J Wood Sci (2002) 48:270–276

ORIGINAL ARTICLE

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Effect of steam explosion treatments on drying rates and moisture distributions during radio-frequency/vacuum drying of larch pillar combined with a longitudinal kerf

Received: March 12, 2001 / Accepted: September 7, 2001

Abstract This study was carried out to investigate the effects of steam explosion treatment on drying rates, moisture distribution, shrinking, and checking during radio-frequency/vacuum drying of Korean larch pillar combined with a longitudinal kerf. All the pillars except the nonkerf/control with high initial moisture content (MC) could be dried within 89 h from the green condition to about 15% MC. In pillars with high initial moistures or in the early stage of drying, the drying rates were sharply accelerated by steam explosion treatments. The final moisture gradients along the transverse direction were gentler for the steam-exploded pillars and for pillars with a longitudinal kerf, respectively, than for the unexploded pillars and for pillars without a longitudinal kerf. The moisture gradients along the longitudinal direction on all the layers were gentler for the pillars with a longitudinal kerf than for those without the kerf. Formation of checking was significantly controlled in the pillars with a longitudinal kerf. All the steam-exploded pillars except the kerf/1-cycle, however, were more severely damaged by checks than the unexploded pillars. A prong test revealed an extremely low level of residual stress for all the dried pillars.

Key words Steam explosion treatment · Radio-frequency/vacuum drying · Pillar · Drying rate · Moisture distribution

Introduction

The need for timber is increasing, and large-diameter logs are in short supply. Most of the Korean larch logs produced have small diameters due to thinning, although they are dense in standing trees; the mechanical properties are good, however to expand their use, it has been recommended that they be made into pillars, or round logs. Apparently, however, Korean larch pillars have some difficulty when a conventional drying process is used, such as a long residence time and surface checking due to a steep moisture gradient because of the poor permeability of large size.

The Hertz-Knudsen equation clarifies that the vapor evaporation rate from lumber surfaces during drying in a vacuum kiln is infinite.[1] Chen and Lamb[2] reported that because the internal moisture movement is the principal factor controlling the drying rate in a vacuum kiln the drying rate during vacuum drying significantly depends on the permeability of the wood.

Steam explosion treatment has proven to be effective for improving wood permeability,[3] thereby increasing dryability.[4–6] Hayashi et al.[5] designed steam explosions based on the residence time in a treatment tank and found that the distribution of the improved dryability was not uniform in the longitudinal and transverse directions. It was highly effective for improving the permeability of a tree disk to be exploded only once after the temperatures of the shell and core within a tree disk were in equilibrium at the setting temperature.[3] It was previously reported that Korean larch pillars with a longitudinal kerf could be significantly prevented from surface checks during radio-frequency/vacuum (RF/V) drying.[6] This study was carried out to investigate the effects of two steam explosion treatments on the drying rates, moisture distribution within a pillar, shrinking, and checking during the RF/V drying process. The first explosion was to occur just after the temperatures of the shell and core within a Korean larch pillar combined with a longitudinal kerf were in equilibrium with the steam temperature of 134°C.

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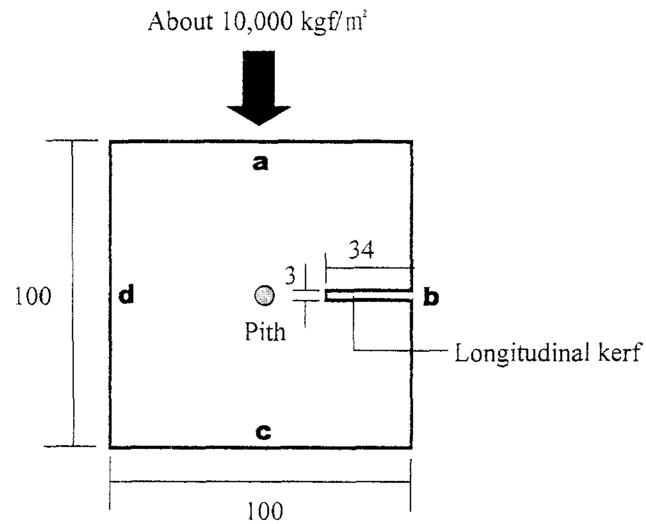

