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ORIGINAL ARTICLE

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Effect of compressive load on the dimensional changes of the Japanese larch dried in a radio-frequency/vacuum drier

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Abstract This study investigated the effect of a compressive load of 0.092 MPa on the dimensional changes of Japanese larch in a humidity chamber after continuous radio-frequency/vacuum drying. The dimensional changes in the loading directions were significantly increased while those perpendicular to the loading directions were decreased. The shrinkages showed higher values in continuous drying than in intermittent drying. For the specimens loaded on their tangential sections, the radial shrinkages were even higher than the tangential shrinkages; thus, the tangential/radial shrinkage ratio was decreased by 0.27. The transverse hygroscopicity was reduced for the specimens loaded on their cross sections, but increased for the specimens loaded on their tangential sections.

Key words Compressive load · Radio-frequency/vacuum drying · Dimensional changes

Introduction

The dimensional changes of wood can be divided into the initial dimensional changes, when green wood is dried to low moisture content (MC) (e.g., 12%), and the subsequent dimensional changes due to seasonal changes in the relative humidity (RH) of the surrounding atmosphere. The former changes are called shrinkage, whereas the latter are called movement.[1,2]

The shrinkage of the wood during its initial drying is closely related to drying defects. Moreover, the movement of the wood under changes in atmospheric humidity can cause many practical problems in subsequent use such as the buckling of solid flooring if it is restrained from expansion by adjacent walls. Extensive research on the dimensional changes of wood under atmospheric conditions has been conducted. Gibson[3] gave an excellent explanation of the mechanism of wood movement that occurs during the processes of adsorption and desorption. Choong[4] determined the causes of dimensional changes. Other researchers[2,5,6] further investigated the dimensional changes subjected to the mechanical stresses including moisture gradients, mechanical restraints, macroscopic tissue swelling anisotropy, and microscopic and submicroscopic anisotropy within the cell wall itself.

Some researchers[7–9] have studied the shrinkage and hygroscopicity of wood during radio-frequency/vacuum (RF/V) drying. However, there are few reports on the dimensional change, especially movement, of larch subjected to cyclic humidity changes after continuous RF/V drying with restraint from external compressive load.

The main objective of this study was to investigate the effect of a compressive load of 0.092 MPa on the dimensional changes of Japanese larch specimens in a humidity chamber after continuous RF/V drying with compressive load. The aims of this research were to effectively reduce or control the drying defects during initial drying, and to provide basic data for design of the dimensional stability of final larch products.

Materials and methods

Preparation of blocks

Four green Japanese larch (*Larix leptolepis* G.) logs with a length of 180 cm and an average diameter of 26 cm were obtained from a sawmill. Each log was first live-sawn into several flitches, and then each flitch from the central part of the log was resawn into two squares (cross section of 45 × 45 mm) from the outer section of the heartwood to minimize ring curvature. The squares were surfaced to a final

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cross-sectional size of 40 × 40 mm. One of the squares was used for compressive load and the other for load-free testing. Then an end-matched series of four blocks, each with a length of 40 mm along the grain, was cut from the surfaced square. Four blocks from each end-matched series, respectively, were used for determining shrinkage and moisture content under compressive load on the tangential section (LT), on the radial section (LR), on the cross section (RT), and under load-free condition (LF) (Fig. 1). Two reference lines, used for measuring tangential length and radial length, were drawn on the cross section, and a reference line, used for measuring longitudinal length, was drawn on the radial section of each block. Twenty-four blocks were prepared for each treatment, respectively. The average green MC of the blocks was 49.2% ± 2.6%.

Compressive-load and load-free testing

The space of a vacuum chamber for this experiment was longitudinally divided into a compressive-load part and a load-free part (Fig. 2). The blocks stacked in the compressive-load part were compressively loaded with 0.091–0.093 MPa. During evacuation of the chamber, the pressure resulting from the difference in absolute pressure between the inside and the outside of the vacuum chamber was applied to an insulation plate located underneath a flexible rubber sheet (3 mm thick) covering the vacuum chamber. The pressure was transmitted to supporting boards, a top grounded plate, and finally to the blocks stacked in the compressive-load part (Fig. 2). The top load resulting from the insulation plate, the supporting boards, and the grounded plate was considered to be negligible. The blocks in the load-free part were kept free from compressive load, by the presence of a void (24 mm in height) between the insulation plate and the top grounded plate, even when a vacuum pump was running (Fig. 2).

