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Dimensional stability and strength properties of particleboard produced by a closed-press system

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Abstract The purpose of this study was to reveal the effects of various levels of mat-moisture content (m.m.c.) and the closed-press system for making single- or three-layer particleboard on the density profile, thickness swelling, specific moduli of elasticity (MOE) and rupture (MOR) and internal bond strength. Internal gas pressure was measured in an enclosed frame; and the larger the m.m.c., the higher the internal gas pressure became. When rising water vapor (steam) struck particles, it plasticized them and cured the adhesive, resulting in improved interparticle contact. The vertical density gradient in the three-layer board was larger than that in the single-layer board. As for thickness swelling by cold-water soaking, the single-layer boards were less affected than the three-layer boards and showed good dimensional stability with increased m.m.c. The open-system boards swelled more than the closed-system boards. The closed-system single-layer board made at high m.m.c. returned nearly to the prime thickness by air-drying after cold-water soaking. Specific MOE and MOR were larger at 15% or 10% m.m.c. than those at other m.m.c. Considerable reductions of specific MOR and MOE of the closed-system three-layer board were observed at 20% or 25% m.m.c.

Key words Particleboard · Closed press system · Density profile · Thickness swelling · Modulus of rupture

Introduction

The effects of wood particle shape, resin content, layer formation, and pressing condition on particleboard qualities have been investigated, and the processing of board production has been developed. The effect of steam is especially important to board production. A study of the "steam shock" process was conducted by Kelly in 1977.[1] It was interesting to note that a steam injection process had been reported in 1973.[2] The effect of steam injection or steam shock on the pressing process is noteworthy,[1–6] as these processes have improved board production. Another process using the conventional press with an enclosed frame (closed-press system) has been developed to determine the effect of steam on the fixation of compressive deformation in wood,[7] but there is insufficient information on particleboard made by the closed-press system with various levels of mat-moisture content. Vaporization and temperature rise may be hastened with high levels of mat-moisture content at the face layers in the closed-press system. As a result, heat may be transferred rapidly to the core, and it may accelerate the plasticization of wood particles and the curing of adhesive.

The purpose of this study was to examine the effects of the closed-press system and various levels of mat-moisture content on the dimensional stability in the thickness direction and related strength properties. Experimental variables were four levels of mat-moisture content, layer formation, the resin content in each layer, and the density profile. Various levels of moisture content in layer mat were chosen because board produced from high moisture content might have some demerits: bursting of the board or a starved joint due to a dilute liquid adhesive. Relations

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among these basic factors and the thickness swelling or strength properties were investigated with relation to the closed- and open-press systems.

Experimental method

Raw material

Scots pine (*Pinus sylvestris* L.) was used as the raw material for this study. Its air-dried density was 0.46 g/cm^3. Wood particles were produced by a ring flaker in which 26 cutting knives were set to make the particles of about 0.6 mm in thickness. They were separated by a screen of 2-mm mesh. The particles in the 2-mm mesh were 8–30 mm in length, 1–5 mm in width, and about 0.6 mm in thickness; those in the 2-mm mesh pass were fine, like sawdust. The former was called normal particles and the latter fine particles. Both were dried to about 4% moisture content.

Fabrication of particleboard

Three kinds of particleboard were made.

1. Single-layer boards were made using normal particles. The target board density was 0.7 g/cm^3 and the target resin content 10%.
2. Three-layer boards were made using normal particles. The mass ratio of the three layers was 1:2:1 (face/core/face). The target board density was 0.7 g/cm^3, and the target resin contents of the face and core layers were 12% and 7%, respectively.
3. Three-layer boards were made using fine particles for the face layers and normal particles for the core layer. The mass ratio of the three layers, the target board density and the target resin content were the same as in item 2.

The adhesive used was melamine-formaldehyde resin (U-814; Mitsui Toatsu) having a solid content of 65%. Ammonium chloride was added to the resin, 1% (wt.), as a hardener.

The initial moisture content (m.c.) in each layer mat, as shown in Fig. 1, was adjusted to 8%–42% by adding the required amount of water to the adhesive solution. This method was derived semi-empirically for uniformity in water and adhesive. By averaging the initial moisture content of each layer, the mean moisture content of an entire mat for the three-layer board was obtained and expressed as the mat-moisture content (m.m.c.): 10%, 15%, 20%, and 25%, respectively. After the adhesive solution was sprayed, the mat-moisture content in each layer was measured, as shown in Table 1.

The formulated adhesive solution was sprayed onto the tumbling particles. Particleboard mats were formed immediately after spraying by two methods: a conventional way of felting on the plate with a pair of distance bars, and a new way (closed-press system, as shown in Fig. 2) of felting in an enclosed frame equipped with a pressure transducer (PH-10KB; Kyowa Electronic Instrument), based on the report of Inoue et al.[7] Internal gas pressure was measured by a diaphragm made from SUS 630, which was connected to the strain gauge in the pressure transducer. It was used accurately up to 200°C. The mat was pressed to the height (15 mm) of the frame or distance bars under 4.0 MPa at 145°C for the first 2 min, 2.0 MPa for the next 2 min, and

Table 1. Example of measured mat-moisture content

Initial mat-moisture content (%)	Mat-moisture content after spraying (%)		
	SL	NTL	FTL
10	12	10	10
15	15	14	13
20	20	17	19
25	24	23	24

SL, single-layer; NTL, normal-particle three-layer; FTL, fine-particle three-layer boards