Fig. 1. Longitudinal kerfs and numbering for transverse shrinkage measurement (a–d). Unit: millimeters

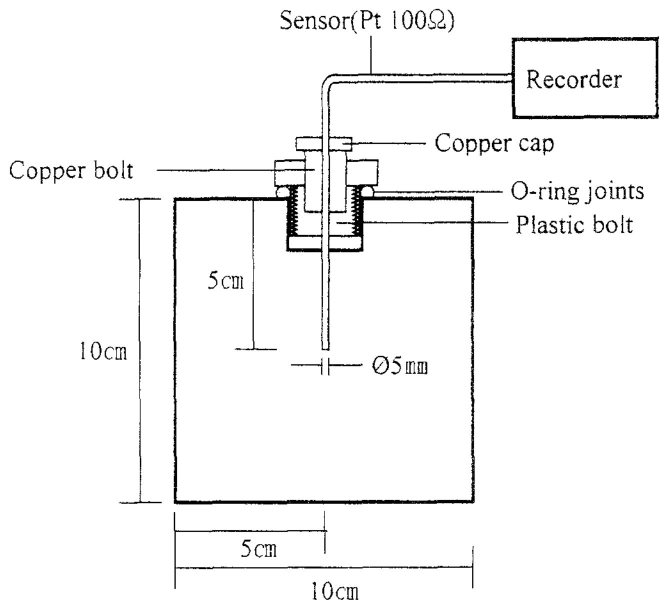

Fig. 2. Cross-sectional view of insertion of a temperature sensor into a pillar

Materials and methods

Preparation of materials

Eighteen Korean larch (*Larix gmelini* var. *principis-rupprechtii*) pillars measuring 10 × 10cm in cross section and 270cm in length with a pith were obtained from a sawmill. At 14cm from each end of the pillar, two 1cm long cross sections were cut off for measurement of green MC. The green MCs were 33.8%–63%.

The pillars were each made 240cm long for further testing. They were divided into two groups: a nonkerf group and a group with a kerf in a longitudinal direction. There were nine pillars in each group, and each group was divided into three parts: controls, those explosed to one cycle (1-cycle), and those explosed to five cycles (5-cycles), corresponding to the number of explosions in the steam tank.

The longitudinal kerf was made at a width of about 3mm and a depth of 34mm in the middle of one side of the pillar by a circular sawing (Fig. 1). At 60cm from one end, a reference line was drawn on each side of all the pillars for measuring transverse shrinkage. The lines were labeled a–d (Fig. 1), and their lengths were measured with digital calipers before and after the RF/V drying test.

Steam explosion treatment

The explosion apparatus consists of a pressure stainless steel cylinder, a leak bulb, an automatic controller, and a steam generator. The cylinder, with a removable bolted cap on one end, is 20cm in diameter and 400cm in length. The maximum pressure is 10atm of absolute pressure. To probe the wood's temperature during a steam-heating process, a Teflon-sheathed platinum temperature sensor was inserted into the center in the transverse and longitudinal directions of a pillar through an eye-bolt. A gap between the sensor and the eye-bolt was sealed by vacuum grease. The eye-bolt was tightly screwed into the pillar to avoid leakage (Fig. 2).

