Optimization of Measurement and Calculation Methods for Viscoelastic Creep Strain and Mechanical Adsorption Creep Strain during Conventional Drying Process of *Pinus sylvestris*

Haojie Chai,* and Lu Li

The traditional measurement method for viscoelastic creep strain and mechanical adsorption creep strain has relatively low accuracy, making it difficult to ensure the data accuracy of specimen strain measurements. In this study, 50-mm-thick *Pinus sylvestris* sawn timber was used as the research object. Along the thickness direction of the test material, the relationship between the free shrinkage coefficient and the moisture content of the test material was studied to optimize the measurement methods of viscoelastic creep strain and mechanical adsorption creep strain during drying process. The results showed that the optimized measurement method for viscoelastic creep strain, which compensates for dimensional change caused by moisture content changes during the creep recovery phase, was applied to different layers in the thickness direction of the test material. The average relative error at the end of the drying stage was reduced 20.1% compared to the traditional method. For the mechanical adsorption creep strain in different layers of the test material's thickness, the optimized measurement method, based on the free shrinkage size calculated from the free shrinkage coefficient and moisture content, reduced the average relative error 59.1% compared to the traditional method.

DOI: 10.15376/biores.19.3.6339-6354

Keywords: Conventional drying of wood; Viscoelastic creep strain; Mechanically adsorbed creep strain; Optimization of measurement methods

*Contact information: School of Artificial Intelligence, Henan Institute of Science and Technology, Xinxiang, 453003, China; *Correspondence: nefuchj@163.com*

INTRODUCTION

The drying stress generated during each stage of the conventional drying process exceeding the elastic limit is an important factor leading to wood drying defects. In situations where it is difficult to directly measure drying stress, studying the strain variation during the drying process of the test material and analyzing the relationship between strain and drying quality, is an important direction to deepen the understanding of drying stress during each stage of drying and optimize the drying process.

Scholars in China and around the world have conducted extensive experimental research and theoretical discussions on various strain patterns during wood drying. Liu *et al.* (2010) systematically introduced the rheological properties of wood and their influencing factors. Zhan *et al.* (2009) studied the dynamic mechanical adsorption characteristics during the conventional drying process of larch plates and established a correlation analysis function for free shrinkage rate. Fu *et al.* (2014) systematically studied

the stress-strain laws during the conventional drying process of birch disks. Li *et al.* (2017) conducted in-depth research on the relationship between cell wall structure and wood viscoelasticity, explaining its mechanism of action at the molecular level. Liu (2018) utilized dynamic mechanical analysis (DMA) with a humidity attachment to study the mechanical adsorption creep characteristics of birch under different moisture content and temperature conditions. Mazzanti and Francesco (2020) outlined the rheological properties of wooden polymers. Alrubaie *et al.* (2020) studied and simulated the viscoelastic behavior of extruded wood-plastic composites of thermally modified wood under hydrothermal treatment. Fu *et al.* (2014) systematically studied the stress-strain laws during the conventional drying process of birch disks. Foreign scholars have made rich research achievements on the free shrinkage characteristics of wood, but there are still the following problems: (1) In the traditional viscoelastic creep strain measurement method, the creep recovery phase of the test strip can cause dimensional changes due to changes in moisture content, which can lead to measurement errors. (2) The traditional mechanical adsorption creep strain measurement method has many operation steps, is time-consuming and energy-consuming, and it is difficult to ensure that the moisture content of the test strip is completely consistent before and after processing, affecting the accuracy of the mechanical adsorption creep strain measurement data. Therefore, it is necessary to optimize the measurement methods for viscoelastic creep strain and mechanical adsorption creep strain (Lin and Lin 2021).

In view of this, this study attempted to compensate for the deformation caused by changes in moisture content during the viscoelastic creep recovery phase. A further goal was to optimize the measurement method for viscoelastic creep strain during the drying process of the test material. Based on the relationship between the free shrinkage coefficient, moisture content, and free shrinkage rate, the authors attempted to calculate the free shrinkage length of each layer of test strips at the moisture content during viscoelastic creep recovery (the reference length after the moisture content remains unchanged and only plastic deformation is eliminated), and accurately calculate the corresponding mechanical adsorption creep strain based on this. The authors also compared the measured values of the optimized measurement method with the traditional measurement method and analyzed the degree of error reduction.

EXPERIMENTAL

Experimental Material

As shown in Fig. 1, *Pinus sylvestris* var. *mongolica* Litv., a 50-year-old Scotch pine produced in the Greater Khingan Forest Region, was processed into a flat-cut lumber piece with dimensions of 4000 mm (length, fiber direction) × 200 mm (width, upper surface layer near chord direction, lower surface layer near radial direction) × 50 mm (thickness, partial radial direction). The initial moisture content was in the range 68.5% to 80.8%. Four conventional drying test specimens with a length of 500 mm were intercepted from each lumber (used for actual shrinkage performance testing during conventional drying), as well as six test pieces (without obvious defects) for free shrinkage performance testing at both ends. The dimensions of the test piece were 10 mm (fiber direction) × 200 mm × 50 mm. Furthermore, each was split into 9 layers with an axe along the thickness of the lumber to obtain test strips for free shrinkage performance testing at each layer of the lumber

thickness (numbered sequentially from the upper surface layer near the chord direction to the lower surface layer near the radial direction).

