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# Effects of microwave pretreatment on drying of 50 mm-thickness Chinese fir lumber

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## Abstract

Low permeability of wood causes problems during drying of timber. This study evaluated the effects of microwave (MW) pretreatment on the conventional drying behavior and mechanical damages of Chinese fir lumber. MW pretreatment of lumber was performed at applied MW energy of 43 kWh/m<sup>3</sup>, and then, the samples were dried in a laboratory drying kiln. The results showed that the drying rate was effectively increased after MW pretreatment. The moisture content (MC) deviation in thickness and residual stress indexes of MW-pretreated samples were significantly decreased in comparison with the control samples, and the appearance quality of wood samples was not clearly affected by the MW pretreatment. Scanning electron microscope (SEM) micrographs demonstrated that pit membranes were damaged after MW pretreatment, and the micro-cracks in radial section as well as detachments between ray parenchyma cells and tracheids were also observed. Consequently, new pathways for moisture migration during drying process were formed after MW pretreatment, which contributed to the improved permeability of Chinese fir lumber and decreased drying time.

**Keywords:** Microwave pretreatment, Chinese fir, Drying rate, Permeability

## Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is one of the most important plantation species in China. It has been widely used in timber construction and manufacturing of bridge, boat, and furniture [1]. However, the large proportion of heartwood and low permeability of Chinese fir causes problems during drying process, such as long drying times, high energy consumption, and a number of drying defects, which seriously restrict its high efficient utilization.

Wood permeability reflects the easiness with which a fluid moves inside the wood under a given pressure gradient. The wood permeability is influenced by the conditions of cell tissues, chemical components, and physical properties of wood, and conditions of cell tissues are the most important factors [2]. In softwood, bordered pit is the primary structure that governs the permeability [3, 4]. Pit aspiration, pit occlusion with extractives, and pit

incrustation are effective in reducing the capillary size of the pit pairs [5]. Increasing the radius and the number of pit membrane openings can improve the permeability of wood; thus, making the wood easier to dry and impregnate [6]. Furthermore, the fluid flow inside softwood includes three primary pathways. In longitudinal direction, fluid moves through the tracheid lumen, pit aperture, and pit membrane pores [4, 7, 8], while in the tangential direction, fluid flow is primarily through tracheids and intertracheid bordered pits [3, 8], and the ray tracheids are regarded as the main radial pathways [9, 10]. Therefore, it could be an effective way to facilitate fluid flow in different pathways to achieve good permeability improvement.

Microwave (MW) treatment is an effective method to increase wood permeability [11, 12]. The MW energy vaporizes the water in wood rapidly during the treatment and the increasing steam pressure causes varying degrees of damage to each cell tissue of wood. Pit membranes, ray cells, tyloses, and even main cell walls are ruptured to form new pathways for moisture migration, which lead to increased permeability and create favorable conditions

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for wood drying, wood functional improvement, and new material preparation [13, 14]. Different degrees of MW modification depend on the process conditions and MW process parameters. With the increase in MW energy, the wood permeability increases and mechanical properties decrease [15]. Low degree of MW modification accelerates the drying rate and does not significantly affect the wood mechanical properties [15, 16]. Meanwhile, drying defects (surface and internal checks; collapse) are reduced with the decrease in drying stress [15, 17, 18]. The increased permeability makes moisture move faster during the drying process, ensuring that the evaporative front is maintained at the wood surface for a long time and moisture gradient is reduced in the thickness direction, thereby decreasing the drying stress. Therefore, MW pretreatment is a proven way to reduce the drying time and drying degradation of refractory wood. However, previous studies have usually concentrated on the MW pretreatment for rapid drying of hardwood; the MW pretreatment of softwood was seldom reported in literature.

In this study, Chinese fir lumber was treated with MW radiation before conventional drying. The effects of MW pretreatment on drying time, drying rate, drying quality, and moisture diffusion were investigated. Scanning electron microscope (SEM) observations were conducted to investigate the occurrence of mechanical damages of cell tissues of wood via MW pretreatment. The results can provide a theoretical and technical support for rapid drying and high-value utilization of Chinese fir.