Table 1. Time required for a complete explosion-treatment process

Pillar	Time required for each explosion cycle (min)					
	1st	2nd	3rd	4th	5th	Total
Nonkerf						
1 Cycle	199.3	–	–	–	–	199.3
5 Cycles	192.7	13.3	14.7	23.7	15.7	260.0
Kerf						
1 Cycle	114.0	–	–	–	–	114.0
5 Cycles	119.0	7.3	8.0	7.3	8.7	150.3

The steam pressure for each explosion treatment was fixed at 3atm of absolute pressure, as recommended previously.[6] It was controlled automatically based on a steam temperature of 134°C corresponding to 3atm inside the cylinder. Each pillar for the 1-cycle explosion treatment was steam-heated until the leak bulb was manually exhausted just after the core temperature of the pillar reached 134°C. Each pillar for the 5-cycle explosion treatment was heated repeatedly for another four cycles of explosions (after the first explosion). The times required for a complete treatment process are summarized in Table 1. The pillars were weighed after each explosion test to compare the weight to the green weight.

RF/V drying process

The RF/V drying process was carried out in a rectangular vacuum chamber that was 102cm wide, 40cm high, and 274cm long. The RF generator, with an output of 7kW, was cycled "on" for 8min and "off" for 2min at a fixed frequency of 11.6 MHz. All the nonkerf pillars were stacked in the bottom layer, and all the kerf pillars were placed in the upper layer, between three aluminum electrodes. The center electrode plate was positive and connected to the RF generator, whereas the top and bottom plates were negative and grounded to the chamber itself. A mechanical pressure of around 10000 kgf/m^2 was applied to surface during the drying process; it was perpendicular to the surface of the longitudinal-kerf pillars stacked in the vacuum chamber (Fig. 1) when the top cover, which consisted of a flexible sheet of rubber, was pulled down onto the surface of the stacked lumber by the differences in absolute pressure between the inside and outside of a vacuum chamber under vacuum.[6] The ambient pressure was maintained at an absolute level of about 60–110 torr (average 85 torr). The drying temperatures during the RF/V drying test, which were 42.5°C from the beginning to 24 h, 47.5°C from 24 to 36 h, 52.5°C from 36 to 48 h, 57.5°C from 48 to 65 h, 62.5°C from 65 h to the end, were controlled automatically based on the core temperature of the pillar. A platinum temperature sensor sheathed with Teflon was inserted into one of the control pillars (no explosion treatment/no kerf) at one side 50 cm away from one end and then sealed tightly with silicone fittings. The RF noise was filtered.

The RF/V dryer was stopped at an appropriate interval to weigh each pillar to determine the MC during drying. The shrinkage of the RF/V-dried pillars was calculated based on the green length and the length at 15% MC.

After the drying test, the numbers and lengths of surface checks and end checks were evaluated on four side or end surfaces. Two 1.5 cm long cross sections were then cut at 40-cm intervals from the end toward the center along the longitudinal direction, with a total of eight sections for each pillar. These sections were used to measure the MC distributions and for the prong test, respectively (Fig. 3). The sections were cut into shell, intermediate, and core portions for measuring the MC distribution along the transverse direction. The final MCs of the pillar were obtained from the moisture distribution. These data were then combined with the initial and final weights and were used to calibrate the initial MC of the pillar. To evaluate the residual drying stress, the case hardenings were calculated using the equation $(L - l)/L \times 100\%$ from the measurements obtained through a prong test (Fig. 3B).

Results and discussion

Drying times and drying rates

Figure 4 shows, respectively, the MC of the pillars with the highest initial MC and the lowest initial MC for each treatment as a function of the drying time. All the pillars except the nonkerf/control with a high initial MC could be dried from the green state to about 15% MC of in-use moisture content for outdoor materials within 89 h. The MC of most

