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ORIGINAL ARTICLE

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Effect of manufacturing parameters on the linear expansion and density profile of particleboard

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Abstract Particleboards were fabricated in the laboratory with different board densities and resin contents to evaluate linear expansion when exposed to both vapor and liquid water. Density profiles were measured to determine the relation to the elastic constants and to the dimensional properties of the boards. It was found that density profiles were affected by the board density and resin content applied. The high-density layer formed in the thickness direction affected the elastic constant measurements. A model introduced to predict the linear expansion closely matched the data during exposure to water. Under conditions of 40°C and 90% humidity, linear expansion increased with increasing board density. An increase in resin content from 6% to 12% slightly increased the linear expansion and decreased the thickness swelling. A linear relation was found between board density and linear expansion per unit of moisture content change.

Key words Particleboard · Linear expansion · Density profile · Elastic constant

Introduction

When wood-based panel products are exposed to humid conditions, dimensional changes take place. Linear expansion (LE) of the board is considerably smaller than thickness swelling (TS). The practical importance of LE has increased recently as has the TS because these boards are used as longer elements than before.

Research determining the LE of reconstituted wood-based boards are not as common compared with research for TS in which the effects of board-making parameters were discussed to improve dimensional stability in the thickness direction. Furthermore, LE has been measured as additional data in the research studies where mechanical properties or other items were discussed.[1–9]

Only a few papers have dealt with LE as a main topic. Vital et al.[10] reported on LEs and TSs of flakeboard and particleboard exposed to different humid conditions. Suchsland,[11] Suchsland and Xu,[12] and Xu and Suchsland[13] focused on measuring LE and the modeling of the mechanism of LE in particleboard. There was less information on how the board-fabricating parameters affected the LE of wood-based panel products.

The objective of this study was to evaluate the effects of board density and resin content (RC) on the LE of particleboard exposed to both vapor and liquid water followed by a drying test. Density profiles and the elastic constants of the boards, affected by the fabricating parameters, were determined to explain the relation to LE.

Materials and methods

Particleboard manufacturing

Homogeneous boards, 340 × 320 × 10mm, were constructed using knife-ringflaker particles with average dimensions of 18.6mm in length, 3.7mm in width, and 0.48mm in thickness. These particles were obtained from sugi (Japanese cedar, *Cryptomeria japonica* D. Don) and had an oven-dried density of 0.39g/cm^3. The furnish was dried to a moisture content of less than 3% before gluing. Duplicate boards were made at each of five density levels (0.4, 0.5, 0.6, 0.7, and 0.8g/cm^3) and at each of four resin contents (3%, 6%, 9%, and 12% of solid weight basis). The mat moisture content before pressing depended on the RC; it was 6.4%, 9.9%, 13.3%, and 16.3% for RCs of 3%, 6%, 9%, and 12%, respectively. Boards with a density of 0.7g/cm^3 and 9% RC were made to serve as controls. Board construction factors were as follows.

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Resin: commercial liquid phenolic resin, 41% solid
Wax: not applied
Press temperature: 180°C
Pressure: 3.5MPa
Total press time: 7.5min
Surface: not sanded

The closing time depended on the board density. It was approximately 15 and 50s for $0.4\,g/cm^3$ and $0.8\,g/cm^3$ boards, respectively.

Mechanical properties

The manufactured boards were trimmed to 300 × 300mm square and tested for flexural stiffness (Eb) and plate shear modulus (G) without failure. These elastic constants were additionally tested with a vibration method using a fast Fourier transform (FFT) analyzer for checking the constants obtained with static tests. The *Eb* and *G* values were determined from the peak frequency of the power spectrum of the tone by tapping the edge of the specimen.[14]

Boards were cut to 300 × 50mm for the dimensional stability tests. Three kinds of Young's moduli (*E1*, *E2*, *E3*) of each specimen were also determined by the vibration method. *E1*, *E2*, and *E3* were elastic constants obtained using the flatwise bending vibration, the edgewise bending vibration, and the longitudinal vibration methods, respectively. These constants were calculated as follows:

$$E1 \text{ and } E2 = 48\pi^2 L^4 \rho f^2 / \left(h^2 m^4\right)$$
$$E3 = 4L^2 \rho f^2$$

where L is the length, ρ is the density of the specimen, and h is the height of the beam vibrating. For *E1* measurements h was the thickness of the specimen, whereas for *E2* measurements it was the width; f is the peak frequency, and m is the constant (4.730 for first vibration mode).[15]

Density profile

Density gradients in the thickness direction of the specimens were measured using a commercial density profiler based on a gamma radiation system. Specimens with dimensions of 50 × 50mm were used, and the measurement was made at 0.1-mm intervals.