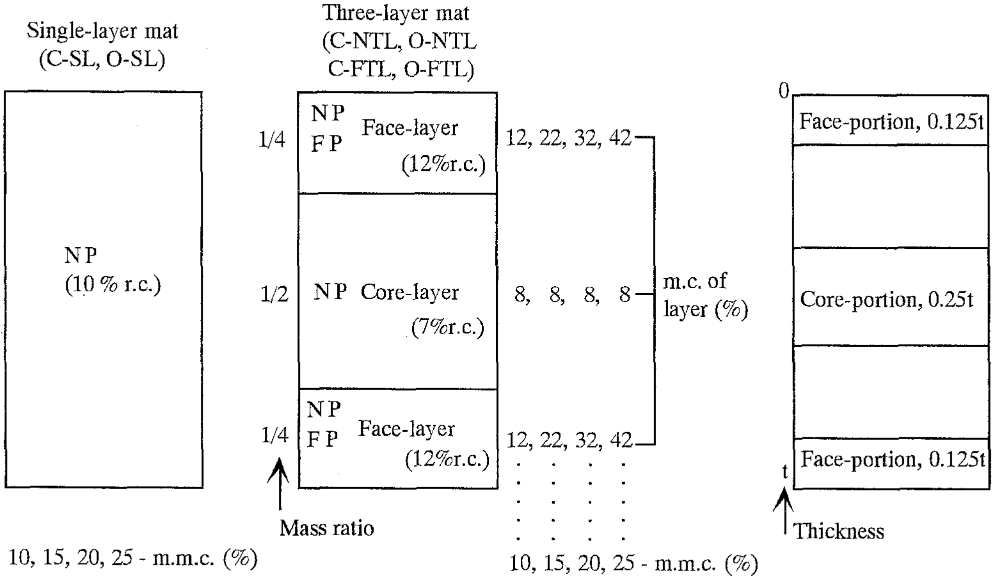

Fig. 1. Construction of particleboard in this study. *C*, closed system; *O*, open system; *NP*, normal particle; *FP*, fine particle; *C-SL*, closed-NP single-layer; *O-SL*, open-NP single-layer; *C-NTL*, closed-NP three-layer; *O-NTL*, open-NP three-layer; *C-FTL*, closed-FP three-layer; *O-FTL*, open-FP three-layer; *r.c.*, resin content; *m.c.*, moisture content; *m.m.c.*, mat-moisture content (average of each layer). Note that, C-SL board, NTL board, C-NTL board, and O-FTL board are often used in the text. The "closed-press system" is simply written as the "closed system"

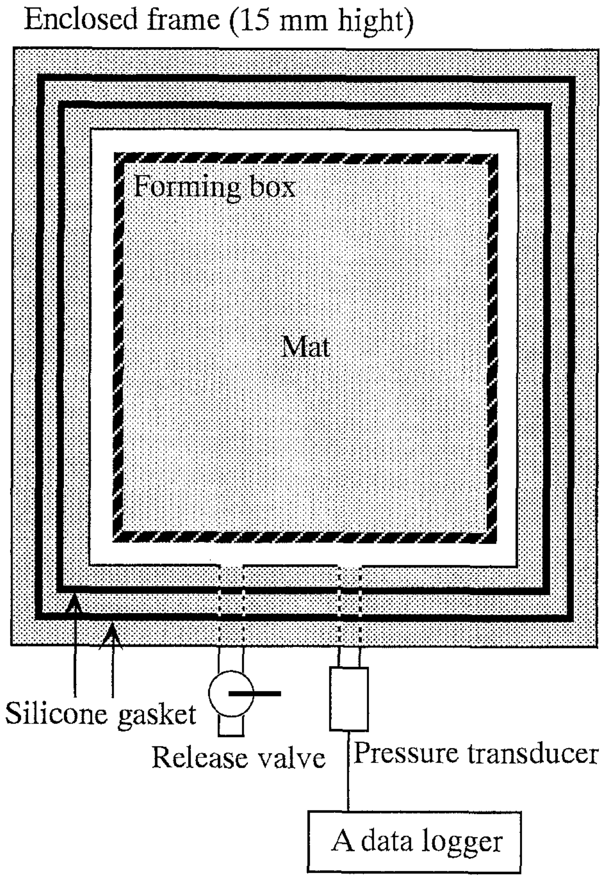

Fig. 2. Molding apparatus in the closed-press system. Forming box was removed from the enclosed frame before pressing

finally 1.0 MPa for 1 min. Then, operating the release valve, the pressure of the sealed gas was reduced to atmospheric pressure over 20 sec. No boards burst. The particleboards were 30 cm in length, 30 cm in width, and 1.5 cm in thickness. The kinds of formed boards are shown in Fig. 1, as are the abbreviations for the closed and open systems.

Tests

Samples were obtained from the boards in which no springback or squashed portions were found after hot pressing. They were conditioned under 20°C and 65% relative humidity for a week. Relative density profiles were measured by a gamma ray density profiler (Geological and Nuclear Science Co.).

Thickness swelling was measured using the following procedure: air-dry (t_1) $\rightarrow$ cold water (20°C) soaking for 24 h (t_2) $\rightarrow$ air-dry for 30 days (t_3) $\rightarrow$ hot water (70°C) soaking for 6 h $\rightarrow$ air-dry for 30 days (t_4), where t_1–t_4 were the thicknesses.

Thickness swelling $\beta_{12} = (t_2 - t_1)/t_1 \times 100\ (\%)$ (1)

Thickness change $\beta_{13} = (t_3 - t_1)/t_1 \times 100\ (\%)$ (2)

$\beta_{14} = (t_4 - t_1)/t_1 \times 100\ (\%)$ (3)

Recovery rate $\alpha = (t_2 - t_3)/(t_2 - t_1) \times 100\ (\%)$ (4)

where the recovery rate is the percentage returning to the prime thickness.