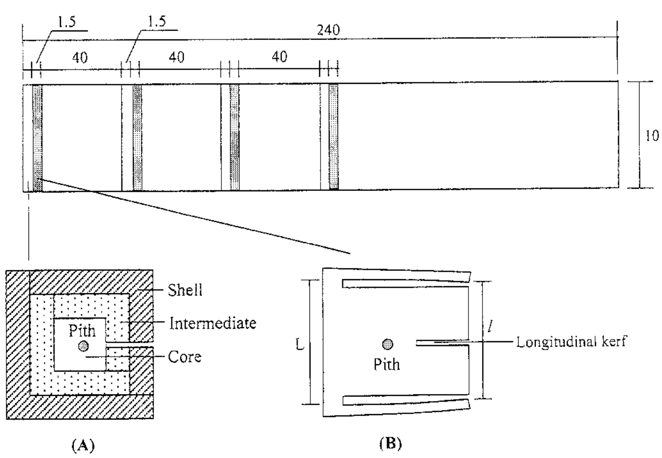

Fig. 3. Preparation of cross sections and specimens to determine the moisture distribution (**A**) and for the prong test (**B**) after RF/V drying. Unit: centimeters

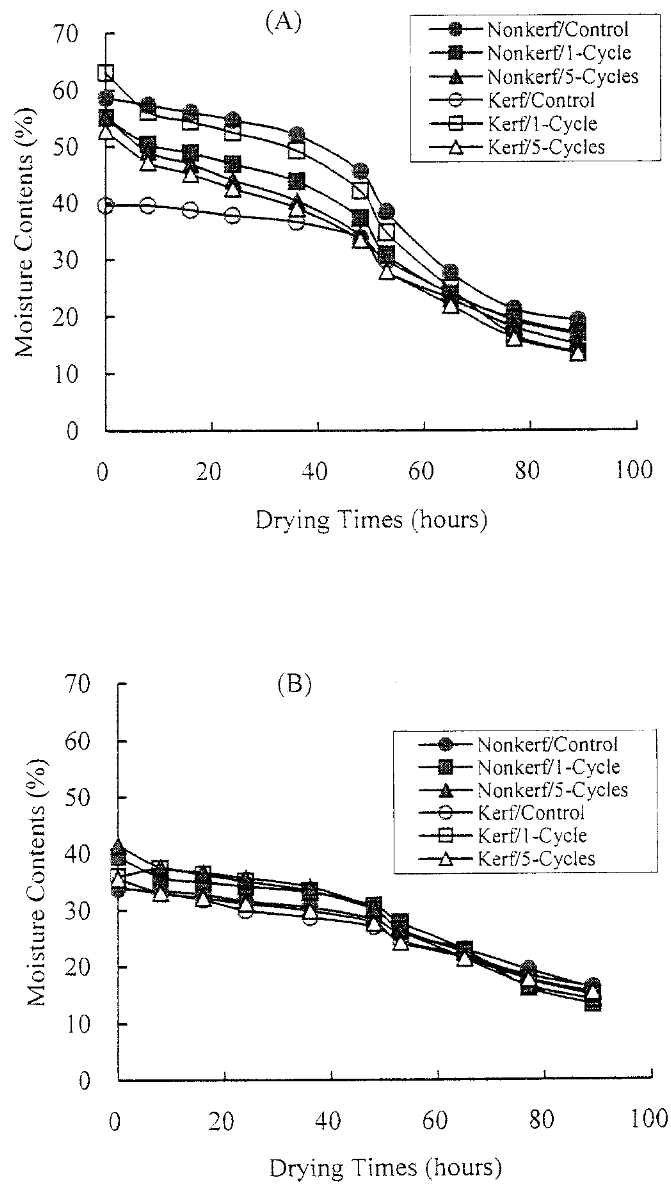

Fig. 4. RF/V drying curves for the pillars with the highest initial MC (**A**) and the lowest initial MC (**B**) among the pillars for each treatment