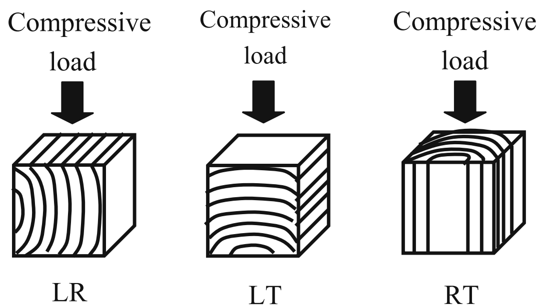


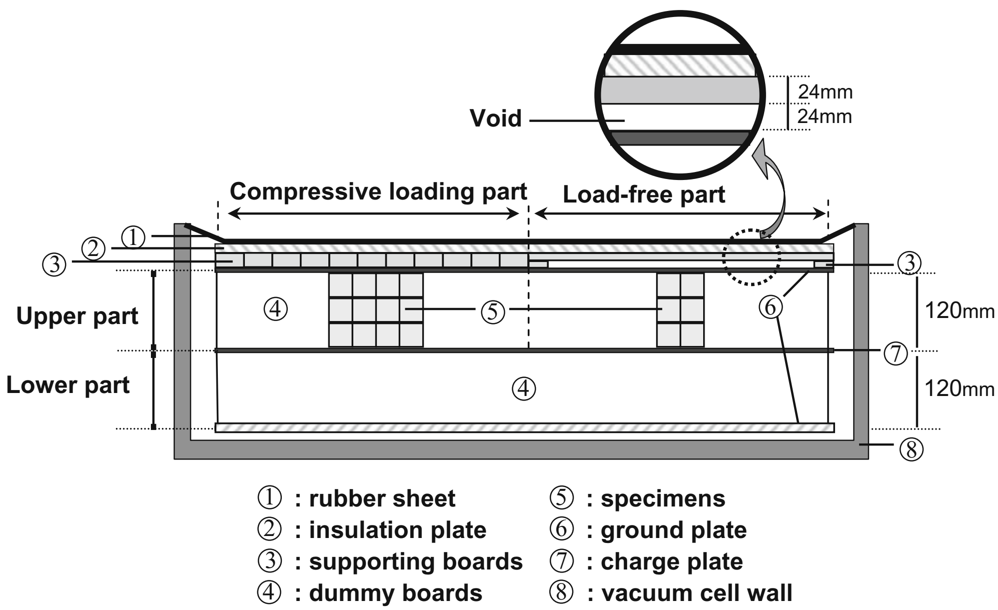
Fig. 1. Three types of compressive loading on the specimens in a vacuum chamber. *LR*, radial section; *LT*, tangential section; *RT*, cross section

Stacking of blocks

The blocks to be used for the loaded LT, LR, and RT tests were solid-stacked in three layers between an electric charge plate and the top ground plate in the compressive load part. The blocks to be used for load-free testing were also solid-stacked in the load-free part (Fig. 2). In order to be uniformly loaded during compression, the blocks to be used for the loaded LT, LR, and RT tests were alternately stacked in each column, each row, and each layer to ensure that it would be nearly identical in the total amount of the shrinkage of each column (Fig. 3). Although the amount of the shrinkage of each block in the direction of the height of the pile was definitely different, the total amounts of the shrinkages of each column (sum of the shrinkages of the three blocks) were nearly identical, because the three differently loaded blocks (LT, LR, RT) were alternately stacked in each column, each row, and each layer to ensure that each column consisted of the three differently loaded blocks.

The board with the temperature sensor was positioned in the lower part. The remainder of the space in the upper

Fig. 2. Compressive-load part and load-free part in the vacuum chamber



part and all of the lower part were filled with dummy boards.

RF/V drying and equilibration treatment

The blocks were heated by a 7-kW RF generator running at a fixed frequency of about 13 MHz for 8 min, and then off for 2 min. The center electrode plate connected to the RF generator was positive, while the top and bottom plates grounded to the chamber itself were negative. The heating temperature of wood was set at 47°C throughout heating period, and automatically monitored and controlled by a Teflon-sheathed platinum sensor inserted into a board. The heating time was 120 h. The ambient vapor pressure was lowered to an absolute value of about 50 mmHg.