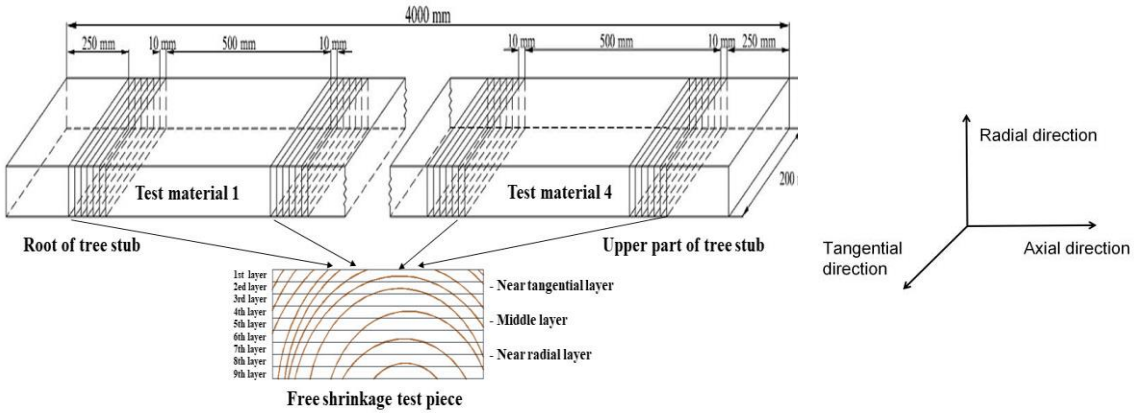


Fig. 1. Preparation of experimental specimens for studying the free and actual shrinkage patterns of *Pinus sylvestris* var. *mongolica* lumber (Zhu *et al.* 2021; CC BY 4.0 license)

Measurement of Various Strains During the Drying Process of *Pinus sylvestris* var. *mongolica* Litv. Specimens

To ensure reliable experimental data, three similarly natured specimens (specimens 1, 2, and 3 shown in Fig. 1) were placed simultaneously in each experiment (with the drying process shown in Table 1) as strain inspection boards (specification: 500 mm × 200 mm × 50 mm). The image analysis method (Fu *et al.* 2016) was used to measure the initial size in the width direction of each layer on the thickness of the inspection board and the size in various stages and states during the drying process. The specific steps of the image analysis method are as follows: First, the image was collected, then the point distance was measured, and finally, the calculation of each strain was carried out through digital image processing.

The formulas for calculating various strains during the drying process of the strain inspection board are shown in Eqs. 3-1 to 3-4,

$$\varepsilon_p = \frac{L_0 - L_1}{L_0} \quad (3\text{-}1)$$

$$\varepsilon_e = \frac{L_1 - L_2}{L_0} \quad (3\text{-}2)$$

$$\varepsilon_c = \frac{L_2 - L_3}{L_0} \quad (3\text{-}3)$$

$$\varepsilon_{mc} = \frac{L_3 - L_4}{L_0} \quad (3\text{-}4)$$

where L_0 is the average value of the size at both ends of the corresponding layer on the thickness of the strain inspection board, that is, the initial length of the test strip (mm); L_1 is the length of the test strip of the corresponding layer before splitting the strain test piece when the inspection board is dried to the target moisture content (mm); L_2 is the length of each layer of test strip after splitting the strain test piece along the line (mm); L_3 is the length of the test strip after being sealed and placed for about 24 h to allow its viscoelastic creep recovery (mm); and L_4 is the length of the test strip after free shrinkage when the

plastic deformation is eliminated and it is equilibrated to the moisture content during L_3 detection (mm).

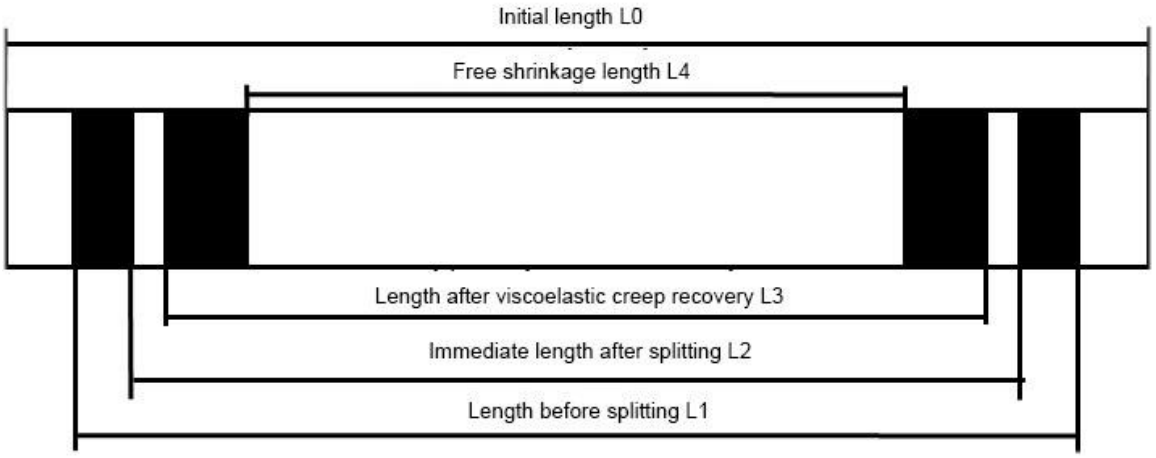


Fig. 2. Measurement of various strains during the drying process of *Pinus sylvestris* var. *mongolica* specimens

Table 1. Conventional Drying Schedule for *Pinus sylvestris* var. *mongolica* Litv.

Moisture Content (%)	Dry Bulb Temperature (°C)	Dry And Wet Bulb Temperature Difference (°C)	Relative Humidity (%)	Equilibrium Moisture Content (%)
Above 40	65	3	86	15.0
40 to 30	67	4	82	13.5
30 to 25	70	6	76	11.1
25 to 20	75	8	70	9.5
20 to 15	80	14	53	6.5
Below 15	90	25	32	3.8

Calculation of the Size of Free Shrinkage of Each Layer of Test Strips on the Thickness of *Pinus sylvestris* var. *mongolica* Litv. Strain Inspection Board

By combining Eqs. 2-2 and 2-3, the length of the free shrinkage strain test strip when freely dried to a moisture content of MC (length after free shrinkage) Lmcf can be obtained, that is,

$$L_{mcf} = \frac{\left((100 - k(FSP - mc)\right) \times L_0}{100} \quad (3\text{-}5)$$

where L_{mcf} is the theoretical calculated length of free shrinkage at a moisture content of MC for each layer of test strip in the actual shrinkage performance test piece (mm); mc is the moisture content at a certain moment below the fiber saturation point of the test strip (%); *k* is the corresponding free shrinkage coefficient of the test strip (%); and FSP is the fiber saturation point of the corresponding layer of the test strip (%).