## Materials and methods

### Sample preparation

Chinese fir logs with 24 cm diameter at breast height were procured from Ya'an of Sichuan province, Southwest part of China. The basic density and oven-dry density of this wood species were 0.33 g/cm<sup>3</sup> and 0.37 g/cm<sup>3</sup>, respectively. Lumber with dimensions of 900 mm (Length) × 90 mm (Width) × 50 mm (Thickness) were sawed from the heartwood region of these logs. Prior to MW pretreatment, all lumbars were cut off the ends and then divided into two groups with dimensions of 300 mm (Length) × 90 mm (Width) × 50 mm (Thickness). One group was used for MW pretreatment, while the other was used as the control group. During this process, 20 mm length specimens were cut as the moisture content (MC) test pieces from 900 mm lumber length direction in order to determine its initial MC. Both groups were also divided into quarter-sawn samples and flat-sawn samples. All the samples were stored in a freezer with a temperature of − 5 °C to prevent the moisture loss. The average initial MC of the samples before MW treatment ranged from 50 to 60%.

### Microwave pretreatment

Continuous feeding MW equipment (Frequency: 915 MHz) (Manufacturer: Nanjing Sanle MW Co, WX20L-19 type) was used for wood MW pretreatment experiments (Fig. 1). The rated power of this equipment was 20 kW, and max cross-sectional dimensions of timber were 100 mm (Width) × 100 mm (Thickness). According to preliminary treatments, internal checks could occur in Chinese fir lumber when the applied MW energy per unit volume of wood was higher than 43 kWh/m<sup>3</sup>, and the mechanical properties of lumber could be significantly decreased. Therefore, the MW energy of 43 kWh/m<sup>3</sup> was chosen for MW pretreatment of Chinese fir lumber in this study, with the aim to reduce drying time without decreasing the quality of dried lumbars. The corresponding parameters of MW power, processing time, and conveyor speed were set as 15 kW, 92 s and 1.3 m/min. In order to prevent the steam pressure inside the wood from leaking quickly along the longitudinal direction, the ends of samples were sealed with epoxy resin before the MW pretreatment. 20 replicas were considered for MW pretreatment, of which the half were quarter-sawn samples, while the other half were flat-sawn samples. The weights of the samples were measured to determine the moisture loss before and after MW pretreatment. The MC decrease after MW pretreatment ranged from 1.2 to 2.5%.

### Drying procedure

Following MW pretreatment, 12 wood samples (6 quarter-sawn samples; 6 flat-sawn samples) with their respective control pairs, totaling 24 samples were dried in a laboratory drying kiln (Type: HD74/TAII. Manufacturer: HILDEBRAND Co, LTD. Japan). The drying schedule is listed in Table 1. The preheating stage and the final treatment last for 10 and 6 h, respectively. 6 random samples (3 quarter-sawn samples; 3 flat-sawn samples) with their respective control pairs were selected to record the MC change during drying process.

The appearance quality of wood samples after drying was analyzed as per China National Standard (Drying quality of sawn timber, GB/T 6491-2012), which is similar to the quality testing method for kiln samples (Chapter 6) [19]. Then, the test pieces were cut for measuring the final MC, MC deviation in thickness, and residual stress index. The cutting schematic of the samples is shown in Fig. 2.

Final MC was determined by oven-dry method using the specimens cut from each sample. As shown in Fig. 3a, the layered MC specimens were divided into thin slices in the thickness direction. The No. 1 and No. 5 slices were surface layers and No. 3 was the center layer. MC



**Fig. 1** WX20L-19 continuous feeding MW equipment

**Table 1** Drying schedule for 50 mm-thickness Chinese fir lumber

Drying stage	Dry bulb temperature (°C)	Wet bulb temperature (°C)
Preheating stage	65	64
MC > 25%	60	54
MC ≤ 25%	72	58
MC ≤ 8.5% (Final treatment)	80	76

deviation in thickness  $\Delta MC_d$  (%) could be calculated using Eq. 1:

$$\Delta MC_d = MC_c - MC_s, \quad (1)$$

where  $MC_c$  and  $MC_s$  are the MC of center layer (No. 3) and the average MC of surface layers (No. 1 and No. 5) (%), respectively.

The residual stress index of lumber was determined using the prong test method. The cutting lines were drawn on the stress specimens, as shown in Fig. 3b. The stress specimens were cut into fork tooth shape after measuring  $S$  and  $L$ . All the prong specimens were equilibrated in room conditions for 24 h to obtain evenly

distribution of MC throughout the specimens [20]. Then,  $S_1$  value was measured and residual stress index  $Y$  (%) was calculated using Eq. 2:

$$Y = \frac{S - S_1}{2L} \times 100\%, \quad (2)$$

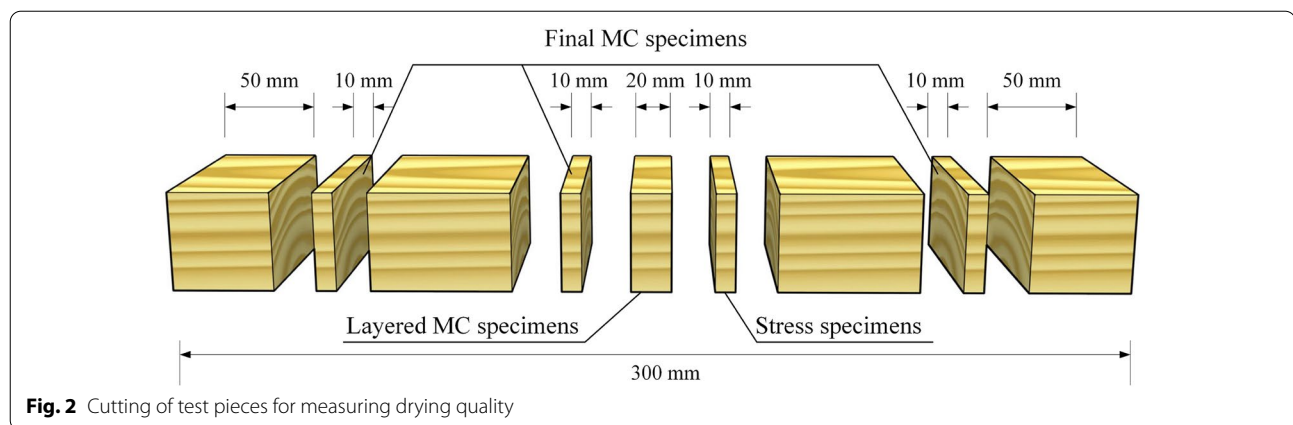
where  $S$  and  $S_1$  are the width of the fork tooth before cutting and after room equalization (mm), respectively, and  $L$  is the length of fork tooth (mm).

#### Moisture diffusion analysis

The moisture diffusion coefficient represents the rate of moisture migration through wood. The following equation was used to describe the falling rate period ( $MC < \text{fiber saturation point}$ ) in the drying process [21]:

$$MR = (M - M_e)/(M_0 - M_e) = A \exp(-kt), \quad (3)$$

where  $MR$  is the fraction of moisture content (%),  $M$  and  $M_0$  are the moisture content at time  $t$  and time  $t=0$  (%),  $M_e$  is equilibrium moisture content (%),  $A$  is a constant,  $k$  is the drying rate constant ( $s^{-1}$ ), and  $t$  is the drying time (s).



**Fig. 2** Cutting of test pieces for measuring drying quality

As shown in Eq. 3, a plot of  $\ln MR$  versus  $t$  was obtained. The Fick's second law of diffusion was used to perform moisture diffusion analysis according to the linear relationship between  $\ln MR$  and  $t$ . The moisture diffusion coefficient  $D_e$  ( $\text{m}^2 \text{s}^{-1}$ ) was calculated using Eq. 4 [22]:

$$D_e = \frac{kL^2}{\pi^2}, \quad (4)$$

where  $L$  is the thickness of wood sample (m) and the value of  $\pi$  is 3.14.

### SEM observation of MW-pretreated wood

In order to investigate the occurrence of mechanical damages of cell tissues before and after MW pretreatment, several 6-mm cubes were cut from the MW-pretreated and control samples. Then, specimens with standard radial surface and tangential surface were prepared for image analysis under Scanning electron microscope (SEM, Hitachi S-4800 N, Tokyo, Japan) instrument. Pits, tracheids, and ray parenchyma cells were selected for primary analysis.