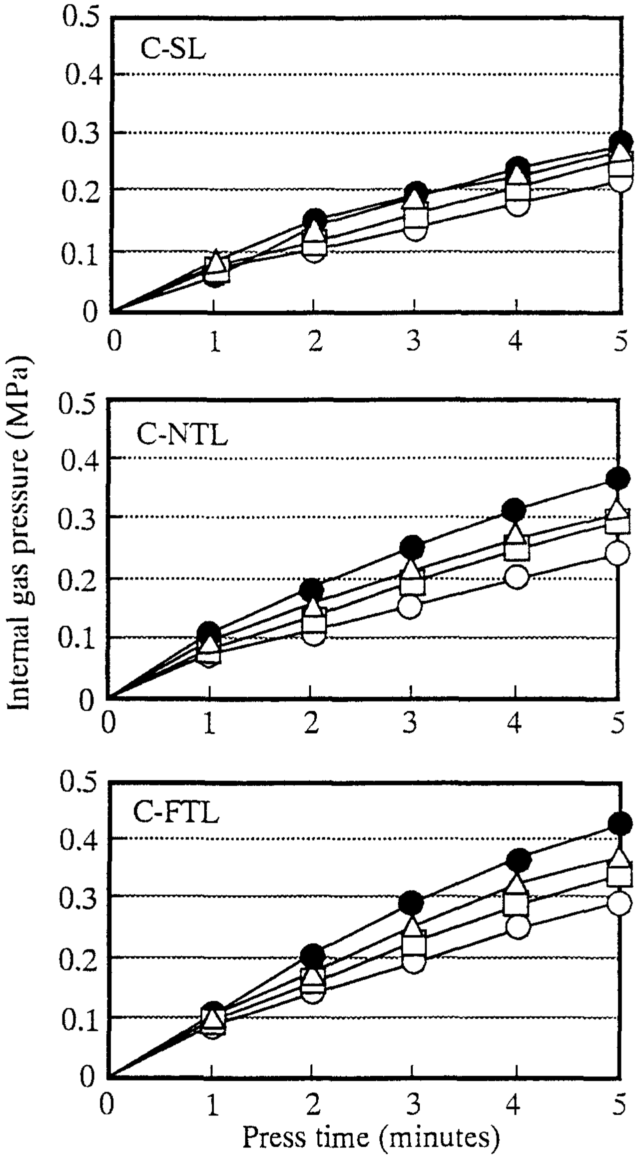

Fig. 3. Relations between press time and internal gas pressure in the closed system. *Open circles*, 10% m.m.c.; *open squares*, 15% m.m.c.; *open triangles*, 20% m.m.c.; *solid circles*, 25% m.m.c.

Measurements of the modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond strength (IB) were conducted according to JIS A 5908 1994. There were six replications from each series.

Results and discussion

Internal gas pressure

The internal gas pressure in the enclosed frame increased gradually as soon as a mat was compressed. Figure 3 shows the relations between the press time and the internal gas pressure for various levels of mat-moisture content. The larger the mat-moisture content, the higher the internal gas pressure became; and the internal gas pressure in the three-layer board was larger than that in the single-layer board. The high pressure of the fine-particle three-layer (FTL) board was due to much vaporized water, which may be easily transferred in the mat because of the fine particles in the face layers. It was clear that high internal gas pressure was produced from the face layers near both heated plates, and a jet of rising water vapor struck piled particles. Heat added to this vapor may affect the plasticizing of wet wood particles and may accelerate curing of the adhesive. Both actions can improve interparticle contact, and so this process may be useful for holding compressive deformation. It was reported that a set of compressed wood was achieved by exposure to heated steam at short intervals.[8]

Relative density profile

The air-dried mean board densities are tabulated in Table 2. Almost all the closed-system boards had an air-dried board density of 0.69–0.74 g/cm^3, which was nearly equal to

Table 2. Distribution of air-dried densities and vertical density gradient

Mat-moisture content (%)	Face-portion density (g/cm^3)		Mean whole-board density (g/cm^3)		Core-portion density (g/cm^3)		VDG (g/cm^4)	
	Closed	Open	Closed	Open	Closed	Open	Closed	Open
SL								
10	0.83	0.72	0.69	0.64	0.61	0.56	0.29	0.21
15	0.84	0.78	0.71	0.66	0.63	0.57	0.28	0.28
20	0.82	0.82	0.72	0.72	0.64	0.66	0.24	0.21
25	0.81	0.80	0.70	0.71	0.66	0.65	0.20	0.20
NTL								
10	0.91	0.73	0.70	0.65	0.57	0.57	0.45	0.21
15	0.95	0.86	0.73	0.68	0.58	0.55	0.49	0.41
20	0.87	0.88	0.74	0.69	0.58	0.50	0.39	0.51
25	0.86	0.85	0.73	0.71	0.59	0.56	0.36	0.39
FTL								
10	0.90	0.80	0.69	0.63	0.57	0.50	0.44	0.40
15	0.95	0.88	0.71	0.63	0.55	0.49	0.53	0.52
20	0.93	0.90	0.73	0.67	0.57	0.52	0.48	0.51
25	0.89	0.89	0.73	0.69	0.55	0.54	0.45	0.47

VDG, verticle density gradients, which was the difference between the face portion density and the core portion density divided by the distance between the face portion and the core portion