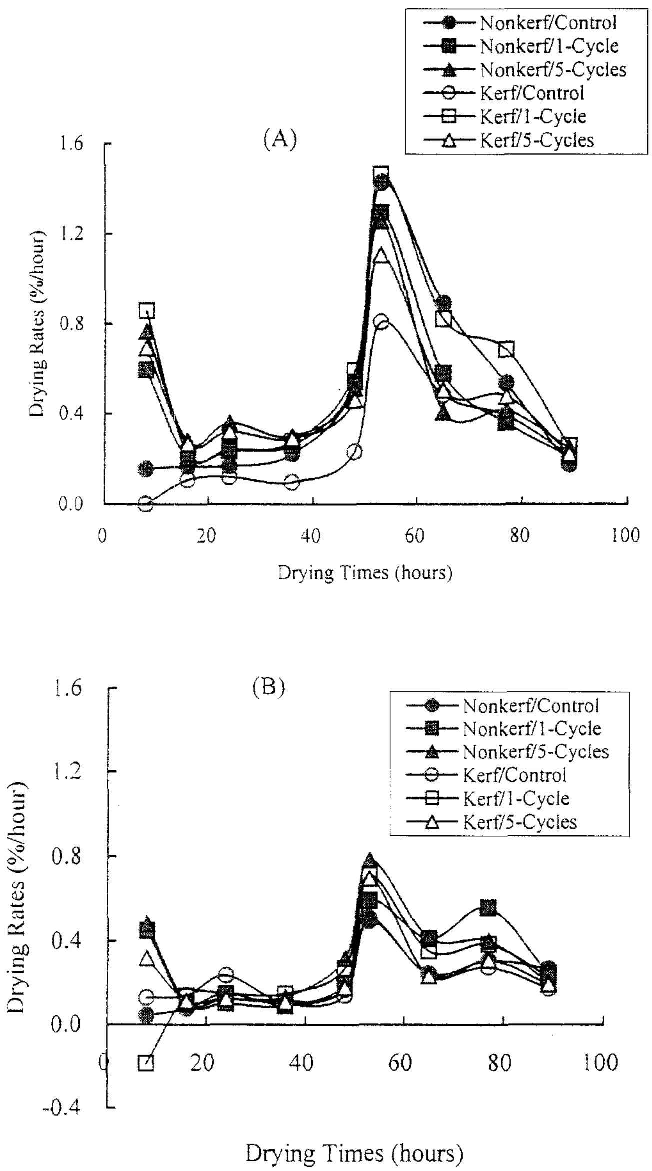

Fig. 5. RF/V drying rate curves for the pillars with the highest initial MC (**A**) and the lowest initial MC (**B**) among the pillars for each treatment

of the steam-exploded pillars could be lowered to less than 15%. The differences in final MC between the steam-exploded pillars and the untreated pillars were prominent for the pillars with high green MC and reached a maximum 5.6% MC between the nonkerf/control and the kerf/1-cycle samples and the kerf/5-cycle samples.

The drying rate data obtained from Fig. 4 are illustrated in Fig. 5. The drying rates for the steam-exploded pillars during the early drying stage were higher than those for the unexploded pillars. The drying rates for the pillars with the highest initial MC during the first 8 h of the RF/V drying run were 0.86% per hour for the kerf/1-cycle samples and 0.16% per hour for the nonkerf/control samples, respectively. The difference thus was 0.70% per hour. Among the pillars with the lowest initial MCs the nonkerf/5-cycle samples and the nonkerf/controls, respectively, were 0.48% and 0.04% per hour; the difference between them was 0.44% per hour. In conclusion the drying rates were sharply accelerated in the pillars with a high MC initially or at the beginning stage of the drying period of the steam explosion treatment.

Some previous reports[3,4] explained this by the fact that movement of free water in a cell lumen toward the surface of lumber is accelerated by improved permeability, which occurs because of opening a pit aspiration during the steam-explosion treatment. During vacuum drying, there is little external moisture movement resistance, and the drying rate, especially above the hygroscopic moisture range, is controlled by the permeability of the wood.[1] It is suggested that the drying time can be significantly shortened by explosion treatment if a sawed product largely contains sapwood, which has a high green MC, such as a log cross section, a round wood, or a pillar with a large cross section. It is thought that the zero and negative values for the drying rates, respectively, for the kerf/control in Fig. 5A and the kerf/1-cycle samples in Fig. 5B were due to absorption of the water condensed on the aluminum electrodes.