## Results and discussion

### Drying test

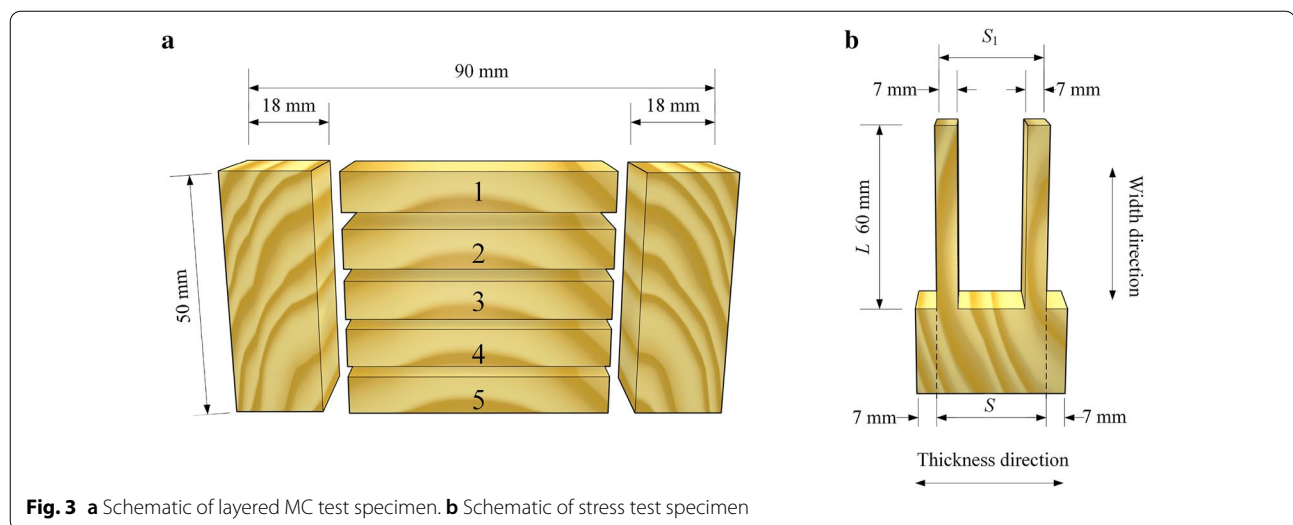
Figure 4 depicts the conventional drying curves of Chinese fir lumber. The drying time of MW-pretreated samples was shorter than that of the control samples. When the MC reached 10%, the drying time of quarter-sawn and flat-sawn samples with MW pretreatment were decreased by 9.51% and 12.61%, respectively, compared to the control group. In addition, during the preheating stage, the wood samples absorbed moisture under high humidity conditions. The MC of MW-pretreated quarter-sawn and control samples were increased by 0.68% and 0.59%, while those of MW-pretreated flat-sawn and control samples were increased by 1.27 and 0.37%,

respectively. The decreased drying time and increased moisture uptake indicate that the moisture migration during the drying process was accelerated after MW pretreatment.

Drying process can be divided into two stages, depending on whether the MC is above or below the fiber saturation point (FSP). The drying rate of wood samples in different drying stages is listed in Table 2. The results showed that MW pretreatment effectively increased the drying rate. In comparison with the control group, the drying rate (whole process) of quarter-sawn and flat-sawn samples with MW pretreatment were increased by 8.66 and 16.56%, respectively. Furthermore, the drying rate were increased in both stages, i.e., early stage ( $\text{MC} > \text{FSP}$ ) and later stage ( $\text{MC} < \text{FSP}$ ). Compared to the control samples, the drying rate in early stage and later stage of MW-pretreated quarter-sawn samples were increased by 45.14 and 11.50%, and those of flat-sawn samples were increased by 40.09 and 15.88%, accordingly. This phenomenon may be due to the MW pretreatment accelerated moisture migration during the drying process, ensuring that the evaporative front was maintained at the wood surface for a long time in early stage. While for control samples, the MC of surface layer dropped rapidly below the FSP, and the evaporative front quickly moved toward inside wood. The drying rate primarily depended on the moisture diffusion in surface layer which is much slower than free water movement. Consequently, the drying rate in early stage was greatly increased after MW treatment.

The MC and residual stress indexes of wood samples after conventional drying are listed in Table 3. The drying uniformity, MC deviation in thickness, and residual stress indexes of the MW-pretreated and control wood samples met the requirements of the 1st drying grade in accordance with China National Standard. During the drying process, the stress develops due to moisture content gradients and non-uniform shrinkage properties





**Fig. 3** a Schematic of layered MC test specimen. b Schematic of stress test specimen

of the wood [23]. The moisture gradient occurs because the moisture evaporating rate from wood surface is higher than that moving from inside wood to its surface [24]. According to Table 3, MW pretreatment improved the moisture distribution in the thickness direction and decreased the drying stress. The MC deviation in the thickness and residual stress index of MW-pretreated quarter-sawn samples were decreased by 48.06 and 42.92%, respectively, in comparison with the control samples. Those indexes of MW-pretreated flat-sawn samples were decreased by 31.79 and 48.59%. Statistical analysis revealed that these differences were significant between the MW-pretreated and control samples. A greater moisture gradient was developed in the control groups in comparison to the MW-pretreated samples. The reasons could be that the MW pretreatment accelerated the moisture movement across the grain, which contribute to reduced moisture gradient, thereby decreasing the residual stress indexes after drying.