Dimensional change

Prior to testing, all specimens, each 50mm wide and 300mm long, were conditioned in an air-circulating chamber at 60°C for 24h to obtain constant moisture conditions and initial dimensions. Three samples were selected randomly for each test: (1) exposed to vapor at 40°C and 90% relative humity (RH; humidity test); and (2) immersion in liquid water at room temperature (immersion test). After reaching saturation in each test, the samples were dried to equilibrium in the chamber at 40°C. It was not sealed so moisture could move through the faces and edges. The length, thickness, and weight of the specimens were measured at certain intervals during both the humidity and the immersion tests.

Linear expansion (LE), thickness change (TS), and weight change (WA, or water absorption) were calculated on the basis of the initial dimensions. LE was determined by measuring the length of the specimen to the nearest 0.01mm using equipment according to ASTM.[16]

Results and discussion

Mechanical properties

Bending stiffness *Eb* and plate shear modulus *G* obtained by the nondestructive static tests are listed in Table 1. These elastic constants increased with increasing board density and resin content. Similar results were reported by Kelly.[17] Elastic constants of 300 × 50mm specimens obtained by the vibration methods are shown in Fig. 1, where all of the constants increased with increasing density.

E2 and *E3* showed a similar increasing trend against the board density. These two constants were thought to represent an average elastic constant throughout the thickness of the board: *E3* was based on the longitudinal vibration of the specimen and *E2* on the edgewise in-plane bending vibration. In this edgewise vibration, the ratio of length to height of the beam, 300:50, was not enough to eliminate a shear effect of the beam. This may be one reason that the *E2* value was lower than the *E3* value for all the board densities tested in this experiment. The *E1* value, obtained by the out-of-plane bending vibration, was close to *E3* at a density of $0.4\,g/cm^3$, but it became almost the same value as *E2* when the board density was $0.8\,g/cm^3$. It was shown that the higher density the board, the relatively lower was the *E1* in the elastic constant measurements. This could be due to the effect of layer construction of the board.

Figure 2 shows the relation between RC and the elastic constants. In the RC range of 6%–9%, *E1* obtained by the flatwise bending vibration increased remarkably, although *E2* and *E3* showed only slight increases. The same consideration mentioned above – that *E1*, *E2*, and *E3* depend on the

Table 1. Elastic properties obtained by static tests and thickness after hot pressing

Target board density (g/cm^3)	RC (%)	Thickness (mm)	*Eb*[a] (GPa)	*G*[b] (GPa)
0.4	9	9.99	1.12	0.58
0.5	9	9.96	1.71	0.87
0.6	9	9.91	2.18	1.13
	3	10.5	1.63	0.84
0.7	6	9.99	2.56	1.19
	9	9.78	2.70	1.42
	12	9.62	3.59	1.56
0.8	9	9.75	3.49	1.55

RC, resin content; *Eb*, flexural stiffness; *G*, plate shear modulus.
[a] Modulus of elasticity obtained by the static bending test.
[b] Modulus of rigidity obtained by the static plate shear test

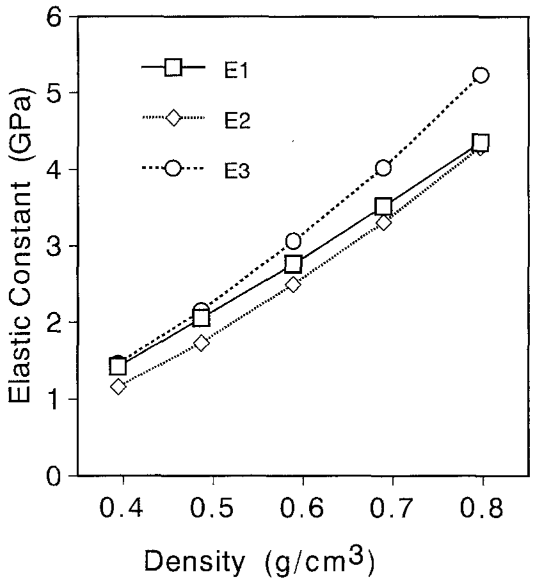

Fig. 1. Effect of board density on the elastic constant determined by vibration methods. *E1*, flat-wise out-of-plane bending vibration; *E2*, edge-wise in-plane bending vibration; *E3*, longitudinal vibration