During the entire RF/V drying stage the average drying rates were 0.32%–0.36% per hour for the steam-exploded pillars and 0.24%–0.28% per hour for the non-steam-unexploded pillars. It can be concluded that the steam explosion treatment had a significant effect on increasing the average drying rate. No significant differences, however, were found between the 1-cycle and 5-cycle samples or between the kerf and nonkerf samples, although the total time required for a complete explosion process was about 34% less in the pillars with a kerf (Table 1).

The peaks in the drying rate curves occurred at 48–53 h. This pattern can be explained possibly by the water in the pillars being vaporized in large amounts because the wood temperature was increased to 52.5°C at 36 h during the drying period. This is above the boiling temperature of 48.5°C, corresponding to the average 85 torr in the vacuum dryer.

Distribution of final moisture contents

Along the transverse direction

The final MCs were lowest in the shell of each pillar and increased to a maximum level in the core of all the RF/V drying testing pillars (Fig. 6). The difference in the final MCs between the core and the shell within a pillar were small at the end surface of a pillar, whereas they rose sharply 40, 80, and 120 cm away from the end; they showed an almost plateaued gradient of 13.4%–22.9% MC for each layer. They were 5.7% at 80 cm and 5.6% at 120 cm away from the end of the nonkerf/control pillar.

The gradients of the final MCs along the transverse direction were gentler for the steam-exploded pillars and the pillars with the longitudinal kerf, respectively, than for the unexploded pillars and the pillars without the longitudinal kerf. This can be explained by the fact that moisture flows easily from the core toward the shell owing to opening a pit aspiration by the steam-explosion treatment. More-