Table 4 shows the appearance quality of Chinese fir lumber after drying. The bow, crook, cup, twist, and internal check indexes of the MW-pretreated and control samples met the requirements of the 2nd grade in accordance with China National Standard. Statistical analysis revealed that there is no significant difference in the appearance quality between the MW-pretreated and control samples, except for twist between the MW-pretreated quarter-sawn and its control samples. The results indicate that the appearance quality of wood samples was not clearly impacted by the MW pretreatment.

#### Moisture diffusion analysis

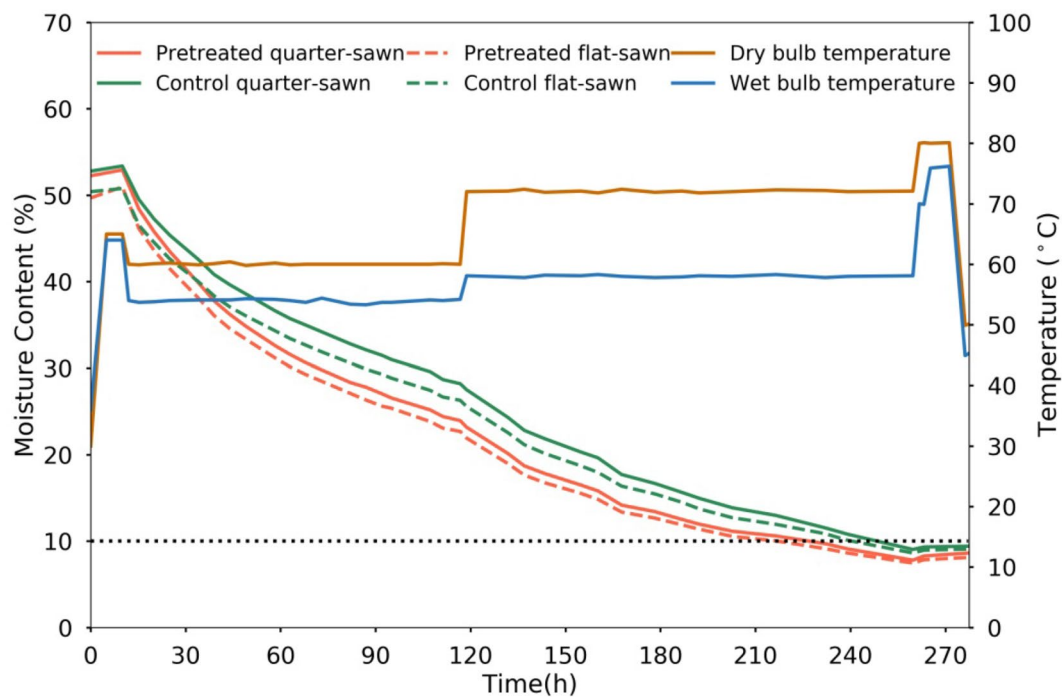
During the later stage ( $MC < FSP$ ) in conventional drying, there is no free water in the wood and the process

of moisture migration is a diffusion behavior. To evaluate the effects of MW pretreatment on moisture diffusion, the moisture diffusion coefficient of the MW-pretreated and control samples was analyzed as displayed in Fig. 5. No significant difference was found both in the quarter-sawn and flat-sawn samples with related control samples. This suggested that the MW pretreatment on Chinese fir lumber is more effective in the early stage of drying than later.

The increase in drying rate may be due to high pressure generated from fast evaporation because of high-intensity MW radiation on wet wood. The high pressure resulted in the rupture of some elements in the wood [25], such as pit membranes, ray cells, and even main cells. Thus, new pathways for moisture migration were formed, leading to an increase in wood permeability, thereby improving drying efficiency of Chinese fir lumber. Several researchers have obtained similar conclusions. The permeability and drying rate of plantation eucalyptus were effectively increased because of damage of cell tissues caused by MW radiation [26]. Zhang et al. [27] found that the MW treatment could significantly reduce the number of aspirated pits in larch wood. Pit membranes and the radial parenchyma were also ruptured which lead to increased moisture absorption and drying rate.

