry\ \ dimension}})/\mathrm{T_{green\ \ dimension}}] \times 100\% \tag{5}$$

$$\mathrm{R_{shrinkage\ \ radio}} = [(\mathrm{R_{green\ \ dimension}} - \mathrm{R_{dry\ \ dimension}})/\mathrm{R_{green\ \ dimension}}] \times 100\% \tag{6}$$

3. Results and Discussion

3.1. Moisture Content History

The moisture content history for the wood disks during drying was depicted in Figure 2. Above a moisture content of 26%, the moisture content curve fluctuated with different distances from the pith; however, below a moisture content of 26%, the distribution of moisture content was almost even at each radial position. Therefore, the effect of the moisture content gradient on transverse rheological behaviors can be neglected.

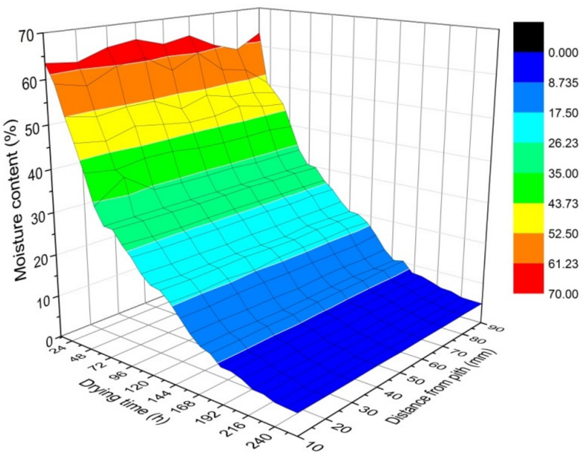

Figure 2. Illustration of the change in moisture content over time in wood disks.

3.2. Difference of Shrinkage Ratios between the Tangential and Radial Directions

The shrinkage ratio is an important parameter that can be used to characterize the performance of wood drying. The shrinkage radio in tangential and radial were calculated by Equations (5) and (6), respectively. The difference of the shrinkage ratio between the tangential and radial directions has been found to strongly affect the internal stress that occurs during drying [17]. For wood disks, the shrinkage ratio for heartwood is different from that of sapwood because the properties of these types of wood vary. The difference of the shrinkage ratio between the tangential and radial directions increased with the decrease of moisture content; at the same moisture content level, the shrinkage ratio in heartwood was slightly higher than that in sapwood (Figure 3). Generally, the tangential shrinkage was assumed to be 1.37 times as large as the radial shrinkage for white birch [18]. In this study, the ratio of the tangential and radial shrinkage in heartwood and sapwood was 1.17–1.54 and 1.12–1.39, respectively.

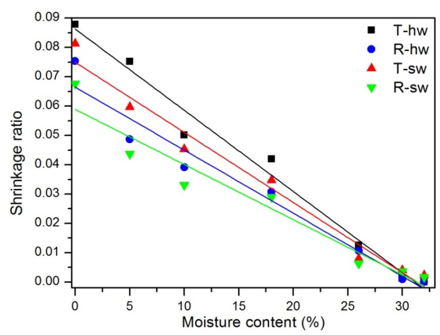

Figure 3. Variation of the shrinkage ratio in heartwood and sapwood of *Betula platyphylla* between the tangential and radial directions. T-hw indicates tangential heartwood; R-hw, radial heartwood; T-sw, tangential sapwood; R-sw, radial sapwood.

3.3. Variations of Drying Strains between the Tangential and Radial Directions

3.3.1. Practical Shrinkage Strain

Figure 4a depicts the variation of practical shrinkage strain between the tangential and radial directions. As this figure shows, at the same moisture content level, the tangential practical shrinkage strain was higher than in a radial direction at each position; this could be attributed to the higher permeability and moisture flow in the radial direction [19,20]. At 26% moisture content, the difference of practical shrinkage strain between the tangential and radial directions was not sharp, but it increased with a decrease in moisture content. This occurs because the difference of shrinkage coefficient between the tangential and radial directions increased as drying continued (Figure 3). The disparities of practical shrinkage strain between the tangential and radial directions were obvious in sapwood; this is closely related to the geometry of wood disks. Because wood disks are round, the practical shrinkage strain in a tangential direction is closer to the radial strain as one approaches the center of the disk; specifically, the difference in the practical shrinkage strain in the tangential and radial directions is proportional to the radius. Pang and Herritsch noted that tangential shrinkage increased from the pith to the seventh growth ring both in earlywood and latewood [21]. In addition, at each level of moisture content, the practical shrinkage strain in heartwood was higher than in sapwood because of the higher density for heartwood.