Based on the fiber saturation point and the free shrinkage coefficient in the width direction of each layer on the thickness of the test material given in Tables 2 to 4, the length

of each layer of test strips on the thickness of the strain inspection board when freely shrunk to a moisture content of mc can be accurately calculated according to Eq. 3-5.

Table 2. Free Shrinkage Performance in the Width Direction of Each Layer on the Thickness of Specimen 1

Layer number	60 °C		80 °C		100 °C	
	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)
1	0.282	24.38	0.272	24.33	0.267	25.41
2	0.281	24.78	0.267	24.78	0.263	25.60
3	0.278	25.11	0.266	25.04	0.260	26.12
4	0.275	24.97	0.272	25.22	0.265	25.71
5	0.264	25.49	0.264	25.09	0.252	26.38
6	0.258	25.07	0.265	25.08	0.254	26.25
7	0.262	24.93	0.249	24.54	0.253	25.77
8	0.258	24.37	0.239	24.43	0.234	25.47
9	0.247	24.81	0.235	24.33	0.235	25.15

Table 3. Free Shrinkage Performance in the Width Direction of Each Layer on the Thickness of Specimen 2

Layer Number	60 °C		80 °C		100 °C	
	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/k (%)	Fiber Saturation Point/FSP (%)
1	0.280	24.35	0.275	25.18	0.266	24.83
2	0.273	24.95	0.276	24.86	0.262	25.22
3	0.273	25.06	0.271	25.42	0.265	26.56
4	0.268	24.78	0.273	25.31	0.265	25.63
5	0.265	24.61	0.260	25.08	0.247	26.17
6	0.255	24.08	0.259	25.09	0.230	25.91
7	0.255	24.25	0.267	24.63	0.235	25.17
8	0.256	23.27	0.250	25.02	0.232	25.00
9	0.243	24.53	0.241	26.34	0.236	23.70

Table 4. Free Shrinkage Performance in the Width Direction of Each Layer on the Thickness of Specimen 3

Layer Number	60 °C		80℃°C		100 °C	
	Free Shrinkage Coefficient/ k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/ k (%)	Fiber Saturation Point/FSP (%)	Free Shrinkage Coefficient/ k (%)	Fiber Saturation Point/FSP (%)
1	0.278	24.71	0.283	23.87	0.267	25.41
2	0.281	25.10	0.283	24.28	0.256	26.10
3	0.284	25.21	0.278	24.73	0.260	26.21
4	0.280	25.13	0.278	24.94	0.253	25.63
5	0.255	26.25	0.257	25.27	0.232	26.67
6	0.259	25.65	0.258	25.21	0.232	26.16
7	0.258	26.45	0.265	25.02	0.226	25.92
8	0.260	24.82	0.259	24.05	0.231	24.94
9	0.239	25.79	0.250	23.90	0.223	25.11

Optimization of Viscoelastic Creep Strain Measurement Algorithm

Traditional measurement and calculation method

Wood creep is a characteristic of wood as a viscoelastic material, which manifests as a change in strain over time under a certain stress. The traditional method of measuring viscoelastic creep deformation during the drying process of the test material involves placing the test strip, after elastic deformation recovery and length measurement, in a sealed bag to remove air or under vacuum sealing treatment. The test material is then left for approximately 24 h before measuring the dimensions after viscoelastic creep recovery, and the viscoelastic creep strain is calculated according to Eq. 3-3.

Optimized measurement and calculation method to compensate for deformation caused by changes in moisture content during the viscoelastic creep recovery phase

During the process of viscoelastic creep recovery of the test strip, there are inevitably slight changes in its moisture content. Therefore, based on the fiber saturation point, free shrinkage coefficient, and changes in moisture content of the test strip, the size changes caused by changes in moisture content are compensated according to Eq. 3-5. Then, the viscoelastic creep strain is calculated according to Eq. 3-3 to improve the accuracy of measurement and calculation. The optimized Eq. for calculating viscoelastic creep strain after simultaneously solving Eqs. 3-5 and 3-3 is shown in Eq. 3-6,

$$\varepsilon_c = \frac{L_2 - (L_3 - \Delta mc_i \times k_i \times L_0/100)}{L_0} \quad (3\text{-}6)$$

where L_0 represents the initial length of the corresponding layer of the test material (mm); L_2 represents the length of each test piece layer measured after splitting open the test material inspection piece along the marked line (mm); L_3 represents the length measured after placing the test strip in a vacuum bag and sealing it for a period of time after measuring

L_2 (mm); Δmc_i represents the change in moisture content of the test strip in layer i during the sealed creep recovery phase (%); and k_i represents the corresponding free shrinkage coefficient of the test strip in layer i (%).

Optimization of Mechanical Adsorption Creep Strain Measurement and Calculation Method

Traditional measurement and calculation method

The traditional method for measuring mechanical creep strain of test materials involves placing the test strips, after viscoelastic creep recovery of each layer, in an environmental condition corresponding to the equilibrium moisture content (EMCL3) consistent with the current moisture content (MCL3). The test strips are then allowed to equilibrate until their moisture content stabilizes, at which point their weight and dimensions (recorded as L3e) are measured. Subsequently, the test strips are soaked in water for 24 h, steamed for 10 h (to eliminate plastic deformation), and then placed in the same environmental conditions (corresponding to EMCL3) for drying and equilibrating until they reach a stable moisture content. Their dimensions are then measured again (recorded as L_4), and the mechanical adsorption creep strain is calculated according to Eq. 3-7,

$$\varepsilon_{mc} = \frac{L_{3e} - L_4}{L_0} \tag{3-7}$$

where L_0 represents the initial length of the corresponding layer of the test material (mm); L_{3e} represents the length of the test strip (mm) when its moisture content stabilizes after equilibration treatment under environmental conditions corresponding to the equilibrium moisture content (EMCL3) at the moisture content (MCL3) after viscoelastic creep recovery of each layer of the test material; L_4 represents the length of the test strip (mm) when it is dried and equilibrated to a stable moisture content under the same environmental conditions mentioned earlier (corresponding to EMCL3).