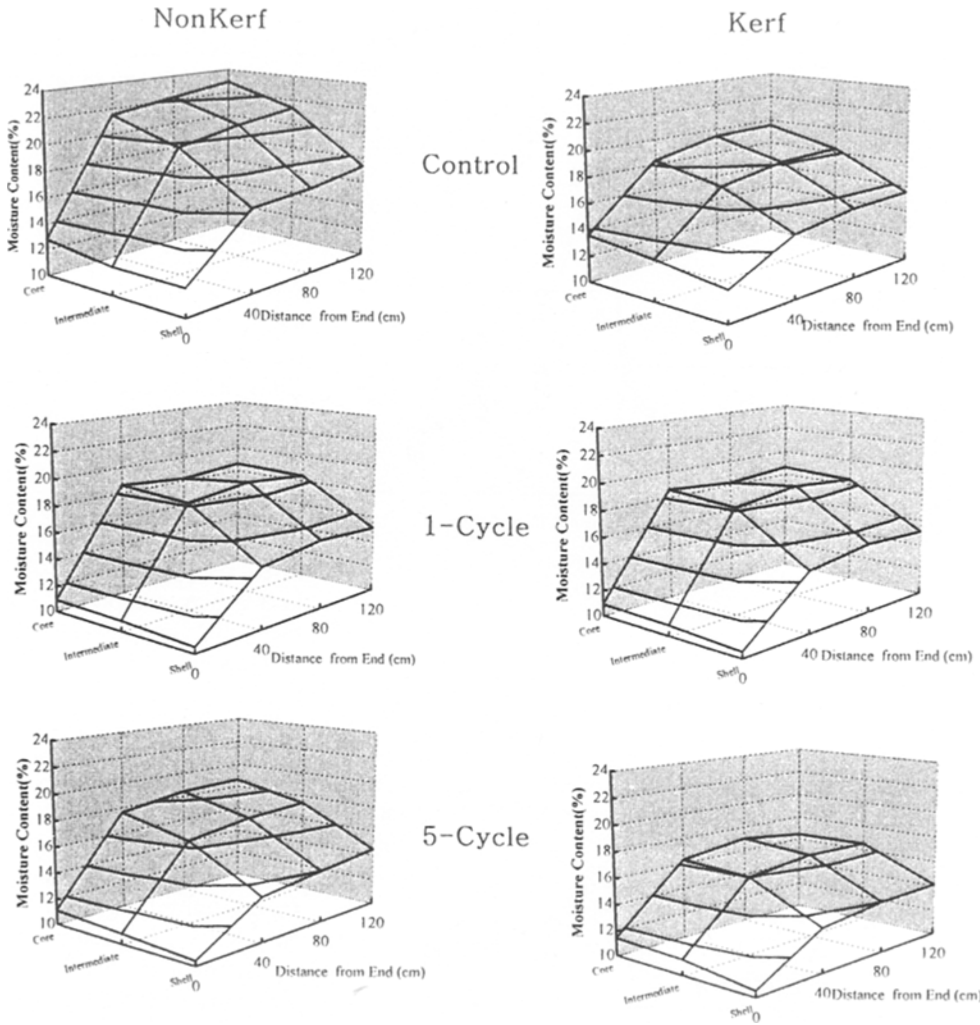

Fig. 6. Distributions of final MC in the RF/V-dried pillars

over, a longitudinal kerf provides an additional surface for vapor evaporation during drying. There was little difference between the 1-cycle and 5-cycle samples.

Along the longitudinal direction

The differences in the final MCs at the end and the center along the longitudinal direction (120 cm away from the end) were, respectively, 3.1%–5.2% in the shell layer, 5.2%–9.2% in the intermediate layer, and 5.0%–10.1% in the core layer (Fig. 6). The MCs were significantly reduced by the steam explosion treatments in pillars without a longitudinal kerf compared to the pillars with a longitudinal kerf, although the pillars without the kerf had relatively high values. It can be concluded from these results that pillars without a longitudinal kerf should be treated more severely during the explosion process (i.e., with higher vapor pressure, longer residence time in an explosion cylinder, or more explosion cycles) than pillars with a longitudinal kerf. The MC gradients along the longitudinal direction for all the layers were gentler for the pillars with the longitudinal kerf than for those without the kerf owing to evaporation of vapor from the longitudinal kerf.

Tangential shrinkage of the RF/V dried pillars

Figure 7 describes the tangential shrinkage corrected to 15% MC on the four sides (a–d) of the RF/V-dried pillars. For all the pillars without a longitudinal kerf the sum of the shrinkage on the surfaces of (a) and (c) was lower than that for (b) and (d); it was clearly reversed for all the pillars with a longitudinal kerf. Shrinkage along the perpendicular direction due to mechanical pressure was effectively restricted by a mechnical pressure of around 10 000 kgf/m^2 in a vacuum press dryer, whereas shrinkage on the other sides was facilitated by it.[7] For the pillars with a longitudinal kerf, however, shrinkage on the (b) side was low because the mechanical pressure was not high enough to restrain expansion of the kerf slot; consquently, the summed shrinkage of (b) and (d) was lower than that of (a) and (c). Compared to the unexploded pillars, the summed shrinkage of (a) and (c) for the steam-exploded pillars was slightly increased in the pillars without a longitudinal kerf, whereas it was decreased in the pillars with a kerf.

The total shrinkage amounts of (b) and (d) for the steam-exploded pillars were 18%–28% (nonkerf pillars) and 2%–22% for the (kerf pillars) higher than those for the

