J Wood Sci (2003) 49:398–404
DOI 10.1007/s10086-002-0501-y

ORIGINAL ARTICLE

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Effect of board density on bending properties and dimensional stabilities of MDF-reinforced corrugated particleboard

Received: January 21, 2002 / Accepted: October 21, 2002

Abstract We investigated the bending properties of composite boards produced by reinforcing both sides of corrugated particleboard with medium-density fiberboard (MDF). Thickness swelling and linear expansion (LE) were measured to assess the dimensional stabilities of the composite board. Although the apparent density of the composite board was 0.48 g/cm^3, its strength was found to be equivalent to that of 18-type particleboard as described in JIS A 5908. The board's parallel/perpendicular anisotropy in strength was 0.9. The modulus of rupture (MOR) of the composite board increased with board density only up to a certain density, beyond which the MOR was constant. On the other hand, the thickness swelling of both corrugated particleboard and the composite board was smaller than that of flat-type particleboard, satisfying the JIS A 5908 standard of 12%. Linear expansion (soaking in water of ordinary temperature for 24 h) of corrugated particleboard was 0.7%–0.9% in the parallel direction and 2.1%–3.1% in the perpendicular direction; hence, anisotropy in linear expansion existed in the corrugated particleboard. The linear expansion of the composite board was 0.6%–0.9% in the parallel direction and 1.8%–2.5% in the perpendicular direction. Although the LE of the composite board was lower than that of corrugated particleboard, it is necessary to improve the LE of composite board for practical use.

Key words Corrugated particleboard · Composite board · Bending strength · Dimensional stability

Introduction

The world's forest area continues to shrink. In the near future it will become more difficult and costly to obtain raw materials directly from the forest. Meanwhile, the demand for wood materials can be expected to continue, along with the demand for comfortable housing. Wood materials manufactured from reconstituted materials such as construction waste will become a necessary alternative to harvested lumber.

Particleboard is one such wood material. Particleboard is not strong enough to perform well for structural uses, but when used as the core of products with laminating veneers, these properties improve. In a previous study[1] we investigated the modulus of rupture (MOR) of veneer-reinforced corrugated particleboard, but even veneer may be difficult to obtain in the future.

In this study, we produced composite board using reconstructed materials: particleboard reinforced with medium-density fiberboard (MDF) and low-density composite board using corrugated particleboard as the core. These composite boards' strength properties and dimensional stabilities (thickness swelling and linear expansion) were then investigated.

Materials and methods

Preparation of corrugated particleboard

The particles used in this study were a mixture of softwood and hardwood and had a shaving-type shape. After the particles were screened, the proportion of particles larger than 8 mm was 1.2% by weight; the proportion of 4- to 8-mm particles was 70.3%; the proportion of 2- to 4-mm particles was 5.7%; and particles less than 2 mm accounted for 22.3% of the total. The particles were dried to about 3% moisture content. Phenol resin with an average solid content of 48.8% was prepared and was used as the adhesive. The target resin content of the board was 10%.

Two corrugated particleboards (C-boards), one of the 20-mm type and the other of the 40-mm type, were prepared according to the previous study.[1] These shapes were similar to the truss structure (Fig. 1). The 20-mm-type C-board

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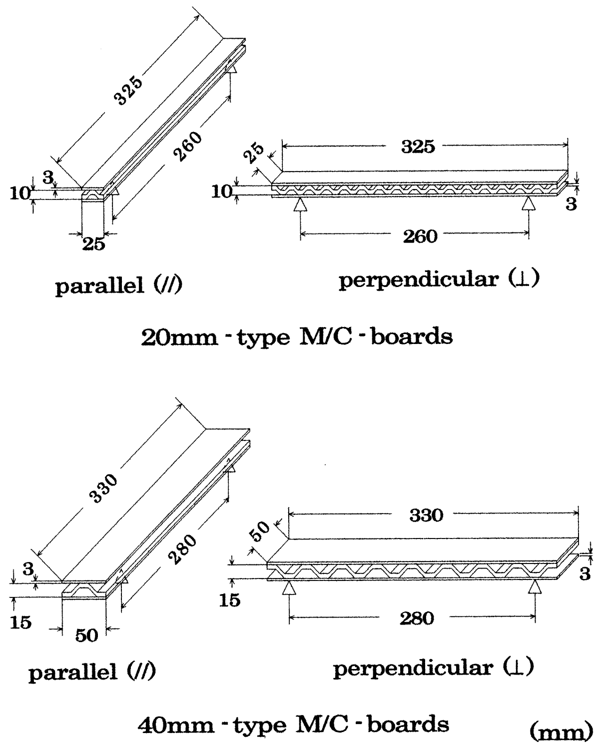