Optimized measurement and calculation method to compensate for deformation caused by changes in moisture content during the viscoelastic creep recovery phase

The measurement method for mechanical adsorption creep strain of test materials is time-consuming, energy-consuming, and complex to operate, and there are certain errors. The main reasons for the errors are: ① It is difficult to completely eliminate plastic deformation through soaking and steaming treatments; ② Before and after the soaking and steaming treatments to eliminate plastic deformation of the test strips, when placed in a temperature and humidity environment corresponding to the equilibrium moisture content equal to the moisture content after viscoelastic creep recovery for equilibration or drying, the treated test strips undergo a drying and desorption process, while some untreated test strips may undergo a moisture absorption process. Due to the hysteresis of moisture absorption in wood, it is difficult to ensure that the moisture content of the test strips before and after treatment is exactly the same, thus affecting the accuracy of the mechanical adsorption creep strain measurement data.

Based on the fiber saturation point, free shrinkage coefficient, and moisture content of the test strip, the precise size (size after free shrinkage) when dried to a moisture content of MCL3 can be calculated according to Eq. 3-5. Then, the mechanical adsorption creep strain can be calculated according to Eq. 3-4. By combining Eqs. 3-5 and 3-4, one can

obtain the optimized calculation Eq. 3-8. The optimized calculation formula is shown in formula 3-8,

$$\varepsilon_{mc} = \frac{L_3 - (100L_0 - k_i(FSP - mc_i) \times L_0)/100}{L_0} \quad (3\text{-}8)$$

where mc_i represents the moisture content (%) of the i^{th} layer of the test strip after being sealed and allowed to recover from creep; k_i represents the corresponding free shrinkage coefficient (%) of the i^{th} layer of the test strip; mc_i also represents the moisture content (%) of the i^{th} test strip below the fiber saturation point; FSP represents the fiber saturation point (%) of the corresponding layer of the test strip.