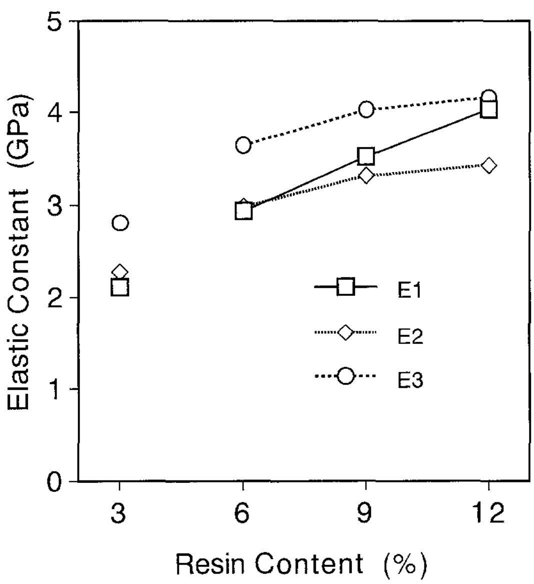

Fig. 2. Effect of resin content on the elastic constant determined by vibration methods

layer structure – can be seen in the behavior shown in Fig. 2. The elastic constants at 3% RC were excluded from this analysis because the appearance of the board with 3% RC was somewhat different from the others; that is, its spring-back after pressing was larger than that of the other boards as shown in the thickness data in Table 1.

Density profile

The density gradients in Fig. 3 shows the many density measurements obtained for samples with different average

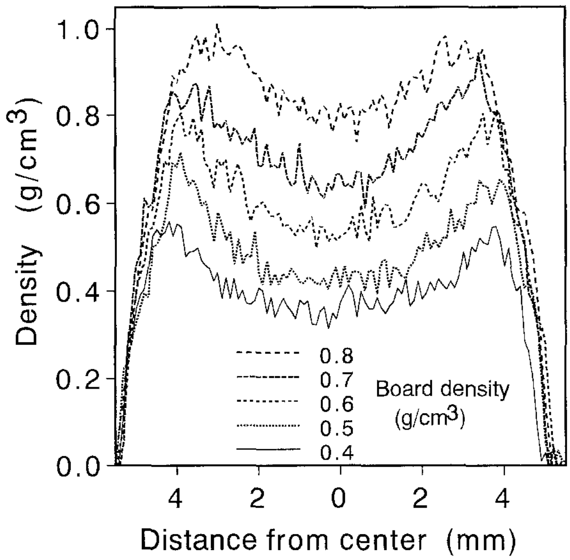

Fig. 3. Effect of board density on the density profile of particleboard

board densities. The results showed a typical density gradient for particleboard[18] with high density layers just inside the board surfaces.

It was found in Fig. 3 that the high-density layer moved toward the inner layers with increasing board density. Polynomial regressions of the density data confirmed this result. It revealed that the peak density was located at around 0.6 mm inside the surface for a 0.4 g/cm^3 board and at 1.1 mm for a 0.8 g/cm^3 board.

The location of the high-density layer affected the elastic constant *E1* because the *E1* measurement was based on an out-of-plane bending vibration. It was obvious that a high-density layer located on the outer layers in the board gives higher bending stiffness rather than that located on the inner layers. Thus the behavior of *E1* shown in Fig. 1 can be explained qualitatively by the fact that the high-density layer shifted into the inner layers as the board density increased.

Figure 4 also shows the density gradients of the same average density boards fabricated with various resin contents. No high-density layer was found in the 3% RC board. Low RC and low mat moisture content were thought to be the reasons a high density layer was not formed in this kind of board during hot pressing.

In the RC range 6%–12%, the position of the peak density seemed to shift outward and the peak density itself became larger when the RC of the board increased. This fact of layer construction of the board, which was confirmed by eighth-order polynomial regression, was reflected by the elastic constant measurements as shown in Fig. 2. This was the main reason that *E1* behavior was different from *E2* and *E3*.