The green lengths of the reference lines for the three major directions of blocks were measured by a digital vernier caliper with an accuracy of 0.01 mm. The lengths and weights of blocks were measured after continuous drying. All the blocks were oven-dried in an air-circulating oven, weighed, and the MCs of the blocks before and after drying were calculated. The shrinkages from green to final MC were calculated, and corrected to those at 11% MC (Table 1).

The RF/V dried blocks were sawn into 5-mm lengths along the grain of the blocks for an experiment of equilibrating treatment. The 5-mm-thick specimens were equilibrated at 90%, 75%, and 60% RH and 25°C. Before and after each equilibration, the tangential and radial lengths and weights of specimens were measured. The tangential and radial movements of specimens were calculated (Table 2).

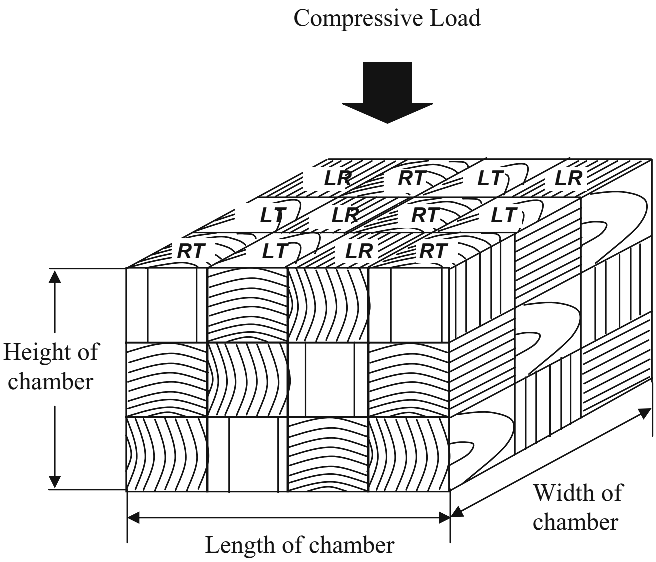


Fig. 3. Stacking of the specimens in the compressive-load part of the vacuum chamber

Results and discussion

Shrinkage

As in previous intermittent drying experiments,[10] the shrinkages in this continuous drying experiment behaved differently in each loading direction and also in the three major directions. The shrinkages in the loading directions were significantly increased because a large amount of rheological or inelastic deformation was formed by the compressive load and changing MC (Table 1).[11]

Although the compressive load of 0.092 MPa is very low compared with other research,[12,13] the hydrogen bonds holding the adjacent cellulose chains might be weaker in RF/V drying than in conventional drying because the potential energy of wood molecules could be at higher levels due

Table 1. Shrinkage from green state to 11% moisture content during radio frequency/vacuum drying

Compressive load	Shrinkage (%)					
	Tangential (T)	Radial (R)	Longitudinal (L)	T/R	T – R	T + R
Load free	5.96 (4.37)	2.69 (2.03)		2.22 (2.15)	3.27 (2.33)	8.65 (6.40)
Loaded RT	4.84 (4.13)	2.57 (1.78)	0.86 (0.33)	1.88 (2.32)	2.27 (2.35)	7.41 (5.91)
Loaded LT	4.16 (3.54)	4.63 (3.02)		0.90 (1.17)	–0.47 (0.52)	8.79 (6.56)
Loaded LR	10.83 (6.70)	1.65 (1.11)		6.56 (6.03)	9.18 (5.59)	12.48 (7.81)

Values in parentheses were obtained from intermittent drying test

Table 2. Movement at 90%, 75%, and 60% relative humidity (RH) and 25°C

Compressive load	Movement (%)								
	From 90% RH to 60% RH			From 90% RH to 75% RH			From 75% RH to 60% RH		
	T	R	T + R	T	R	T + R	T	R	T + R
Load free	2.42	0.96	3.38	1.10	0.44	1.54	1.34	0.53	1.87
Loaded RT	2.29	0.90	3.19	1.07	0.45	1.52	1.23	0.46	1.69
Loaded LT	2.70	1.21	3.91	1.27	0.57	1.84	1.45	0.64	2.09
Loaded LR	2.83	0.88	3.71	1.32	0.39	1.71	1.52	0.50	2.02

to the energy absorbed in the alternating electric field during RF/V drying. Thus, the hydrogen bonds can be easily affected by such a low level of load.[11]