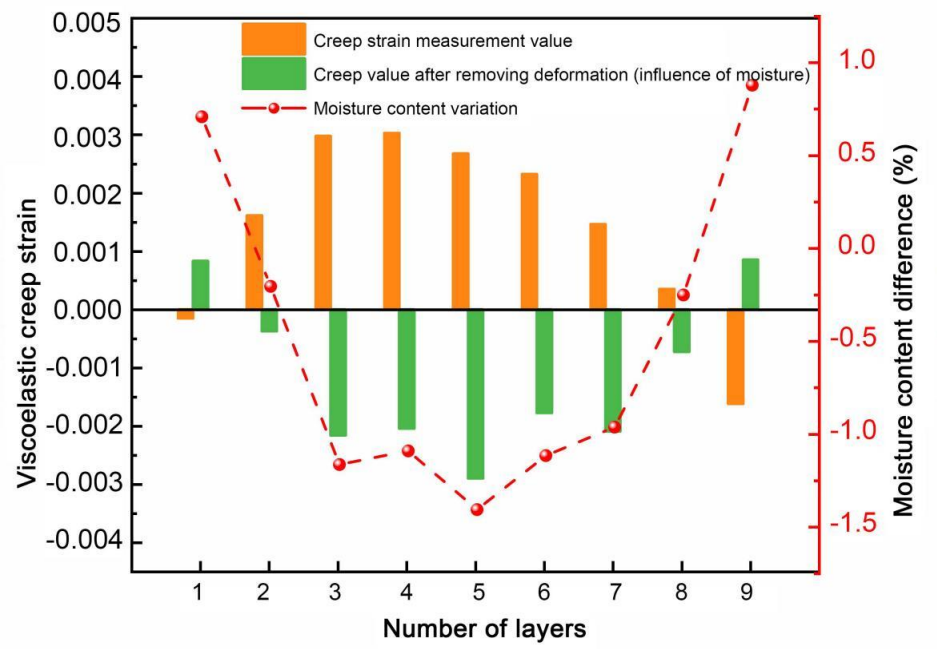
RESULTS AND DISCUSSION

Optimization of Viscoelastic Creep Measurement Method

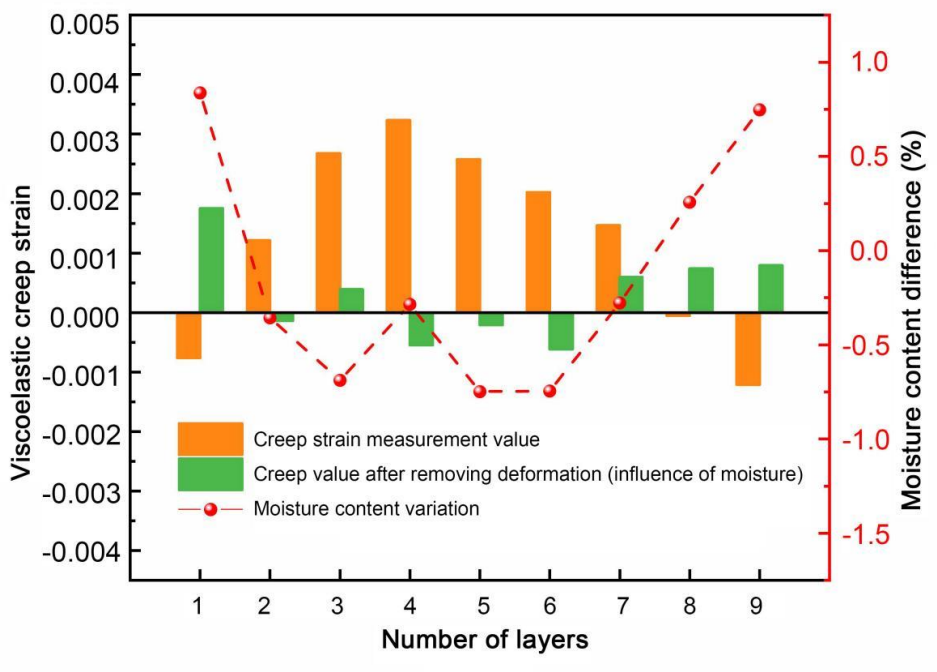
Figure 3 compares the optimized measurement method based on compensating for deformation caused by moisture content changes during viscoelastic creep recovery with the traditional method for measuring viscoelastic creep strain. The comparison focuses on various test materials, and Table 5 shows the absolute and relative errors between the two methods. The free shrinkage coefficients for different layers of each test material are selected from Tables 2, 3, and 4. The differences in moisture content across the thickness of the test materials during various drying stages (the difference between the moisture content after creep recovery and during elastic strain measurement) are shown by the red curve in the figure. When the moisture content was 24%, the moisture content of the *Pinus sylvestris* test material changed significantly during the viscoelastic creep recovery phase. The moisture content difference in the fifth layer of the test material was as high as 1.4%. Based on the relationship between the free shrinkage coefficient and moisture content of the corresponding layer of the test material, the deformation caused by changes in moisture content during the creep recovery phase was compensated by 0.75 mm. After removing this deformation, the viscoelastic creep strain properties of the surface and core layers of the *P. sylvestris* test material had changed. Specifically, the surface layer transitioned from tensile viscoelastic creep strain to compressive creep, while the core layer adjusted to tensile creep strain. As shown in Table 5, when the moisture content of the test material was 24%, the absolute error between the viscoelastic creep strain calculated by the optimized measurement method and the traditional measurement method ranged from -0.0056 to 0.0010. However, the relative error of strain measurement using different creep strain measurement methods was generally greater than 100% at this stage, with a minimum value of 94.2%. The large discrepancy between the two methods is attributable to the small value of viscoelastic creep strain (below 0.01), where small changes in dimensions can lead to significant errors.

When the test material was dried to a moisture content of 18%, the difference in moisture content across its thickness layers during the viscoelastic creep recovery phase decreased. As a result, the relative error between the viscoelastic creep strain calculated by the optimized measurement method and the traditional measurement method decreased. The average relative error of the test material at this moisture content stage was reduced to 71.8%. At the final drying stage, the viscoelastic creep strain value of the *Pinus sylvestris* test material decreased significantly. Additionally, due to minimal changes in moisture content across the thickness layers of the test strips during the viscoelastic creep recovery

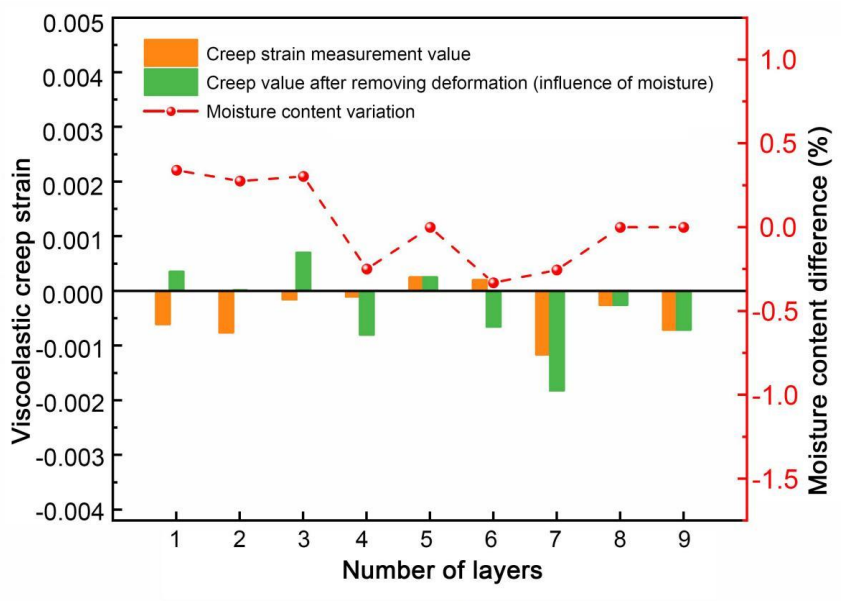
phase in the later stages of drying, the average relative error between the viscoelastic creep strain calculated by the optimized and traditional measurement methods further decreased to 20.1%.



(a) At 24% moisture content



(b) At 18% moisture content



(c) At 12% moisture content

Fig. 3. Optimization of viscoelastic creep strain for *Pinus Sylvestris* test material

Table 5. Comparison between Traditional Measurement Method and Optimized Measurement Method that Compensates for Deformation during Viscoelastic Creep Recovery Phase

Number of Layers	Moisture Content 24%		Moisture Content 18%		Moisture Content 12%	
	Absolute Error	Relative Error (%)	Absolute Error	Relative Error (%)	Absolute Error	Relative Error (%)
1	-0.0010	94.2	-0.0023	254.6	-0.0009	48.4
2	-0.0020	540.9	0.0012	112.1	-0.0008	38.1
3	0.0051	237.9	0.0021	149.0	-0.0008	22.6
4	0.0051	248.2	0.0026	402.4	0.0007	38.1
5	0.0056	192.7	0.0004	17.1	0	0.0
6	0.0041	231.1	0.0003	20.7	0.0009	11.3
7	0.0036	169.9	-0.0002	12.7	0.0006	22.3
8	0.0011	148.9	-0.0005	111.3	0	0.0
9	-0.0025	288.2	-0.0005	79.9	0	0.0

The results indicate that, based on the comparison between the optimized creep strain measurement that compensates for deformation caused by moisture content changes during the viscoelastic creep recovery phase and the traditional method of strain measurement, the traditional method had a relatively large relative error and poor accuracy in measuring creep strain values. The accuracy of the measurement gradually increased as the moisture content decreased.