#### SEM images of MW-pretreated wood

The SEM images of MW-pretreated and control wood samples are displayed in Figs. 6 and 7. In general, the main pathways for tangential fluid flow in softwood are tracheids and intertracheid bordered pits, while the radial fluid flow occurs primarily through ray cells. Nevertheless, the pits of Chinese fir heartwood are usually covered with the amorphous material and most of the



**Fig. 4** Conventional drying curves of MW-pretreated and control wood samples

**Table 2** Drying rate of MW-pretreated and control samples in different drying stages

Sample	Drying rate (%/hr)		
	Early stage (MC > FSP)	Later stage (MC < FSP)	Whole process
Pretreated quarter-sawn	0.337	0.129	0.188
Control quarter-sawn	0.232	0.116	0.173
Pretreated flat-sawn	0.393	0.135	0.210
Control flat-sawn	0.280	0.117	0.180

pit membranes are encrusted. Figure 6a, b shows that the bordered pits and cross-field pits of control samples were intact and mostly occluded, which severely hindered the migration of moisture. In MW-pretreated samples (Fig. 6c, d), fine fractures were visible on the pit membranes. Hence, the radius and number of pit membrane openings were increased, which led to a faster movement of moisture through the pits; thus, the permeability in tangential direction was improved.

The transient cell wall capillary network has a great influence on the fluid flow from cell to cell. Several micro-cracks were generated in the radial cell walls of longitudinal tracheids after MW pretreatment, and the cracks mostly originated from the both ends of cross-field pit apertures (Fig. 7c). According to Muzamal, the

**Table 3** MC and residual stress index of MW-pretreated and control samples after drying

Sample	Final MC (%)	Drying uniformity (%)	MC deviation in the thickness (%)	Residual stress index (%)
Pretreated quarter-sawn	8.55	$\pm 0.54$	$1.34 \pm 0.46$	$1.29 \pm 0.44$
Control quarter-sawn	9.23	$\pm 0.87$	$2.58 \pm 1.17$	$2.26 \pm 0.85$
Sig.	—		*	*
Pretreated flat-sawn	8.02	$\pm 0.43$	$1.03 \pm 0.27$	$1.28 \pm 0.82$
Control flat-sawn	9.01	$\pm 0.62$	$1.51 \pm 0.38$	$2.49 \pm 0.88$
Sig.	*		*	*

Values of drying uniformity are standard deviations of the final MC. \* Means significant at 0.05 level, — Means not significant at 0.05 level

presence of cross-field pits in the cell walls resulted in stress concentration under steam pressure, and the resultant stress concentration promoted the formation of cracks in these regions [28]. These micro-cracks would provide new capillaries for moisture diffusion and make moisture easier to move through cell wall to adjacent cell lumen. In addition, detachments between ray parenchyma cells and longitudinal tracheids also occurred (Fig. 7d), new pathways for moisture migration were created in the radial direction and the radial permeability was improved as well [29].

Overall, MW pretreatment improved the permeability of wood in tangential and radial directions by creating new pathways for moisture migration. Therefore, the

drying time was shortened effectively. These damages are in agreement with reports from He et al. [30]. Furthermore, the cited authors observed that this degree of MW treatment could significantly increase liquid permeability without much decrease in the mechanical properties.