Fig. 1. Dimensions of parallel and perpendicular specimens of medium-density fiberboard (MDF)-reinforced corrugated particleboard (*M/C-boards*) and the span lengths of bending tests

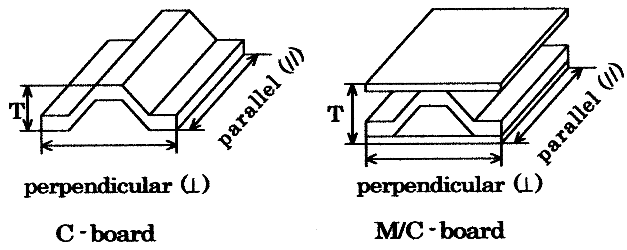

Fig. 2. Measuring directions for thickness swelling (*T*) and linear expansion (parallel, perpendicular) of corrugated particleboard (*C-board*) and M/C board

measured 400 × 300 mm and was 5 mm (10 mm) thick. The target board densities (oven-dried) were 0.45 (0.23), 0.55 (0.28), 0.65 (0.33), 0.75 (0.38), and 0.85 (0.43) g/cm^3. [The values in parentheses show "apparent thickness" and "apparent density" including hollow parts.] The 40-mm-type C-board measured 400 × 300 mm and was 5 mm (15 mm) thick. The target board densities were 0.45 (0.15), 0.55 (0.18), 0.65 (0.22), 0.75 (0.25), and 0.85 (0.28) g/cm^3.

For comparison, the conventional standard flat-type particleboards (S-boards) were produced using a process similar to that used for the C-boards. The target thickness of the S-boards was 10 or 15 mm, and the target densities were 0.45, 0.55, 0.65, 0.75, and 0.85 g/cm^3.

Preparation of specimens for the strength test

A parallel-to-the-ridge direction specimen (//) and a perpendicular-to-the-ridge direction specimen (⊥) were cut from the C-boards. The specimens measured 325 × 25 mm for the 20-mm type and 330 × 50 mm for the 40-mm type. The S-boards were cut into specimens of similar sizes. We next adhered MDF to the face and back surfaces of the C-board with a resorcinol resin adhesive (Deernol D-33N; Oshika). Its application quantity was 400 g/m^2. The conditions for adhesion were 40°C and 1.85 MPa for 24 h. The MDF was the P-type in JIS A 5908, 3 mm thick, density 0.75 g/cm^3, MOR 36.6 MPa, and MOR under the wet condition (test B: boiling for 2 h and further soaking in water of ordinary temperature for 1 h) 13.3 MPa. Specimens reinforced by MDF are called M/C-board. For comparison, S-boards were reinforced using a similar preparation process (M/S-board).

Bending strength test

The bending strengths of the C-boards and M/C-boards were tested according to JIS A 5908 (Fig. 1). When corrugated particleboard is used as a structural material, its bending property under wet conditions is important. Therefore, the bending strength under wet conditions was tested on JIS A 5908 (test B: boiling for 2 h and further soaking in water of ordinary temperature for 1 h). The span lengths were 260 and 280 mm for the 20-mm- and 40-mm-type specimens, respectively. S-boards and M/S-boards were tested using the same method.

Dimensional stability

Specimens for thickness swelling (TS) were prepared as shown in Fig. 2. The 20-mm-type specimen was 25 × 25 mm, and the 40-mm-type specimen was 50 × 50 mm.

Measuring the TS was based on JIS A 5908. The linear expansion (LE) was measured using the specimen that was measured for the TS. LEs of the C-board and M/C-board were measured in two directions: parallel and perpendicular (Fig. 2). The back side of the specimen was measured for LE in the perpendicular direction. A caliper with an accuracy of 1/20 mm was used to measure LE. Similar tests were performed on S-boards and M/S-boards.