Optimization of Mechanical Adsorption Creep Strain Measurement Method

Exploration of the effectiveness of the soaking and steaming method in eliminating plastic deformation of test materials

Mechanical adsorption creep refers to the irreversible deformation of wood dimensions caused by the slippage of microscopic cellulose molecular chains in the wood cell wall under unsteady conditions. However, this plastic deformation can also be recovered under high temperature and high humidity conditions. Under stress, the breakage, slippage, and reorganization of intermolecular hydrogen bonds between cellulose molecular chains in wood cells require energy consumption. During the drying process, through the effects of hot air convection, heat conduction, *etc.*, the wood continuously absorbs heat, increases in temperature, and gains internal energy, resulting in a larger mechanical adsorption creep strain. As a biomass material, wood can recover its size with moisture absorption, and plastic deformation is basically eliminated under boiling conditions.

Tables 6, 7, and 8 show the changes in size and moisture content of the test strips in each layer of the strain gauges after viscoelastic creep recovery, followed by soaking and steaming, at moisture contents of 24%, 18%, and 12%, respectively. After soaking, the size of the test material (above 199.20 mm) and its moisture content (around 75%) exceeded the initial state. After steaming, the moisture content of the test material further increased and the size increased slightly, with an average moisture content of about 125.50%. As drying progressed, the moisture content of each layer of test strips after soaking remained at around 75%, but the amount of size recovery decreased. At a moisture content of 12%, the size of each layer of test strips after soaking was around 198.5 mm.

Table 6. Comparison of Test Strip Size After Soaking and Steaming at 24% Moisture Content

Number of Layers	Initial Size (mm)	Size After Soaking (mm)	Moisture Content After Soaking (%)	Size After Steaming (mm)	Moisture Content After Steaming (%)
1	198.12	199.83	73.83	200.51	104.26
2	198.14	199.63	76.10	200.47	123.71
3	198.10	199.55	72.33	200.33	120.55
4	198.08	199.48	68.50	200.21	119.66
5	198.11	199.49	71.73	200.19	126.79
6	198.10	199.32	75.39	199.82	130.33
7	198.20	199.27	75.73	199.64	133.51
8	198.28	199.18	75.32	199.38	133.08
9	198.33	199.21	73.06	199.17	131.69

Table 7. Comparison of Test Strip Size After Soaking and Steaming at 18% Moisture Content

Number of Layers	Initial Size (mm)	Size After Soaking (mm)	Moisture Content After Soaking (%)	Size After Steaming (mm)	Moisture Content After Steaming (%)
1	198.12	199.60	75.70	200.43	147.77
2	198.14	199.23	76.87	200.38	153.38
3	198.10	199.01	68.35	200.30	140.83

4	198.08	198.87	66.37	200.03	139.88
5	198.11	198.72	66.83	199.83	140.89
6	198.10	198.78	69.23	199.65	143.42
7	198.20	198.66	70.91	199.49	144.60
8	198.28	198.75	70.69	199.38	145.50
9	198.33	198.81	71.57	199.18	149.13

Table 8. Comparison of Test Strip Size After Soaking and Steaming at 12% Moisture Content

Number of Layers	Initial Size (mm)	Size After Soaking (mm)	Moisture Content After Soaking (%)	Size After Steaming (mm)	Moisture Content After Steaming (%)
1	198.12	199.30	76.11	200.12	154.61
2	198.14	198.86	71.55	200.02	146.96
3	198.10	198.61	70.21	199.91	144.38
4	198.08	198.50	67.25	199.74	107.20
5	198.11	198.32	70.15	199.49	143.88
6	198.10	198.31	71.95	199.43	141.25
7	198.20	198.25	72.84	199.23	142.89
8	198.28	198.20	75.55	199.14	148.35
9	198.33	198.59	75.87	198.90	153.35

The size of each layer of test strips in the width direction also decreased slightly (about 0.30 mm) after steaming, and the moisture content after steaming gradually increased as drying progressed. This indicates that the method of soaking and steaming to restore the plastic deformation of *Pinus sylvestris* test materials during the drying process to obtain the free shrinkage size is related to the moisture content of the test materials during drying. The lower the moisture content, the more difficult it is to restore the size of the test materials.

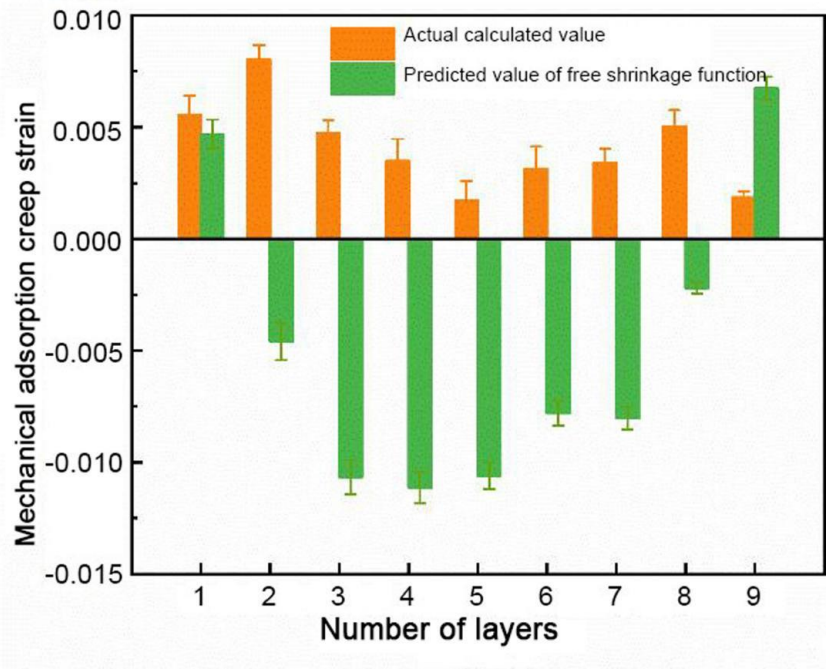
Optimizing mechanical adsorption creep strain measurement based on the relationship between free shrinkage coefficient and moisture content