Dimensional changes

Using the specimens with the density profiles and elastic characteristics mentioned above, linear changes and thick-

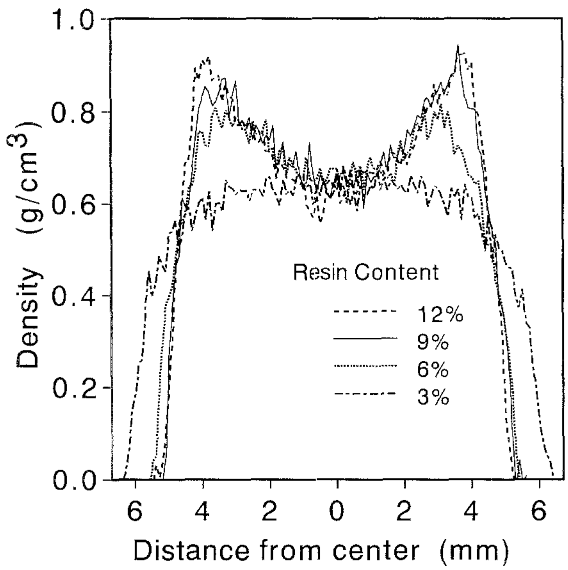

Fig. 4. Effect of resin content on the density profile of particleboard

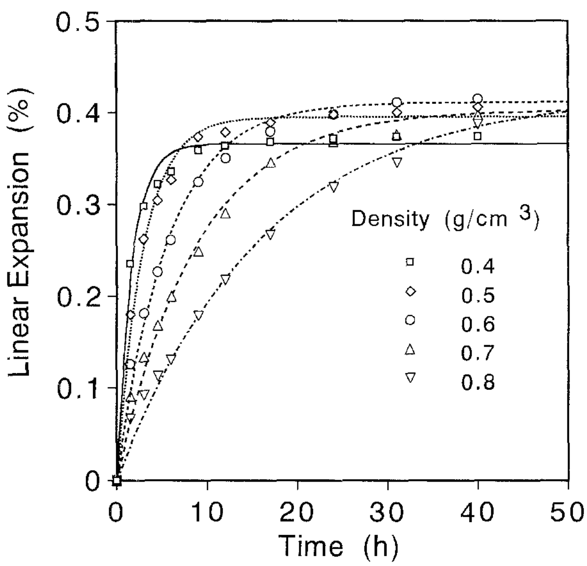

Fig. 5. Linear expansion behavior of particleboard at different densities under humid conditions at 40°C and 90% relative humidity (RH)

ness changes were determined to evaluate the effects of the board-fabricating factors of density and RC.

Effect of board density on LE

The linear expansion behavior of the boards with various densities during the humidity test at 40°C and 90% RH is shown in Fig. 5. Measurements were continued until the equilibrium at which weight change occurred at less than 0.1% per 24h was reached. Figure 5 shows the LE changes of the first 50h within the total measurements made up to 210 hours.

Table 2. Coefficient β for LE and TS changes in the humidity test

Board density (g/cm^3)	β(h)	
	LE	TS
0.4	1.69	8.10
0.5	2.89	12.7
0.6	5.63	16.4
0.7	8.74	23.9
0.8	16.2	40.1

LE, linear expansion; TS, thickess swelling; β, rate of increase

Linear expansions for all the boards increased rapidly at the beginning of the humidity test and leveled off toward saturation values. The LE of the lowest density board, $0.4 g/cm^3$, seemed to reach its saturation value at around 10h, whereas the LE of $0.8 g/cm^3$ board was still increasing after 50h. Figure 5 also shows that the larger the board density, the higher is the saturation LE value; and the more time is required to reach it.

For evaluating the LE change versus exposure time, the exponential equation that had been used for describing thickness changes of particleboard or medium-density fiberboard (MDF)[19,20] was employed:

$$T = \alpha\left[1 - \exp(t/\beta)\right] \quad (1)$$

where T is linear expansion, t is time, and α and β are empirical constants. The constant α represents an estimated saturation value when t tends to infinity, and the constant β indicates a rate of increase.

The curves, which were obtained by nonlinear least-squares regression, were in good agreement with the experimental data as shown in Fig. 5. Thus it was concluded that this equation can be used for LE prediction as well as TS.