On the other hand, the shrinkages perpendicular to the loading directions were decreased because of Poisson ratio effects (Table 1). The shrinkages were affected by the load: most in the tangential direction, less in the radial direction, and the least in the longitudinal direction because of the differences in mechanical strength among the three major directions, and in microscopic and submicroscopic anisotropy within the tangential and radial walls of longitudinal cells.[14]

Compared with intermittent drying, the shrinkage in continuous drying exhibited different trends. On the whole, the shrinkages showed higher values in continuous drying than in intermittent drying. This may be because more rheological deformations might be accumulated during continuous drying than during intermittent drying, due to longer loading duration and less opportunity to release the accumulated stresses in continuous drying.[15] This is similar to the situation in press drying where high pressure, long drying time, and high temperature increase thickness loss caused by creep.[16]

For the loaded LT test, the radial shrinkage was unexpectedly high, even higher than the tangential shrinkage, which might be associated with some collapses in the smallest cell-wall thickness.[17] Thus, T/R ratio and T–R difference were decreased by 0.27 and 0.99%, respectively, compared with intermittent drying (Table 1). This implies that the deformation of squares can be reduced when a compressive load is applied to their tangential surfaces during RF/V drying.

For the loaded RT test, the radial shrinkage increased more than the tangential shrinkage. Consequently, T/R ratio and T–R difference were decreased by 0.44 and 0.08%, respectively, compared with intermittent drying (Table 1). This is because the tangential expansion is greater than the radial expansion when a compressive load is applied parallel to the grain of a specimen, and the directions of the expansions are opposite to those of the shrinkages.[18] The decrease of difference between tangential and radial shrinkage can contribute to reduction in the deformation of larch woods when the compressive load is applied to their cross sections during RF/V drying.

Tangential and radial movement

From the results of other researchers,[19,20] the movement observed in this experiment can be considered a result of the accumulated mechanosorptive strain in the total restrained shrinkage strain being recovered under cyclic humidity changes. In general, the behavior of movement under humidity changes from 90% to 60% RH was similar to that of the restrained shrinkage except for the tangential movement of the loaded LT specimen (Table 2). In the direction of increased shrinkage, the movements of the loaded specimens were also larger than that of the load-free specimen. This is probably because the amount of the recovered viscous component was increased due to cyclic humidity changes and without mechanical restraint, for example, the tangential movement of the loaded LR specimen and the radial movement of the loaded LT specimen.[21] In the direction of decreased shrinkage, the movements of the loaded specimens, except the tangential movement of the loaded LT specimen, were also smaller than that of the load-free tangential and radial movements of the loaded RT specimens, and the radial movement of the loaded LR specimen.

A notable observation was that the tangential movement of the loaded LT specimen appeared to be quite high in spite of it having the lowest tangential shrinkage (Table 1). According to Mõrath[22] and Pentoney,[23] the tangential radial shrinkage in gross wood of conifers is greater by virtue of the denser latewood shrinking more than the earlywood. During drying, the tangential shrinkage was most largely restrained due to the most increased radial shrinkage under loading on the tangential section of specimen. However, during equilibration, the large tangential movement took place due to no mechanical restraint and a potential trend to dimensional change in the tangential direction under humidity changes.

Sum of tangential and radial movement

The sum of tangential and radial movements was the highest for the loaded LT specimen, and lowest for the loaded RT specimen from 90% to 60% RH (Table 2). This indicates that the transverse hygroscopicity of specimens was reduced for the loaded RT condition, but increased for the loaded LT condition due to the effect of compressive load. Thus, it is recommended that a compressive load should be applied to the log cross section in RF/V drying in order to improve the dimensional stability of final products.