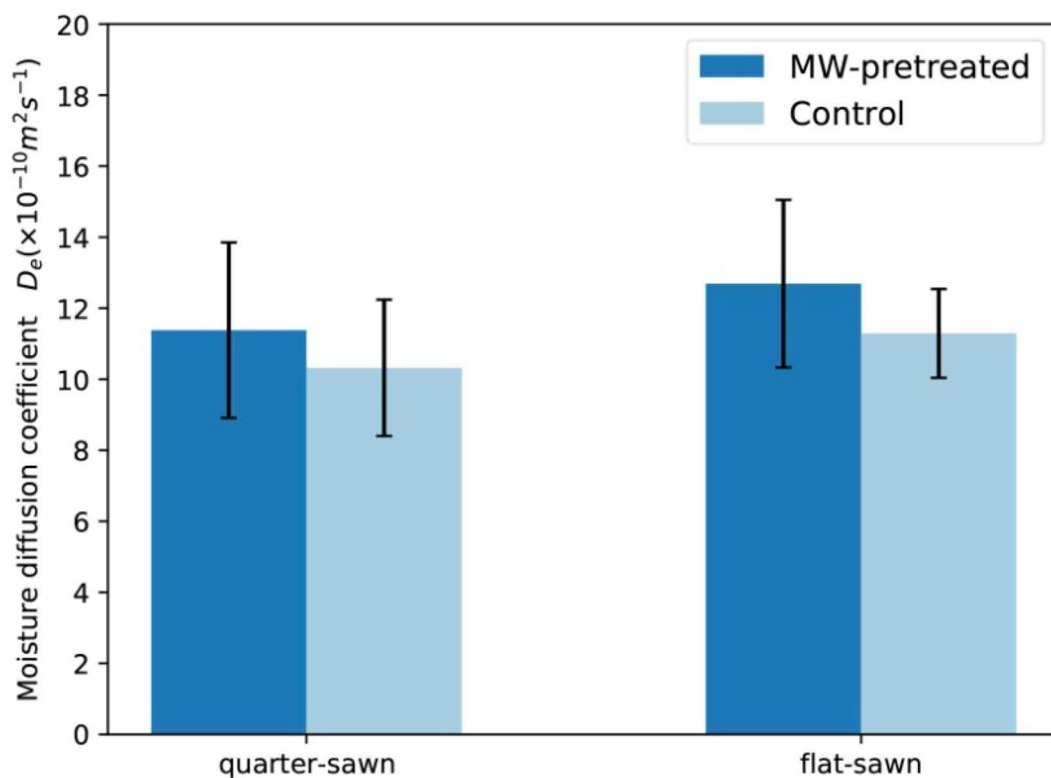
### Conclusions

MW pretreatment (applied MW energy: 43 kWh/m<sup>3</sup>) can be used for improving drying characteristics of Chinese fir lumber. Drying rate was effectively increased in conventional drying process. MW pretreatment is more effective during the early stage of drying; this stage involves the migration of free water in wood. The MC deviation in thickness and residual stress indexes of MW-pretreated

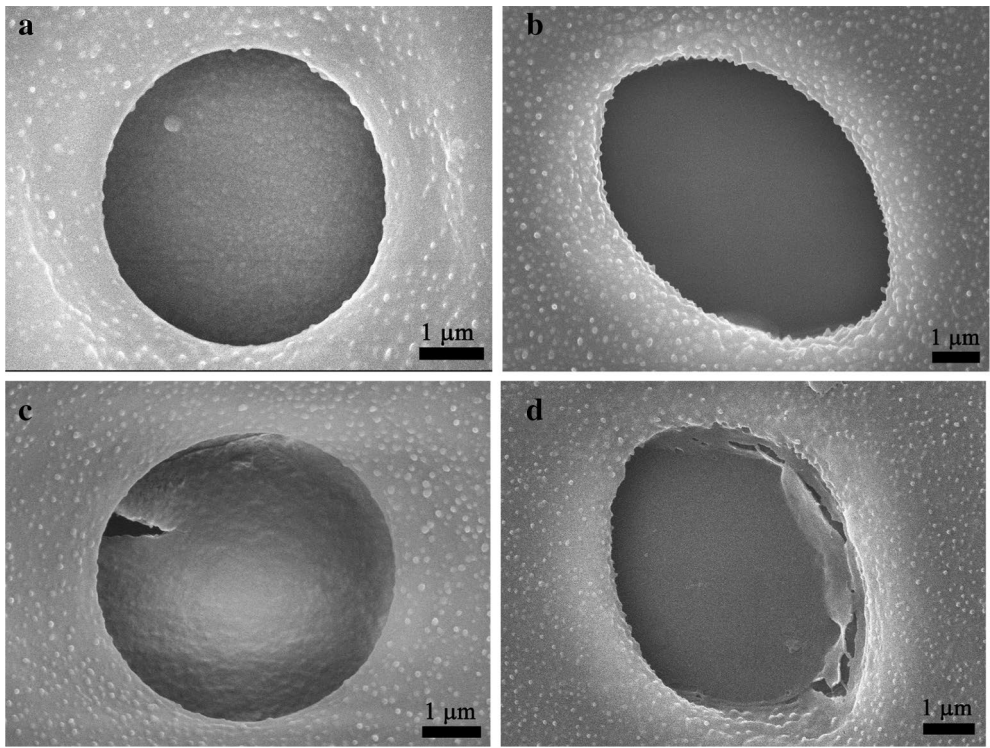
**Table 4** Appearance quality of MW-pretreated and control samples after drying

Sample	Bow (%)	Crook (%)	Cup (%)	Twist (%)	Internal checks
Pretreated quarter-sawn	0.43 ± 0.04	0.48 ± 0.04	0.10 ± 0.17	0.48 ± 0.04	No
Control quarter-sawn	0.48 ± 0.04	0.50 ± 0.07	0.23 ± 0.23	0.18 ± 0.20	No
Sig.	—	—	—	*	
Pretreated flat-sawn	0.45 ± 0.08	0.45 ± 0.05	0.58 ± 0.21	1.38 ± 0.81	No
Control flat-sawn	0.43 ± 0.05	0.47 ± 0.05	0.48 ± 0.12	1.00 ± 0.55	No
Sig.	—	—	—	—	