Because the constant β indicated the time until LE reaches about 63% of the saturation value, $\alpha(1 - e)$, the increasing rate of each LE curve can be compared using β. The rate of increase, β, increased with increasing density, as shown in Table 2; the β of the $0.4 g/cm^3$ board was about 1.7h, whereas that of the $0.8 g/cm^3$ board was 16.2h. As shown in Table 2, the β increased by a factor of approximately 1.8 for each $0.1 g/cm^3$ increase of the board density.

LE per unit MC change

Dimensional test results of both the humidity test and the immersion test are summarized in Table 3. The LE and WA values after reaching equilibrium at 40°C and 90% RH are shown in this table. It was obvious that LE increased with increasing density according to moisture change. The WA values in the humidity test ranged from 15.3% to 16.8% and were based on the initial weights before testing. For better understanding, LE behavior was recalculated on the basis of MC change, LE/MC, instead of evaluating LE/WA.

Figure 6 shows the relation between LE/MC and board density. There was a strong linear relation between the

Table 3. Dimensional stability test results

Density (g/cm^3)	Humidity test						Immersion test					
	LE (%)		TS (%)		WA (%)		LE (%)		TS (%)		WA (%)	
	W	D	W	D	W	D	W	D	W	D	W	D
0.4	0.36	0.00	11.6	5.6	16.5	2.9	0.46	−0.13	13.6	4.1	190	−0.9
0.5	0.39	0.00	14.2	7.2	16.8	3.1	0.48	−0.16	16.7	5.8	150	−0.9
0.6	0.41	0.00	16.8	9.0	16.6	3.1	0.51	−0.18	18.6	7.6	118	−1.0
0.7	0.41	−0.01	17.0	8.9	15.5	3.1	0.50	−0.20	21.5	9.2	94	−0.6
0.8	0.43	−0.02	17.8	8.8	15.3	3.1	0.45	−0.28	22.4	9.5	70	−0.8

Humidity test: exposed to the humid condition at 40°C and 90%, relative humidity. Immersion test: water immersion at room temperature.
W, wet condition and D, dried condition at 40°C; WA, water absorption

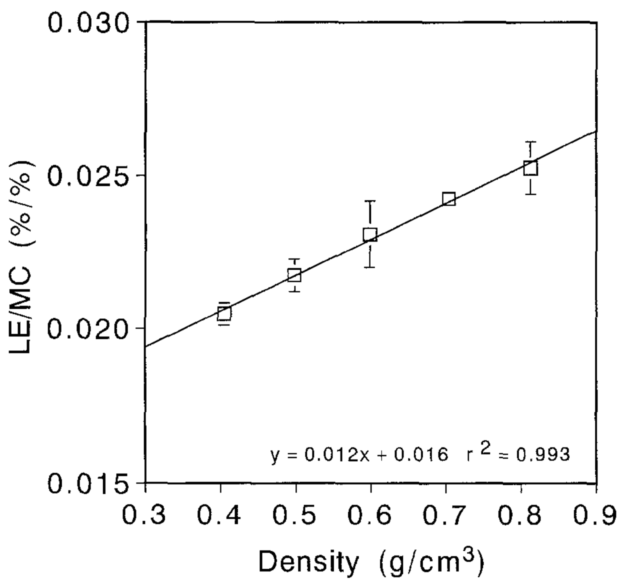

Fig. 6. Linear expansion per unit moisture content change for particleboard at various board densities during the humidity test at 40°C and 90% RH. *Bars* show one standard deviation

board density and LE/MC, and the following regression equation was obtained.

$$Lm = 0.016 + 0.012\rho \tag{2}$$

where Lm is LE per unit MC change. LE/MC changed from 0.021 to 0.026%/%, corresponding to the density range of 0.4–0.8 g/cm^3. This equation can provide predictions on linear change of particleboard in service conditions because the MC change of this humidity test ranged from about 2% to 18%. However, it should be noted that the LE/MC could be affected by parameters other than density, such as resin type, particle shape, and so on.

EL and TS in the humidity test

One of the factors to be noted was the increasing rates of LE and TS during the humidity test. The TS during the humidity test was also evaluated using Eq. (1). The experimental data, not shown here, was in agreement with the curves derived from Eq. (1). The values of β listed in Table 2 showed that the TS of the high-density board needed more time to reach the saturation.

The behaviors of LE and TS in the humidity test were different in terms of time dependence. TS was continuing to increase after LE had almost reached its saturation. This trend was confirmed by comparing the β values; the β for TS was much larger than that for LE.