Figure 4 compares the mechanical adsorption creep strain of *Pinus sylvestris* test materials during the drying process using the steaming method with the estimated mechanical adsorption creep strain values based on the relationship between the free shrinkage coefficient and moisture content of the test materials. Table 9 shows the absolute and relative errors between the two methods. When the moisture content was 24%, the mechanical adsorption creep strain of the test material calculated by restoring plastic deformation using the steaming method was all positive, and the mechanical adsorption creep strain was smaller in the middle layer and larger on the surface layer (around 0.008). The size of the test material after free shrinkage was calculated based on the relationship between the free shrinkage coefficient and moisture content, and its mechanical adsorption creep strain was the tensile plastic deformation on the surface layer and compressive mechanical adsorption creep strain on the middle layers. At this moisture content stage, the average relative error between the optimized measurement method and the traditional method for mechanical adsorption creep strain of the test material reached 148%, indicating

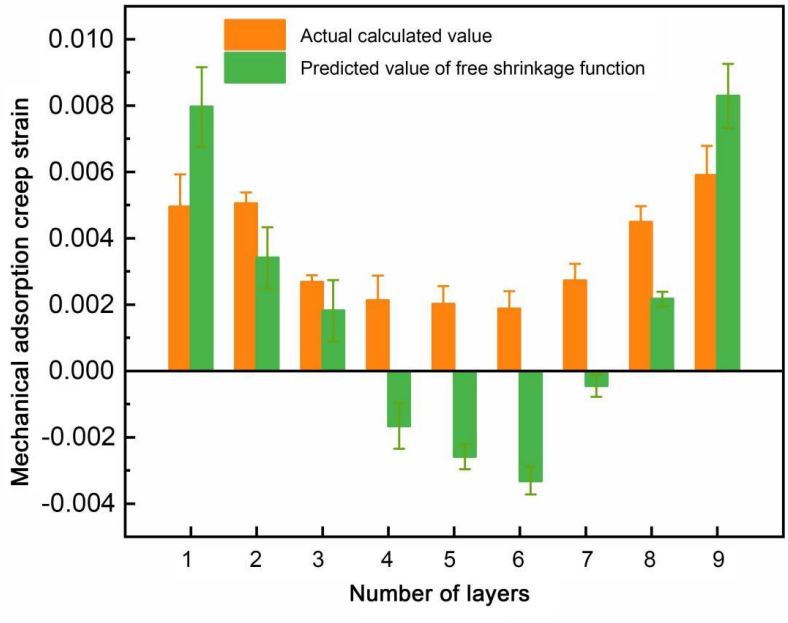
poor accuracy of the traditional method for estimating mechanical adsorption creep strain at high moisture content stages.

At 18% moisture content, there was a significant relative error between the optimized measurement method and the traditional method for adsorption creep strain in the middle layers of the test material. The relative error for the 7th layer was as high as 707.5% (with an absolute error of 0.0032), and the average relative error at this moisture content stage was 125%. At the end of the drying process, both methods yielded the same type of mechanical adsorption creep strain in each layer of the test material's thickness, which was tensile mechanical adsorption creep strain. The average absolute error of strain was 0.0016, and the average relative error had dropped significantly to 59.1%.

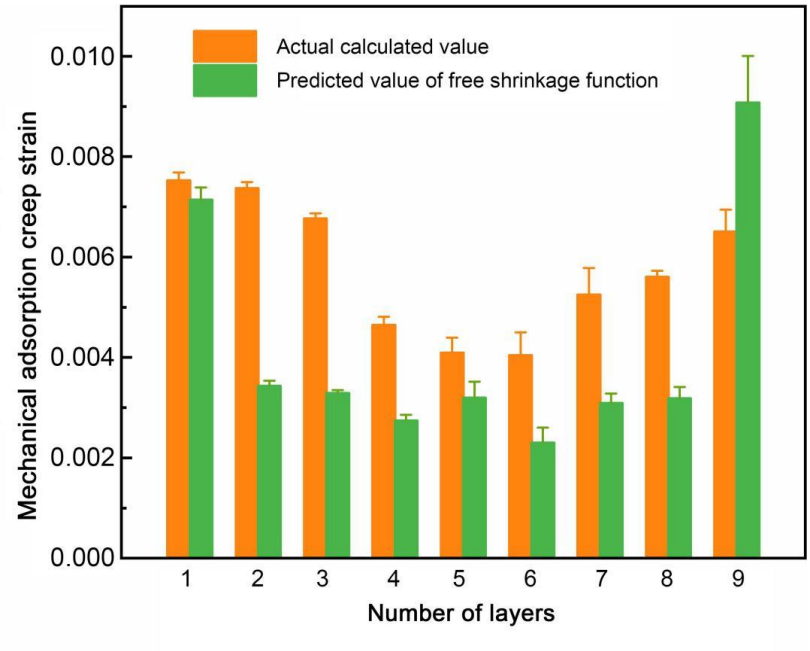
Experiments have shown that the traditional soaking and steaming method has low accuracy in measuring the mechanical adsorption creep strain of test materials, making it difficult to meet the requirements for in-depth study of mechanical adsorption creep strain during the drying process of the test materials. To improve the reliability of experimental data, it is necessary to use the size after free shrinkage calculated based on the relationship between the free shrinkage coefficient and moisture content to determine the mechanical adsorption creep strain of the test material.