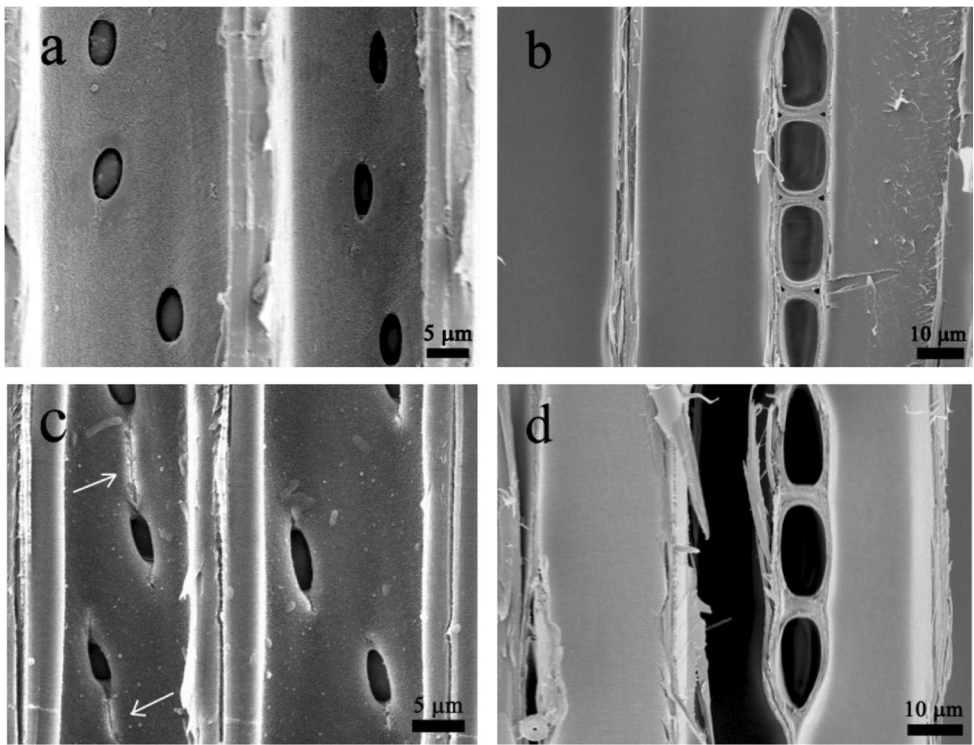
\* Means significant at 0.05 level, — Means not significant at 0.05 level



**Fig. 5** Moisture diffusion coefficient in the later stage of MW-pretreated and control samples



**Fig. 6** SEM images of wood pits: **a** bordered pit of control sample; **b** cross-field pit of control sample; **c** bordered pit of MW-pretreated sample; and **d** cross-field pit of MW-pretreated sample



**Fig. 7** SEM images of longitudinal tracheids and ray cells: **a** radial section of control sample; **b** tangential section of control sample; **c** radial section of MW-pretreated sample; and **d** tangential section of MW-pretreated sample



samples were decreased significantly in comparison with the control samples, which can improve dimensional stability during the remanufacturing of the dried timber. The appearance quality of wood samples was not clearly impacted by the MW pretreatment. MW pretreatment damaged a part of pit membranes, radial cell walls of longitudinal tracheids, as well as separated the ray parenchyma cells and longitudinal tracheids, which makes moisture easier to move during wood drying. The new moisture pathways due to MW pretreatment were likely the primary causes of the improved permeability and decreased drying time.

### Abbreviations

FSP: fiber saturation point; MC: moisture content; MW: microwave; SEM: scanning electron microscope;  $D_g$ : moisture diffusion coefficient;  $L$ : the length of fork tooth in prong test method the thickness of wood sample in diffusion coefficient calculation;  $M$ : the moisture content at time  $t$ ;  $M_0$ : the moisture content at time  $t = 0$ ;  $M_e$ : equilibrium moisture content;  $MC_c$ : the MC of center layer;  $MC_s$ : the average MC of surface layers;  $MR$ : the fraction of moisture content;  $S$ : the width of the fork tooth before cutting in prong test;  $S_1$ : the width of the fork tooth after room equalization in prong test;  $t$ : the drying time;  $Y$ : residual stress index with prong test method;  $\Delta MC_d$ : moisture content deviation in thickness of lumber.

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### Authors' contributions

XW and YZ conceived and designed the experiments. XW, ZF, XG, FZ, and JJ performed the experiments and analyzed the data. XW wrote the draft of this manuscript. YZ reviewed and edited the manuscript. All the authors read and approved the final manuscript.

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### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

### Competing interests

The authors declare that they have no competing interests.

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