Results and discussion

Bending property

The cross-sectional shapes of the C-board and M/C-board were obviously different from that of the S-board. Therefore, the bending stresses for the C-board and M/C-board are considered to be different from that of the S-board. To calculate the MOR of the C-boards and M/C-board we therefore tried to calculate the moment of inertia of a particular area. Given the complexity of the cross-sectional shape of C-boards and M/C-boards, it was difficult to set a

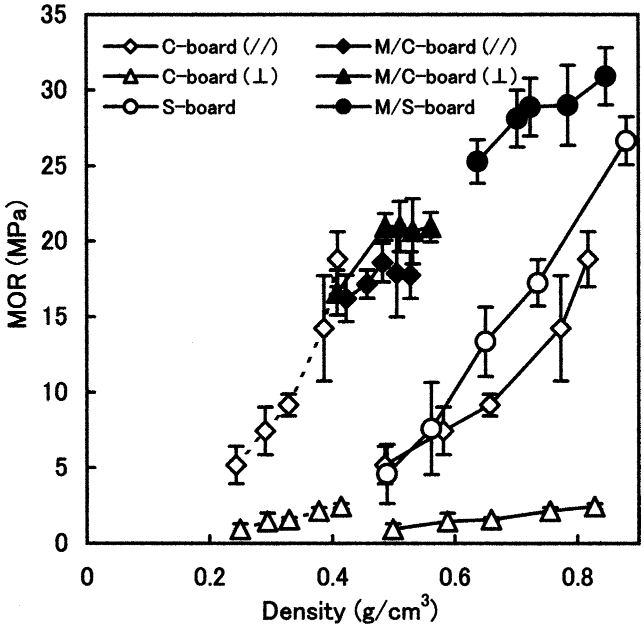

Fig. 3. Relation between modulus of rupture (*MOR*) and density of 20-mm-type C-board, M/C-board, standard flat-type particle board (*S-board*), and M/S-board. The densities of C-boards (*dotted lines*) and M/C-boards were their apparent densities.

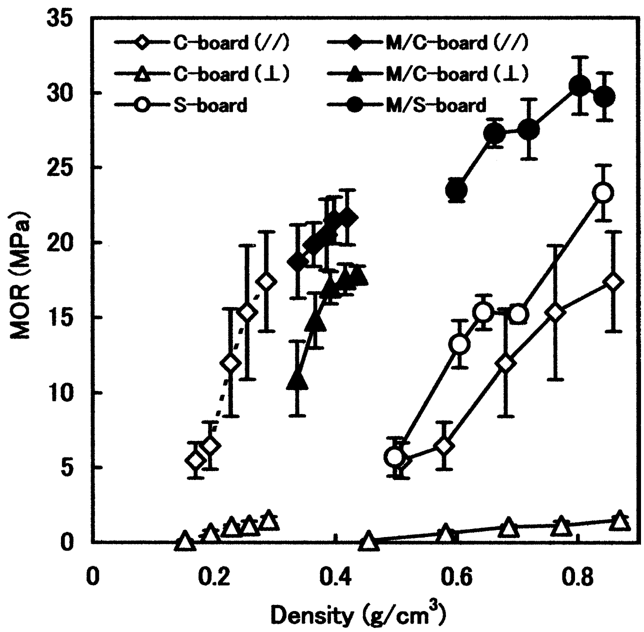

Fig. 4. Relation between MOR and density of 40-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-boards (*dotted lines*) and M/C-boards were their apparent densities.

neutral axis for the perpendicular direction. Therefore, for this study the MOR for the perpendicular direction of the C-boards and M/C-boards was calculated by the method defined in JIS A 5908.

Figures 3 and 4 show the relations between the MOR and the density of the 20-mm- and 40-mm-type boards. The MOR of the C-board was lower than that of the S-board. In our previous paper[1] C-board was reinforced with veneer to improve its strength. However, veneer is anisotropic in strength. In this study, we expected that C-board reinforced with MDF as a composite board would result in an increased MOR.

The MOR of M/C-board was equal to that of 18-type particleboard as defined by JIS and was greater than that of S-board according to JIS. Compared at every density, for the 20-mm type, the MOR of the M/C-board (//) was 0.9–3.1 times that of the C-board, and the MOR of the M/C-board (⊥) was 8.5–17.6 times that of the C-board. For the 40-mm type, the MOR of the M/C-board (//) was 1.2–3.4 times that of C-board, and that of the M/C-board (⊥) was 11.7–73.4 times higher. The MOR of most of the M/C-boards was greater than that of the C-board alone.