(a) At 24% moisture content



(b) At 18% moisture content



(c) At 12% moisture content

Fig. 4. Free and actual mechanical adsorption creep strain of each layer on the thickness of *Pinus sylvestris* test material

Table 9. Comparison of Mechanical Adsorption Creep Strain Calculated by Traditional and Optimized Measurement Methods

Number of Layers	Moisture Content 24%		Moisture Content 18%		Moisture Content 12%	
	Absolute Error	Relative Error (%)	Absolute Error	Relative Error (%)	Absolute Error	Relative Error (%)
1	0.0009	18.6	-0.0030	37.8	0.0004	53.7

2	0.0126	274.6	0.0016	48.2	0.0039	115.0
3	0.0154	144.5	0.0009	47.5	0.0035	105.8
4	0.0145	131.3	0.0037	228.1	0.0019	69.7
5	0.0123	116.2	0.0046	178.2	0.0009	28.0
6	0.0109	140.1	0.0052	156.4	0.0019	90.9
7	0.0114	142.1	0.0032	707.5	0.0022	69.8
8	0.0072	329.5	0.0023	107.2	0.0024	75.8
9	-0.0049	72.3	-0.0024	28.8	-0.0026	28.3

CONCLUSIONS

In this paper, conventional drying treatment was performed on *Pinus sylvestris* test materials. The measurement methods for viscoelastic creep strain and mechanical adsorption creep strain were optimized based on the relationship between free shrinkage coefficient and moisture content. Through comparing the optimized measurement method with the traditional measurement method, the experimental conclusions are as follows:

1. Comparing the optimized measurement method for viscoelastic creep strain based on the relationship between free shrinkage coefficient and moisture content with the traditional measurement method, in the corresponding moisture content stage, the absolute error between viscoelastic creep strains is small (the error value is between -0.0025 and 0.0056), but the relative error is large and decreases continuously with drying progress. The average relative error at the end of drying is 20.1%. This indicates that the traditional method has low accuracy in measuring viscoelastic creep strain, and the optimized measurement method, which compensates for the deformation caused by changes in moisture content during the viscoelastic creep recovery stage, can effectively improve the accuracy of viscoelastic creep measurements at various stages of the drying process.
2. During the drying of the test material, the plastic deformation and moisture content of the test material at various stages of drying are restored using the soaking and steaming method. The lower the moisture content, the more difficult it is to restore the size of the test material. Compared with the traditional measurement method, the optimized measurement method for mechanical adsorption creep strain of the test material, which is based on the size after free shrinkage calculated from the relationship between the free shrinkage coefficient and moisture content, has a minimum average relative error of 59.1% at the end of drying. The relatively large error indicates that the traditional method for measuring mechanical adsorption creep strain has low accuracy, making it difficult to ensure precise measurement of mechanical adsorption creep strain during the drying process of the test material.
3. The optimized measurement method can improve the accuracy and efficiency of the wood drying process and reduce the deformation and defects during the drying process. In the future, it can be further combined with advanced detection technologies and data analysis methods to achieve real-time monitoring and accurate prediction of creep strain.

ACKNOWLEDGMENTS

This work was financially supported by the Science and Technology Project of Henan Province (222102110205), Key research Project of higher education institutions in Henan Province (23A520034).

REFERENCES CITED

Alrubaie, M. A. A., Lopez-Anido R. A., Gardner, D. J., Tajvidi, M., and Han, Y. (2020). "Modeling the hygrothermal creep behavior of wood plastic composite (WPC) lumber made from thermally modified wood," *Journal of Thermoplastic Composite Materials* 33(8), 1109-1124. DOI: 10.1177/0892705718820404

Fu, Z. Y., Zhao, J. Y., and Cai, Y. C. (2014). "Calculation and analysis of strain caused by abnormal direction of dry shrinkage of tree plate," *Engineering Science of China* 16(04), 25-29.

Fu, Z. Y., Zhao, J. Y., Yang, Y. L., and Cai, Y. C. (2016). "Variation of drying strains between tangential and radial directions in Asian white birch," *Forests* 7(3), article 59. DOI: 10.3390/f7030059

Li, A. X., Lu, J. X., and Jiang, J. L. (2017). "Progress in wood cell wall structure and its rheological properties," *Forestry Science* 53(12), 136-143. DOI: 10.11707/j.1001-7488.20171215

Lin, C. Y., and Lin, S. R. (2021). "Investigating the accuracy of ultrasound viscoelastic creep imaging for measuring the viscoelastic properties of a single-inclusion phantom," *International Journal of Mechanical Sciences* 199(1), article ID 106409. DOI: 10.1016/j.ijmecsci.2021.106409

Liu, J. L., Yang, C. X., and Wang, S. H. (2010). "Analysis of the physical and mechanical properties of the enhanced-heat-treated eucalyptus wood," *Wood Processing Machinery* 21(03), 1-4. DOI: 10.3969/j.issn.1001-036X.2010.03.001

Liu, J. B. (2018). *Research on Mechanical Adsorption Creep of Birch in a Wide Temperature Range*. Zhejiang A&F University.

Mazzanti, V., and Francesco, M. (2020). "A review of wood polymer composites rheology and its implications for processing," *Polymers* 12(10), article 2304. DOI: 10.3390/polym12102304

Zhan, J. F., Gu, J. Y., and Cai, Y. C. (2009). "Dynamic mechanisorption properties of the conventional drying process of larch plates," *Journal of Beijing Forestry University* 31(02), 108-113. DOI: 10.3321/j.issn:1000-1522.2009.02.017

Zhu, X. D., Zhao, J. Y., Gao, W. H., Qian, C., Duan, Y. J., Niu, S. C., and Cai, Y. C. (2021). "Laws governing free and actual drying shrinkage of 50 mm thick Mongolian Scotch pine timber," *Forests* 12(11), article 1500. DOI: 10.3390/f12111500

Article submitted: May 21, 2024; Peer review completed: July 4, 2024; Revised version received: July 15, 2024; Accepted: July 17, 2024; Published: July 22, 2024.
DOI: 10.15376/biores.19.3.6339-6354