Conclusions

For larch dried under external restraint with RF/V drying and equilibration of dried specimens under humidity changes, the shrinkages in the loading directions were significantly increased while those perpendicular to the loading directions were decreased. The shrinkages showed higher values for continuous drying rather than for intermittent drying. For the loaded LT specimen, the radial shrinkage was higher than the tangential shrinkage. Thus, T/R ratio and T–R difference were decreased by 0.27 and 0.99%, respectively. For the loaded RT specimen, the radial shrinkage increased more than the tangential shrinkage. Consequently, T/R ratio and T–R were decreased by 0.44 and 0.08%, respectively.

Movements in the loading directions were also all increased while those perpendicular to the loading directions, except the tangential movement of the loaded LT specimen, were all decreased. Transverse hygroscopicity was reduced for the loaded RT specimen, but increased for the loaded LT specimen.

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References

1. Stevens WC (1963) The transverse shrinkage of wood. Forest Prod J 13:386–389
2. Dinwoodie JM (2000) Timber – its nature and behavior. E&FN Spon. London, pp 58, 130–132
3. Gibson EJ (1965) Creep of wood: role of water and effect of a changing moisture content. Nature 206:213–215
4. Choong ET (1969) Effect of extractives on shrinkage and other hygroscopic properties of ten southern pine woods. Wood Fiber Sci 1:124–133
5. Skaar C (1988) Wood–water relations. Springer, Berlin Heidelberg New York, pp 153–159, 283
6. Zhou YG, Fushitani M, Kubo T (2000) Effect of stress level on bending creep behavior of wood during cyclic moisture changes. Wood Fiber Sci 32:20–28
7. Lee AWC, Harris RA (1984) Properties of red oak lumber dried by a radio-frequency/vacuum process and dehumidification process. Forest Prod J 34:56–58
8. Taniquchi Y, Nishio S (1991) High frequency power-vacuum drying of wood. IV. Comparison of physical and mechanical properties of lumber dried by several drying methods. J Jpn Wood Res Soc 37:405–414
9. Lee NH, Jung HS (2000) Comparison of shrinkage, checking, and absorbed energy in impact bending of Korean ash squares dried by a radio-frequency/vacuum process and a conventional kiln. Forest Prod J 50:69–72
10. Li C, Lee NH (2004) Effect of compressive load on shrinkage of larch blocks under radio-frequency/vacuum heating. Wood Fiber Sci 36:9–16
11. Li C, Lee NH (2008) Effect of compressive load on the moisture content of oak blocks during radio-frequency/vacuum drying. Forest Prod J 58:34–38
12. Hoffmeyer P (1993) Non-linear creep caused by slip plane formation. Wood Sci Technol 27:326–327
13. Wu Q, Milota MR (1995) Rheological behavior of Douglas-fir perpendicular to the grain at elevated temperatures. Wood Fiber Sci 27:288–289
14. Naderi N, Hernandez RE (1997) Effect of re-wetting treatment on the dimensional changes of sugar maple wood. Wood Fiber Sci 29:340–344
15. Chafe SC (1995) Predrying and continuous and intermittent drying in boards of *Eucalyptus regnans* F. Muell. II. Changes in shrinkage and moisture content during drying. Holzforschung 49:234–238
16. Tang YF, Simpson WT (1990) Perpendicular-to-grain rheological behavior of loblolly pine in press drying. Wood Fiber Sci 22: 326–342
17. Tabarsa T, Chui YH (2000) Stress–strain response of wood under radial compression. Part I. Test method and influences of cellular properties. Wood Fiber Sci 32:144–152
18. Burgert I, Okuyama T, Yamamoto H (2003) Generation of radial growth stresses in the big rays of konara oak trees. J Wood Sci 49:131–134
19. Kunesh RH (1961) The inelastic behavior of wood. A new concept for improved panel forming process. Forest Prod J 11:395–406
20. Ugolev BN (1976) General laws of wood deformation and rheological proportions of hardwood. Wood Sci Technol 10: 169–181
21. Shiraishi N, Kajita H, Norimoto M (1993) Recent research on wood and wood-based materials. Kyoto University, Japan, pp 141–145
22. Mõrath E (1932) Studien über die hygroskopischen Eigenschaften und die Hãrte der Hõlzer. Mitt Holzforsch Darmstadt
23. Pentoney RE (1953) Mechanisms affecting tangential and radial shrinkage. J Forest Prod Res Soc 32:27–32