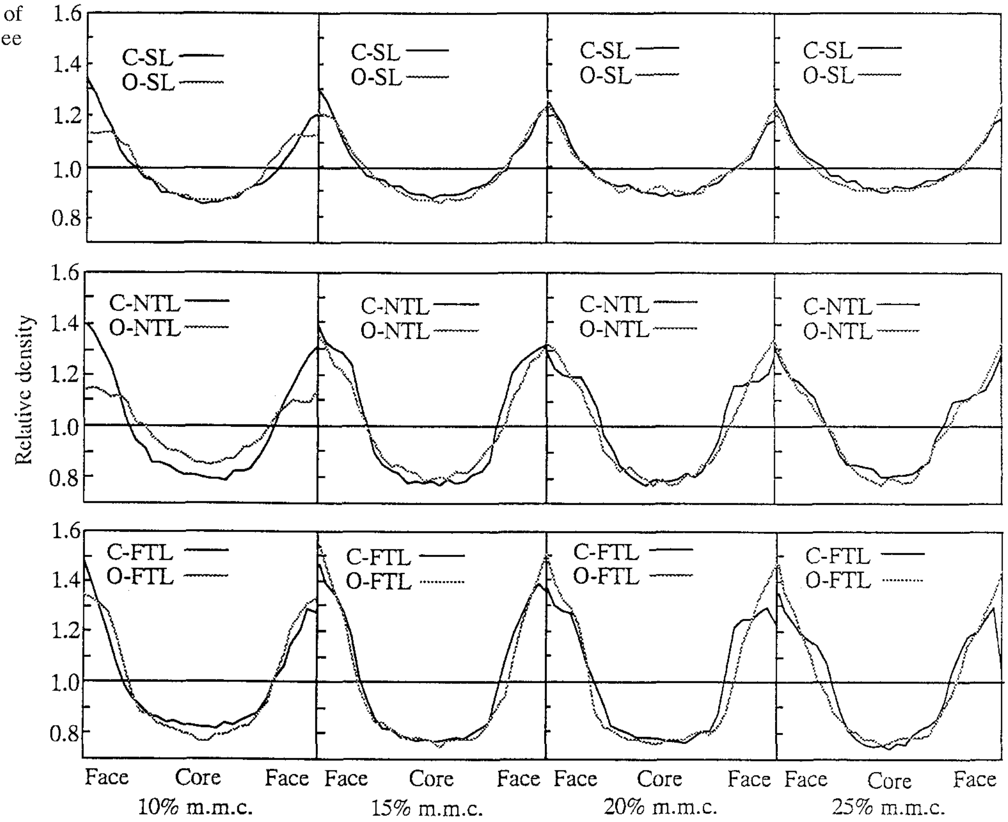

Fig. 4. Relative density profile of various boards. For abbreviations see the legend to Fig. 1

the target board density of 0.7 g/cm^3. The open system boards had a wide range of 0.63–0.72 g/cm^3.

Relative density was expressed as the (density at 0.5-mm intervals in the thickness direction)/board density. The relative density profiles are shown in Fig. 4. Those of the single-layer boards produced a smooth parabola for the most part, but unusual profiles with a large shoulder and turning point were found in the face layers of the closed three-layer boards at 20% and 25% m.m.c., compared with smooth profiles in those of the open three-layer boards.

The thickness of the face portion was defined as 0.125*t* in the depth from the surface, where *t* was board thickness (Fig. 1). The air-dried density of this portion was measured and recorded in Table 2. It is interesting to note that the densities of the closed system at 10% and 15% m.m.c. were larger than those of the open system.

The core portion was the bottom of the parabola in Fig. 4, and its thickness was defined as 0.25*t*. The density of the core portion is shown in Table 2. The vertical density gradient (VDG) was calculated from the difference of the density and the distance between the face portion and core portion (Table 2). The VDG of the normal-particle three-layer (NTL) and FTL boards was larger than that of the single-layer (SL) board. The face portion of the three layer board was highly compressed and increased the VDG.

Dimensional stability in the thickness direction

Figure 5 shows the thickness swelling after 24 h of water soaking. The degree of thickness swelling of the closed-system boards was less than that of the open-system boards at each m.m.c. except for the SL board at 10% m.m.c. and the FTL board at 25% m.m.c. There was a similar tendency among the SL, open-system (O)-NTL, and O-FTL boards; that is, the higher the moisture content in the mat, the lower was the thickness swelling. A large decrease in β_{12} at 15% m.m.c. was seen with reference to the closed-system (C)-NTL and the C-FTL boards. It probably was caused by more effective interparticle contact and fixation of the compressive deformation among piled particles.

The degree of thickness swelling of almost all the single-layer boards was less than that of the three-layer boards. This phenomenon was correlated with an increase in IB strength of the SL board (see below). Among the three-layer boards, the swelling of the FTL boards was lower than that of the NTL boards.

The values for each board at 10% m.m.c. were approximately equal to 10%–18% in water-soaked swelling of ordinary-made or commercial particleboard.[9,10] Investigating the effect of mat-moisture content on thickness swelling, the β_{12} ratio at 15%, 20%, or 25% to β_{12} at 10% m.m.c. was calculated; the results are shown in Table 3. The C-SL