This difference could be due to the fact that the LE measured here appeared as an average value of expansion in each layer of the board. Some restrictions in the plane directional expansion might occur between the layers when each layer has different potential to expand according to the moisture change. TS was qualitatively thought to be a sum of the expansion in thickness direction of each layer.

Effect of vapor and liquid water

Table 3 lists the data for LE, TS, and WA determined at absorption (wet) conditions and desorption (dry) conditions that followed the humidity or immersion test. Dimensional changes (LE and TS) of the immersion test were slightly larger than those of the humidity test for all the board densities tested in this experiment. However, there were remarkable differences in WA values for the humidity and immersion tests.

One of the differences was found in the LE values of dry conditions. After water immersion these values ranged from −0.28% to −0.13%, whereas those after the humidity test were close to zero. This finding showed that the specimen reduced its length after water immersion followed by drying at 40°C. This shrinkage was possibly caused by "Poisson's effect," corresponding to the thickness changes.

Effect of resin content in the humidity test

Figure 7 shows the relation between exposure time and the LE of the board under different RC conditions. The data for the first 100 h are shown, even though the measurements

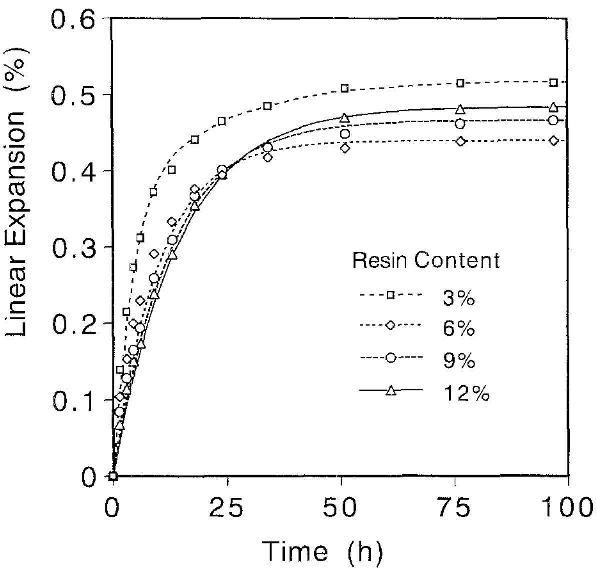

Fig. 7. Linear expansion behavior of particleboards with different resin contents under humid conditions at 40°C and 90% RH

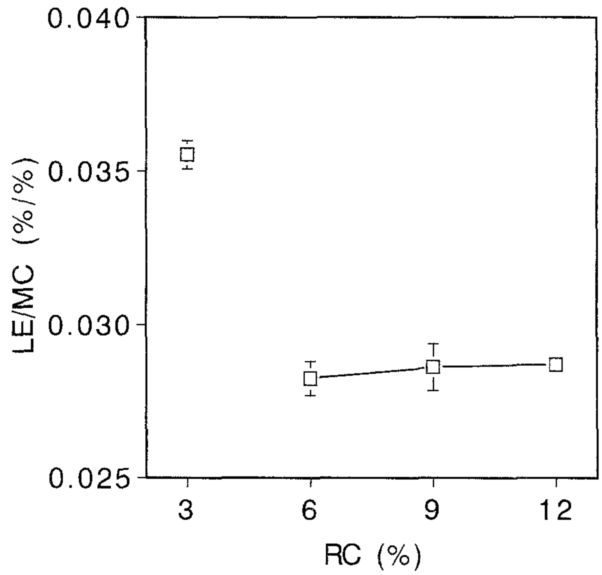

Fig. 8. Linear expansion per unit moisture content change for particleboard with various resin contents during the humidity test at 40°C and 90% RH. *Bars* show one standard deviation

were continued up to 270h. The shapes of the curves were almost the same as those showing LE changes in Fig. 5. Eq. (1) can be applied to predict the behavior.

The board with 3% RC exhibited behavior different from that of the others because of the layer structure shown in Fig. 4. In the RC range 6%–12%, the difference among the boards was small but clear. At the beginning of the exposure, 6% RC board showed the largest LE among the three, and the LE curves crossed over at around 27h. Finally, the high RC board had more LE than the low RC board when the sample reached the leveling-off stage.

No clear reason for this phenomenon was found, although, differences of the layer structure and hygroscopicity of PF resins cured in the board are candidates for investigation. Further research is necessary in this area.