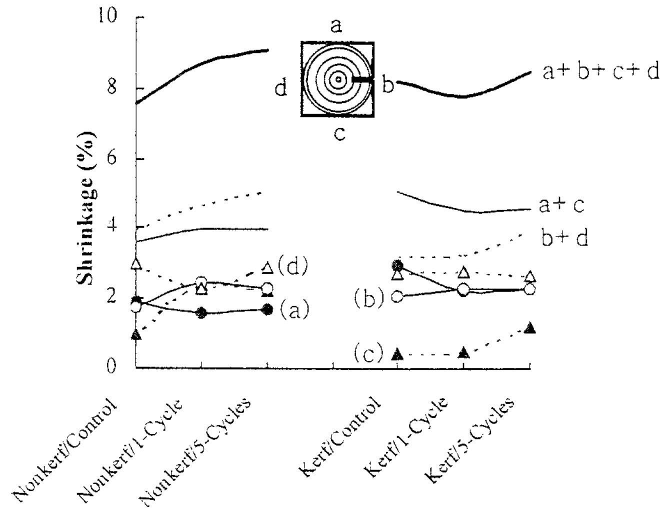

Fig. 7. Tangential shrinkage corrected to 15% MC of the RF/V dried pillars

Table 2. Formation of checking on the pillars during the RF/V drying test

Pillar	Surface check		End check	
	No.	Length (cm)	No.	Length (cm)
Nonkerf				
Control	9.7	207.4	1.7	3.9
1 Cycle	29.7	207.1	3.3	3.7
5 Cycles	24.3	216.7	0.3	0.7
Kerf				
Control	5.3	22.6	0.3	0.7
1 Cycle	0	2.9	0	0
5 Cycles	10.7	92.9	2.0	3.7

unexploded pillars. This might be related to the extractives content, microfractures on the cell wall during the explosion, or both.

Formation of surface checking and end checking

Table 2 illustrates the formation of checking on the pillars during the RF/V drying test. Numbers and total lengths of surface checks on the pillars with the longitudinal kerf were much less than those on the pillars without the kerf, as were the numbers and lengths of end checks. Longitudinal kerfs had a significant effect on reducing the formation of surface checking and end checking, which increased the appearance quality of the dried pillars. This might be because the tensile stress along the tangential direction built up on the shell of the pillar during the early drying stage by moisture gradients could be released through a longitudinal kerf.[6]

All the steam-exploded pillars except the kerf/1-cycle samples were more severely damaged by checking than the unexploded pillars. A reasonable explanation is that the tensile strength perpendicular to the longitudinal axis was decreased because of thermal degradation, and microfractures occurred in the pillars during the steam explosion treatment.

Table 3. Average case hardening of the RF/V-dried pillars

Pillar	Average case hardening of pillars, by distance from end (%)			
	0 cm	40 cm	80 cm	120 cm
Nonkerf				
Control	0	0	0.73	0.78
1 Cycle	0.71	0.49	1.46	0
5 Cycles	0	0.76	1.61	−0.14
Kerf				
Control	0	0.88	0	0
1 Cycle	−0.19	1.63	2.00	0.87
5 Cycles	−1.20	1.87	1.22	1.72

Case hardening

The case hardening of the RF/V-dried pillars is summarized in Table 3. The prong test revealed a low level of residual stress for all the RF/V-dried pillars, although moisture gradients along the transverse direction were still steep for some of the specimens cut 40, 80, and 120 cm away from the end (Fig. 6). This might be due to the set effect obtained from restrained shrinking by the mechanical pressure during the drying stage.

Conclusions

All the pillars except the nonkerf/control with high initial MC could be dried within 89 h from the green state to about 15% MC. In the pillars with high initial MC or in the beginning stage of the drying period, the drying rates were sharply accelerated by the steam explosion treatment. The final moisture gradients along the transverse direction were gentler for the steam-exploded pillars and for those with the longitudinal kerf than for the unexploded pillars and those without the kerf. The moisture gradients along the longitudinal direction on all the layers were gentler for the pillars with the longitudinal kerf than for those without the kerf. The total shrinkage on the two sides parallel to the mechanical pressure of 18%–28% for the nonkerf pillars and 2%–22% for the kerf pillars were higher for the steam-exploded pillars than for the unexploded pillars. Formation of checking was significantly controlled in the pillars with a longitudinal kerf. All the steam-exploded pillars except the kerf/1-cycle samples, however, were more severely damaged by checks than the unexploded pillars. The prong test revealed a low level of residual stress for all the dried pillars.

Acknowledgment This work was conducted by the Graduate Internship Program of Chonbuk National University, Korea.

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