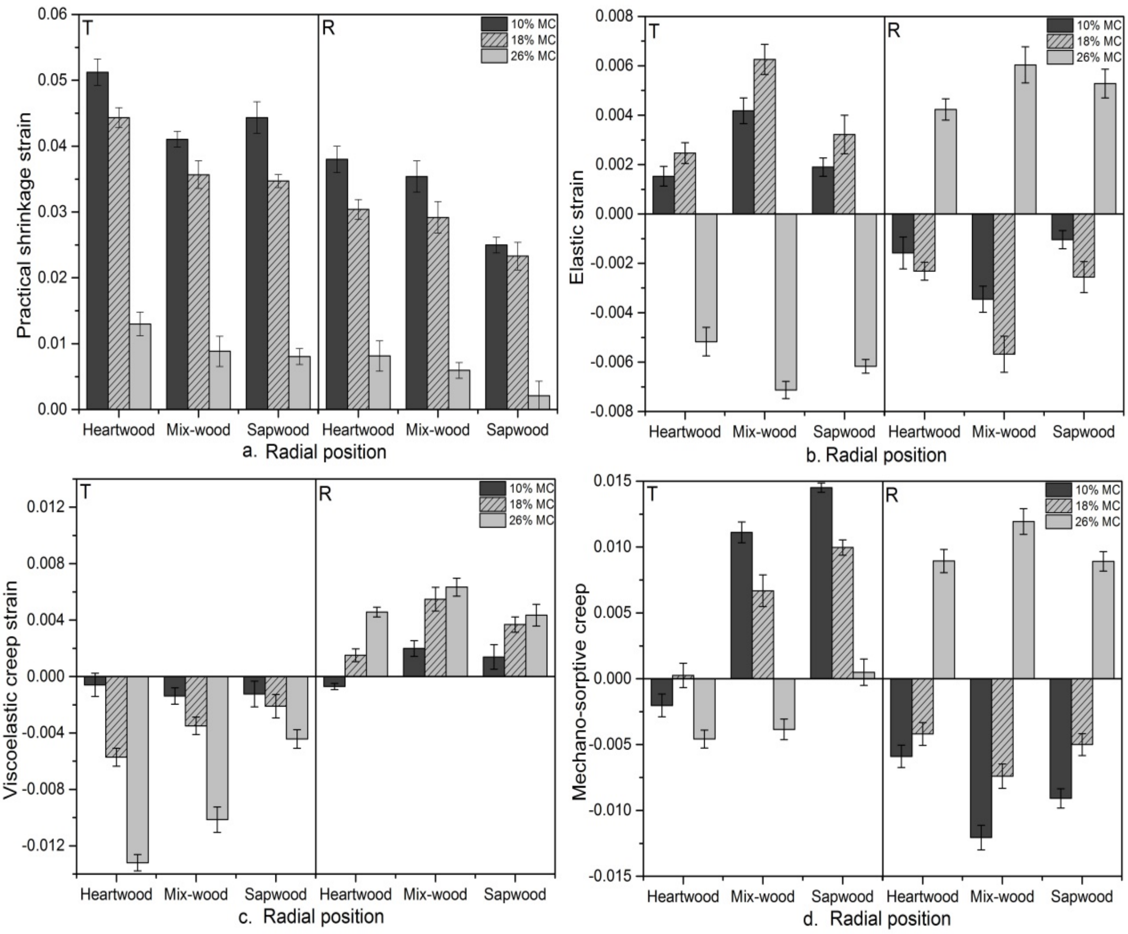

Figure 4. Effect of radial position and moisture content on drying strains for tangential and radial directions. (**a**) Practical shrinkage strain; (**b**) Elastic strain; (**c**) Viscoelastic creep strain; (**d**) Mechano-sorptive creep. T indicates Tangential; R indicates Radial.