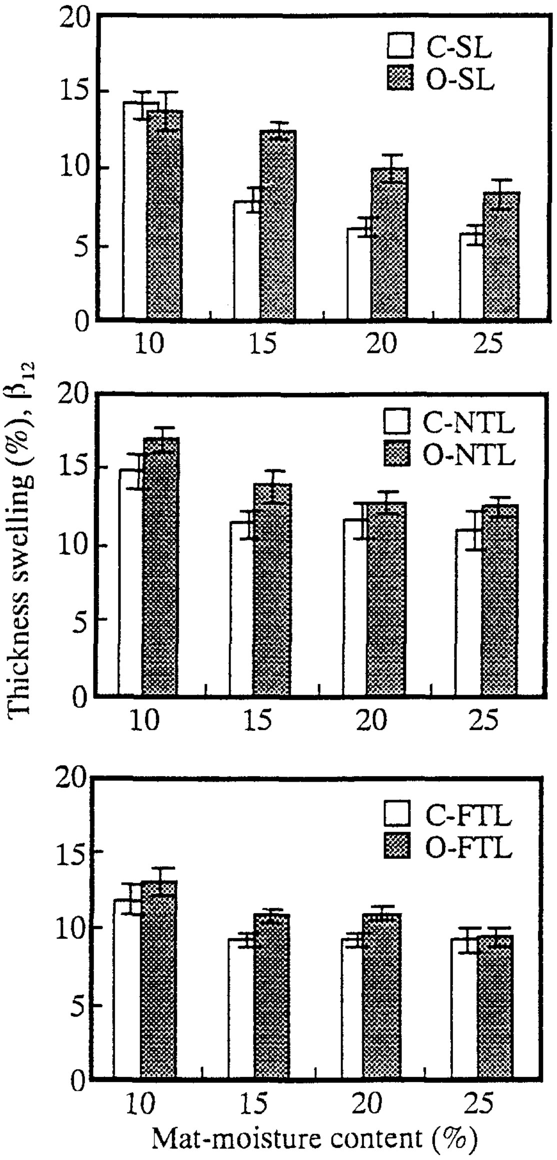

Fig. 5. Relations between mat-moisture content and thickness swelling after 24 h of cold-water soaking. Vertical lines denote standard deviations

Table 3. Effect of mat-moisture content on swelling ratio after 24 h of cold-water soaking

m.m.c. (%)	Closed				Open			
	10	15	20	25	10	15	20	25
SL	1.00	0.56	0.43	0.40	1.00	0.91	0.73	0.61
NTL	1.00	0.77	0.79	0.74	1.00	0.82	0.75	0.73
FTL	1.00	0.78	0.78	0.78	1.00	0.83	0.83	0.73

Swelling ratio was calculated from each β_{12} to β_{12} at 10% m.m.c.
m.m.c., mat-moisture content

board promoted an extensive reduction of the swelling ratio and satisfied good dimensional stability whose values were at least 50%–60%, as antiswelling efficiency was (1-swelling ratio) ×100. It was noted that the single-layer board contained much more moisture in the core layer than in the three-layer board and the effect of the closed system was strong, manifesting as a rising temperature and the plasticizing of particles.

It is well known that dimensional change in the thickness direction has a close relation to both reversible and irreversible swelling among piled wood particles.[11,12] To investigate this problem, we conducted experiments using Eqs. (2) and (3). Figure 6A shows the results calculated from Eq. (2) (β_{13}), which was an index of the shrinking ability. The thickness change (β_{13}) of the closed-system boards was statistically (95% confidence limit) smaller than that of the open-system boards in many levels of mat-moisture content, and the mean values decreased with an increasing mat-moisture content. The shrinking ability of the closed system board was strengthened in the order NTL < FTL < SL boards as regards 15%–25% m.m.c.

The recovery rates (α) were calculated from Eq. (4) and are shown in Table 4. The closed-system boards made a larger recovery than the open-system boards in many cases. By paying attention to α, which was more than about 60%, we found that the recoverable property of each board improved at high mat-moisture contents. An amount of $(100 - \alpha)$ is assumed to be connected with irreversible loosening of the interparticle bond by cold-water soaking.

Figure 6B shows the results calculated from Eq. (3) (β_{14}), which was an index of drastic loosening of the interparticle bond by hot-water soaking and release from the compressive set. It is interesting to note that the minimum β_{14} appeared in the 15% m.m.c. of both the NTL and the FTL boards: 10.8% for the C-NTL and 9.3% for the C-FTL (15% m.m.c.). Those of β_{12} were 11.4% for C-NTL and

Table 4. Recovery rate (α) by air-drying after 24 h of water soaking

m.m.c. (%)	Closed (%)				Open (%)			
	10	15	20	25	10	15	20	25
SL	43	60	77	87	43	48	58	68
NTL	43	51	57	65	39	47	53	58
FTL	51	58	62	71	43	51	53	63