Figure 8 shows the relation between RC and LE per unit MC change. The high value for 3% RC board was due to low bond quality and the different layer structure. No significant difference was observed in the LE/MC for 6% and 12% RC boards, which proved that the high LE of high RC board was caused only by the larger amount of water the specimen can absorb compared with the low RC board.

Conclusion

This study evaluated the effects of board density and RC on the LE and density profile of particleboard. Results obtained can be summarized as follows. The high-density layers in the thickness direction of the board shifted inward as the average board density increased. The density profile was also affected by the RC applied. The elastic constants determined by the three vibration test methods qualitatively depended on the density profiles formed under various board density and RC conditions.

It was found that Eq. (1) effectively predicted the LE behavior of the board exposed to both vapor and liquid water. In the humidity test at 40°C and 90% RH, the LE increased with increasing board density. An increase in RC from 6% to 12% slightly increased the LE. A linear relation between LE/MC and board density presented by Eq. (2) was found, whereas LE/MC remained constant for the RC change form 6% to 12%.

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References

1. Vital BR, Lehmann WF, Boone RS (1974) How species and board densities affect properties of exotic hardwood particleboards. For Prod J 24(12):37–45
2. Hse CY (1975) Properties of flakeboards from hardwoods growing on Southern pine sites. For Prod J 25(3):48–53
3. Shuler CE, Kelly RA (1976) Effect of flake geometry on mechanical properties of Eastern spruce flake-type particleboard. For Prod J 26(6):24–31
4. Chow P (1979) Phenol adhesive bonded medium-density fibreboard from *Quercus rubra* L. bark and sawdust. Wood Fiber 11(2):92–98
5. Sekino N, Suzuki, M (1984) Swelling and creep of isocyanate-bonded oriented particleboard (in Japanese). Mokuzai Gakkaishi 30:17–22
6. Kajita H (1987) Oriented particleboard with sugi thinnings (*Cryptomeria japonica*). I. Effects of degree of particle alignment and board density on physical and mechanical properties. Mokuzai Gakkaishi 33:865–871
7. Avramidis S, Smith LA (1989) The effect of resin content and face-to-core ratio on some properties of oriented strand board. Holzforschung 43:131–133
8. Au KC, Gertjejansen RO (1989) Influence of wafer thickness and resin spread on the properties of paper birch waferboard. For Prod J 39(4):47–50

9. Sun BCH, Hawke RN, Gale MR (1994) Effect of polyisocyanate level on physical properties of wood fiber composite materials. For Prod J 44(4):53–58
10. Vital BR, Wilson JB, Kanarek PH (1980) Parameters affecting dimensional stability of flakeboard and particleboard. For Prod J 30(12):23–29
11. Suchsland O (1972) Linear hygroscopic expansion of selected commercial particleboards. For Prod J 22(11):28–32
12. Suchsland O, Xu H (1989) On the measurement of linear expansion of particleboard and medium density fiberboard. For Prod J 39(6):39–42
13. Xu W, Suchsland O (1997) Linear expansion of wood composites, a model. Wood Fiber Sci 29:272–281
14. Sobue N, Kato A (1992) Simultaneous determination of orthotropic elastic constants of strand full-size plywoods by vibration method. Mokuzai Gakkaishi 38:895–902
15. Dong Y, Nakao T, Chiaki T, Tanaka A, Nishino Y (1992) Evaluation of the characteristics of wood based panels by the in- and out-of-plane vibration technique (in Japanese). Mokuzai Gakkaishi 38:678–686
16. ASTM D 1037-92 (1992) Standard methods of evaluating the properties of wood-based fiber and particle panel materials, linear variation with change in moisture content.
17. Kelly MW (1977) Critical literature review of relationships between processing parameters and physical properties of particleboard. USDA General technical report FPL-10, pp 36–44
18. Laufenberg TL (1986) Using gamma radiation to measure density gradients in reconstituted wood products. For Prod J 36(2):59–62
19. Suzuki S, Saito F, Arima T (1985) Properties of particleboards made form wood element from demolished building (in Japanese). Wood Ind 40(1):15–20
20. Suzuki S, Saito F (1988) Fatigue properties of particleboards. I. Effect of aging treatment on tensile properties parallel to the surface. Mokuzai Gakkaishi 34:590–596