3.3.2. Elastic Strain

At 26% moisture content, tensile elastic strain is present in a tangential direction, but compressive elastic strain is present in a radial direction. At 18% moisture content, the elastic strain reverses, *i.e.*, compressive elastic strain occurs tangentially and tensile elastic strain occurs radially; both types of strain decreased as drying reached 10% moisture content (Figure 4b). The elastic strain represents the level and direction of drying stress when cut wood disks are used as specimens to measure strain. As a result, below the fiber saturation point, the tangential tensile stress is gradually reduced, and then is converted into compressive stress after the transition state without stress is reached. At each moisture content level, tangential elastic strain is balanced with radial inverse elastic strain. When moisture is uniformly distributed, the drying stress is induced by shrinkage anisotropy, *i.e.*, the difference in shrinkage between the tangential and radial directions; therefore, the change of stress state is caused by plastic deformation. Both tangential and radial stress decreased with a decrease in moisture content; this mainly occurs because the modulus of elasticity increased with the decrease in moisture content and the relaxation of stress caused by creep. The elastic strains in mixed wood were higher compared with other radial positions; this is caused by the large difference in wood properties in the mixed wood when compared with heartwood and sapwood. Additionally, the radial elastic strain is slightly smaller than tangential strain, because the modulus of elasticity in a radial direction is larger than in a tangential direction.

3.3.3. Viscoelastic Creep Strain

Tensile viscoelastic creep strain occurs in a tangential direction; however, compressive viscoelastic creep strain occurs in a radial direction at each moisture content level (Figure 4c). Below the fiber saturation point, viscoelastic creep strains all decreased both tangentially and radially with a decrease in moisture content, although this strain nearly recovered at close to 10% moisture content. In a tangential direction, after the tensile stress switched to compressive stress, the tensile viscoelastic creep strain decreased sharply with the interaction between the recovering of tensile viscoelastic creep and the generation of compressive viscoelastic creep. In a radial direction, a similar phenomenon occurs, but the stress is felt in the opposite direction. The viscoelastic creep strain is not easy to generate at low levels of moisture content, which means that the generation of viscoelastic creep strain is closely related to the moisture content of the wood. Compared with the tangential direction, the viscoelastic creep strain in a radial direction is difficult to recover, and this can be attributed to the existence of wood rays.

3.3.4. Mechano-Sorptive (MS) Creep

The difference observed in MS creep between the tangential and radial directions was depicted in Figure 4d. At 26% moisture content, tensile MS creep was observed in a tangential direction under tensile stress. At 18% and 10% moisture content, compressive MS creep was generated with the effect of compressive stress. This phenomenon occurs for two possible reasons: first, the previous tensile MS creep did not recover, but a greater amount of compressive MS creep was generated in the areas without creep under compressive stress, so that compressive MS creep was observed. Second, the previous tensile MS creep was recovered under compressive stress and then compressive MS creep was generated. Additionally, the tangential compressive MS creep at 10% moisture content was higher than at 18% moisture content; The same conclusion was reported by Rice and Youngs [3], who believe that MS creep is clearly with a function of moisture change and increases with the decrease of moisture content.

At 26% moisture content, compressive MS creep was observed in a radial direction, and this creep in sapwood was lower than in mixed wood and heartwood; this occurs because the compressive strain decreased with the increased radius from the pith to bark. At 18% and 10% moisture content, a smaller amount of radial tensile MS creep was generated. This can be explained as follows: wood density as well as the number and structure of wood rays determine the strength of wood. White birch has diffuse-porous wood in that the microfibers participated in transverse tension with no difference between tangential and radial stress. However, some longitudinal microfibers also participated in creating radial tension; therefore the radial tensile strength was greater than that in a tangential direction, so that radial tensile MS creep was smaller than tangential creep.

4. Conclusions

For wood disks of *Betula platyphylla*, the tangential shrinkage was 1.12–1.54 times that in a radial direction and the difference of shrinkage ratio between the tangential and radial directions increased with decreasing moisture content. The difference of practical shrinkage strain between the two directions was proportional to the distance from the pith. Both the elastic strain and viscoelastic creep strain decreased with decreasing moisture content and the two strains in the tangential direction were higher than in the radial direction at the same moisture content level. When compared with tangential viscoelastic creep strain, this type of strain was difficult to recover in the radial direction. At each moisture content level, there were opposite MS creep strains between the tangential and radial directions; before stress reversal, the tensile MS creep occurred in the tangential direction while compressive MS creep occurred in the radial direction; after stress reversal was finished, this situation was reversed.

Acknowledgments: The National Natural Science Foundation of China (Grant No. 31270595) and the Fundamental Research Funds for the Central Universities of China (Grant No. 2572015AB08), financially supported this research.

Author Contributions: Zongying Fu conceived and designed the experiments; Jingyao Zhao and Yeli Yang performed the experiments; Zongying Fu and Yingchun Cai analyzed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MS	Mechano-sorptive
MC	Moisture content

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