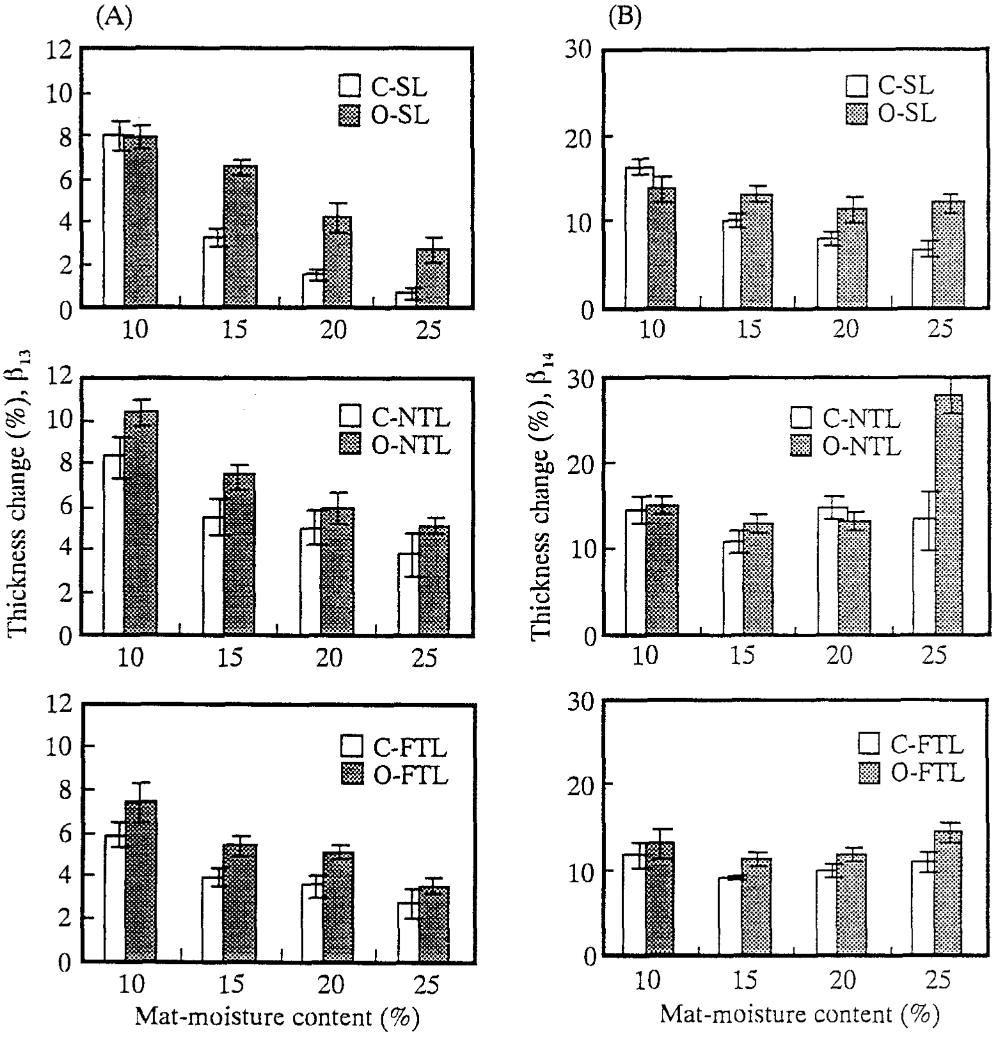

Fig. 6. Relations between mat-moisture content and thickness change by air-drying after 24 h of cold-water soaking (**A**) or 6 h of hot-water (70°C) soaking (**B**). *Vertical lines* denote standard deviations

9.3% for C-FTL (15% m.m.c.). The value of β_{14} of the C-SL board was 6.5% (25% m.m.c.), and that of β_{12} of the C-SL board was 5.6% (25% m.m.c.). As these data indicate, the fixation of the board thickness was broken by the severe treatment of hot-water soaking. The C-SL boards produced at high mat-moisture content showed good property.

Strength properties

Specific moduli of elasticity and rupture (MOE/board density, MOR/board density) are shown in relation to the mat-moisture content in Fig. 7. As can be seen from the closed-system boards, both specific MOE and MOR at 10% and 15% m.m.c. were larger than those at 20% and 25% m.m.c. Those of the open-system boards represented a peak at 15% or 20% m.m.c. Specific moduli may have been affected by the effective interparticle contact in the face layer, especially at 15% m.m.c. The maximums of both specific moduli of the O-NTL and O-FTL boards at 15% m.m.c corresponded with the minimum values of β_{14}. It was thought that this phenomenon was caused by formation of endurable interparticle bonds.

The authors plotted the relations between the air-dried density of the face portion and the MOE or MOR, as shown in Fig. 8. The MOEs and MORs of each type of board showed maximum values at 10% or 15% m.m.c in many cases. Mallari et al. noted that for producing good strength properties the optimum moisture content of a particle mat was 13%–18%.[13] Each board at 25% m.m.c. showed smaller MOE and MOR values than that of 15% m.m.c. despite almost the same face portion density. It was probably caused by deterioration of the interparticle bonds as mentioned later.

Figure 9 shows the relations between the IB of the core layer and air-dried density of the core portion. There was a linear regression except for an unreasonable value of the O-SL board at 25% m.m.c. The C-SL board had sufficient efficiency. It was noted that compaction ratios were 1.3–1.4 in single-layer board and 1.1–1.2 in three-layer board. The IB of commercial boards was reported to be 0.4–0.5 MPa in an air-dried condition.[14] Therefore, the closed system was recommended for improving the IB. The NTL boards at 20% and 25% m.m.c. and the FTL boards at 25% m.m.c. ruptured in the face layer. Weakness of the internal bond of the face layers was probably due to squeezing the adhesive with water vapor movement in the face mats.

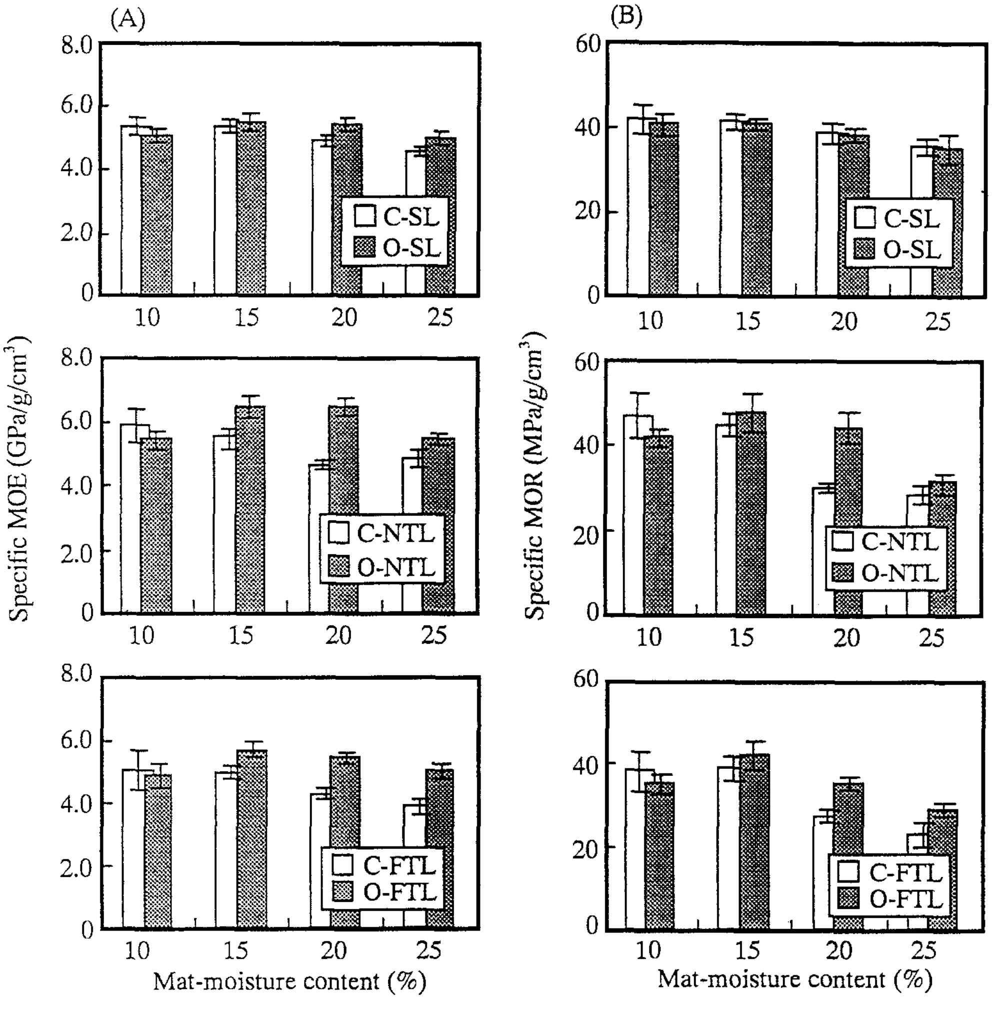

Fig. 7. Relations between mat-moisture content and specific modulus of elasticity (MOE) (**A**) or specific modulus of rupture (MOR) (**B**). *Vertical lines* denote standard deviations

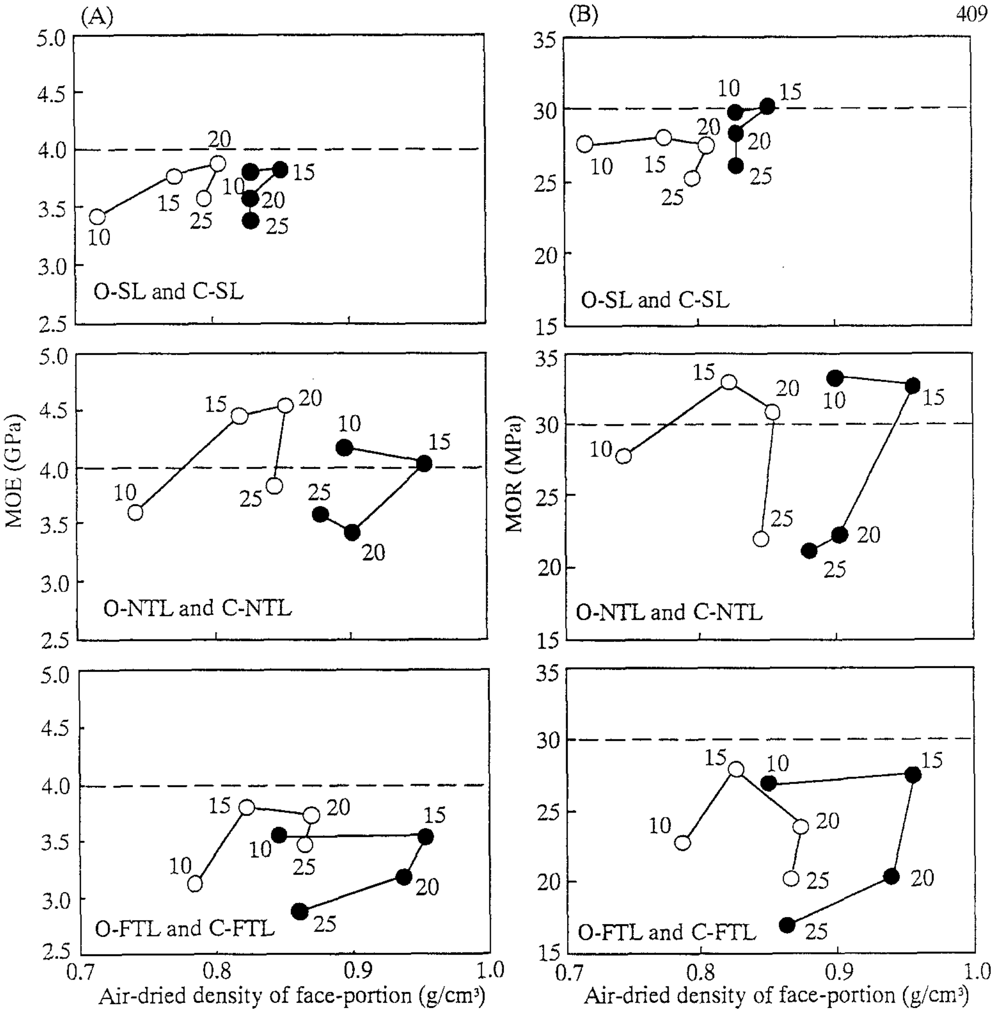

Fig. 8. Relations between the air-dried density of the face portion and the MOE (**A**) or MOR (**B**). *Open circles*, open-press system; *solid circles*, closed-press system. Numbers in the graphs indicate the mat-moisture content

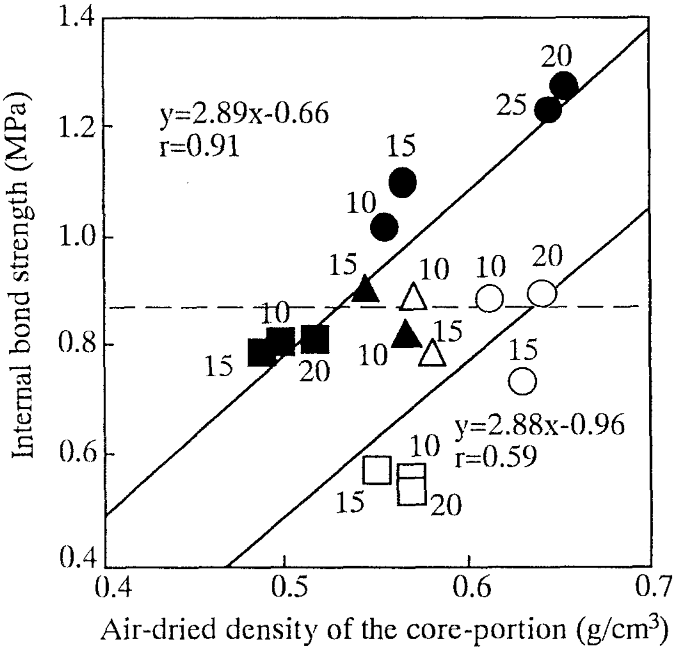

Fig. 9. Relations between the air-dried density of the core portion and the internal bond strength of the core layer. *Solid circles*, C-SL; *open circles*, O-SL; *solid triangles*, C-NTL; *open triangles*, O-NTL; *solid squares*, C-FTL; *open squares*, O-FTL. Numbers in the graphs indicate the mat-moisture content (%). Regression lines are indicated in the graph

To evaluate strength properties, the MORs, MOEs and IBs above the dashed lines in Figs. 8 and 9 are suggested. The single-layer board had good IB. The NTL boards at 15% m.m.c. had face layers with initial moisture contents of 22% and high MOEs and MORs. It was concluded from the above strength properties that particle configuration and compatibility in relation to the amount of adhesive improved about 15% m.m.c. by both closed and open systems. The three-layer board had some disadvantages at 20% and 25% m.m.c. when the initial moisture content was 32%–42% in the face layer. However, most of the MORs and IBs of each board at high m.m.c. exceeded the level recommended by JIS A 5908 1994 (e.g., 18MPa MOR and 0.3MPa IB).

Conclusion

We investigated the effects of the closed-press system and various levels of mat-moisture content on thickness swelling and related strength properties. We reached the following conclusions.

1. As soon as hot-pressing started, the internal gas pressure increased in the enclosed frame. The rising steam struck piled particles and, as a result of the rapid temperature rise, plasticized particles and cured the adhesive.

2. The relative density profile was similar to a parabolic curve. The vertical density gradient of the three-layer board was larger than that of the single-layer board.

3. Thickness swelling decreased with an increase in mat-moisture content. The closed-system board swelled less than the open-system board, and the single-layer board swelled less than the three-layer board. The closed system was more effective during formation of the single-layer board.

4. The thickness of the closed single-layer board at high mat-moisture contents returned nearly to the prime thickness after cold-water soaking followed by air-drying. The three-layer board from 15% m.m.c. showed minimal irreversible swelling after hot-water soaking and air-drying.

5. The closed-press system improved internal bond strength. The single- and three-layer boards at 15% m.m.c. had conclusively good bending properties. The closed-system three-layer board at 20%–25% m.m.c. showed much lower bending properties. However, the MORs and IBs of each board at high mat-moisture content were equal to or larger than the level recommended by JIS A 5908 1994.

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References

1. Kelly MW (1977) Critical literature review of relationships between processing parameters and physical properties of particleboard. USDA General Technical Report FPL-10
2. Shen KC (1973) Steam-press process for curing phenolic-bonded particleboard. For Prod J 23(3):21–29
3. Hata T, Subiyanto B, Kawai S, Sasaki H (1989) Production of particleboard with a steam-injection press. III. Effects of injection time and timing on board properties (in Japanese). Mokuzai Gakkaishi 35:1080–1086
4. Hata T (1994) Steam-injection press process (in Japanese). Wood Ind 49(1):2–7
5. Sasaki H, Kawai S (1988) Principle of production and process of wood-based materials (in Japanese). J Soc Mater Sci Jpn 37:1349–1356
6. Sasaki H (1996) Function of water vapor in manufacturing wood composites and the application (in Japanese). J Soc Mater Sci Jpn 45:363–368
7. Inoue M, Kadokawa N, Nishio J, Norimoto M (1993) Permanent fixation of compressive deformation by hygro-thermal treatment using moisture in wood (in Japanese). Wood Res Tech Notes 29:54–61
8. Inoue M, Norimoto M, Tanahashi M, Rowell RM (1993) Steam or heat fixation of compressed wood. Wood Fiber Sci 25:224–235
9. Kawai S (1997) Properties of wood-based materials (in Japanese). In: Imamura Y, Kawai S, Norimoto M, Hirai T (eds) Wood and wood-based materials. Toyo-shoten, Tokyo, p 47
10. Mishiro A, Arima T, Okuma M (1976) The effects of moisture on the properties of particleboard (I) (in Japanese). Wood Ind 31:299–301
11. Beech JC (1975) The thickness swelling of wood particleboard. Holzforschung 29(1):11–18
12. Suchsland O (1973) Hygroscopic thickness swelling and related properties of selected commercial particleboards. For Prod J 23(7):26–30
13. Mallari VC, Kawai S, Sasaki H, Subiyanto B, Sakuno T (1986) The manufacturing of particleboard. I. Types of adhesives and optimum moisture content. Mokuzai Gakkaishi 32:425–431
14. Suzuki S, Saito F (1986) Fatigue behavior of particleboard in tension perpendicular to the surface. II. Effect of moisture content. Mokuzai Gakkaishi 32:801–807