The MORs of the C-board, S-board, and M/S-board increased as board density increased. With the M/C-board, however, the MOR increased with board density only up to a certain density, beyond which the MOR was constant. Observations of the breaking point in the M/C-board after the bending tests showed that the corrugated particleboard of the core broke down in the region of the core that had a low density; but as the core density increased and the MOR became constant, the MDF as face material was the element that broke down. Therefore, the bending strength of M/C-board depends on the core strength in low-density areas and on the strength of the face material in high-density areas. Past a certain minimum core density, the strength of the boards is influenced more by the face strength than the core strength.

The M/C-board used in this report was similar to the truss structure. It has been reported that the truss is the optimum structure for improving the strength properties of boards because it exhibits an excellent load communication. Because the MDF as face material was the limiting factor in strength beyond a certain core density, the use of high-strength facing materials can improve the MOR of M/C-board beyond the values achieved in this study.

Subsequently, we examined anisotropy in strength. Regarding the MORs of 20-mm-type C-board and M/C-board, the mean ± SD parallel/perpendicular direction ratios were 6.2 ± 1.0 and 0.9 ± 0.1, respectively. Similarly, the parallel/perpendicular ratios were 16.6 ± 11.4 and 1.3 ± 0.2 for the MORs of 40-mm-type C-board and M/C-board, respectively. Based on these results, it is clear that M/C-board is not anisotropic in strength, and that the MOR of M/C-board is greatly influenced by the MDF used. In the C-board, anisotropy in strength influenced solely by board density in the case of the lowest density sample, 0.45 g/cm^3; anisotropy in strength was not influenced by board density in the M/C-board.

The strength anisotropy of the 20-mm-type board is lower than that of the 40-mm-type board. This is presumably due to the differences in apparent density. The apparent density of 20-mm-type boards is higher than that of 40-mm-type boards.

The MORs for the perpendicular specimens of M/C-board were calculated by the method defined in JIS A 5908. The structure of these M/C-boards was similar to the truss

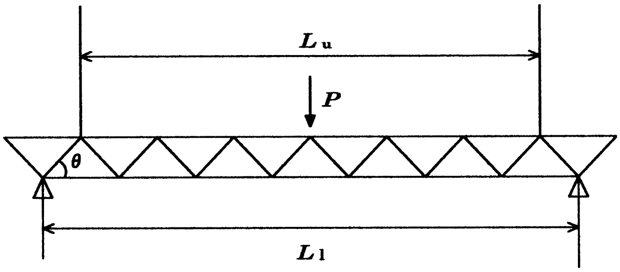

Fig. 5. Truss model for structural analysis of perpendicular specimens of composite board. L_u and L_l, lengths of the upper and lower chords, respectively; P, load; θ, angle of the diagonal member

structure. Then, perpendicular specimens of M/C-board were considered to be the truss beam, and the deflections of load-point under of 9.8N load were theoretically calculated and compared with the measured value of M/C-board. The truss model, based on data in the literature,[2] is shown in Fig. 5. The calculated values were obtained according to the following equation, which shows the relation between load P and deflection δ for structural calculation of the truss.

$$\delta\left(\frac{1}{2}\right) = \frac{P}{8\sin^2\theta}\left(\frac{2\cos^2\theta}{L_l - L_u} \times \frac{L_u^2}{E_m \times A_m} + \frac{L_l - L_u}{\cos\theta \times E_p - A_p}\right) \tag{1}$$

where L_l and L_u are the length of the lower chord and upper chord, respectively (refer to Fig. 5); E_m is Young's modulus of MDF (measured value 2.5GPa); E_p is Young's modulus of particleboard; A_m and A_p are cross-sectional areas of MDF and particleboard, respectively; P is the load (P = 9.8N); and θ is the angle of the diagonal member ($\theta = 45°$).

Figure 6 shows the relations between the deflection calculated by Eq. (1) under 9.8N load to the center and the core density in 20-mm- and 40-mm-type M/C-board. The theoretical deflection calculated by Eq. (1) decreased slightly with increasing core density, and the deflection of the 40-mm-type M/C-board was smaller than that of the 20-mm-type M/C-board. These deflection tendencies were the same as the measured value for M/C-board.

The theoretical deflections were larger than the measured deflections for both 20-mm- and 40-mm-type M/C-board. In the case of the truss the joint of parts is considered a point and movable, whereas in the case of the M/C-board the joint is a plane and immovable. The differences in joint characteristics are reflected in the difference between the theoretical deflections and the measured deflections, especially for 20-mm-type M/C-board.

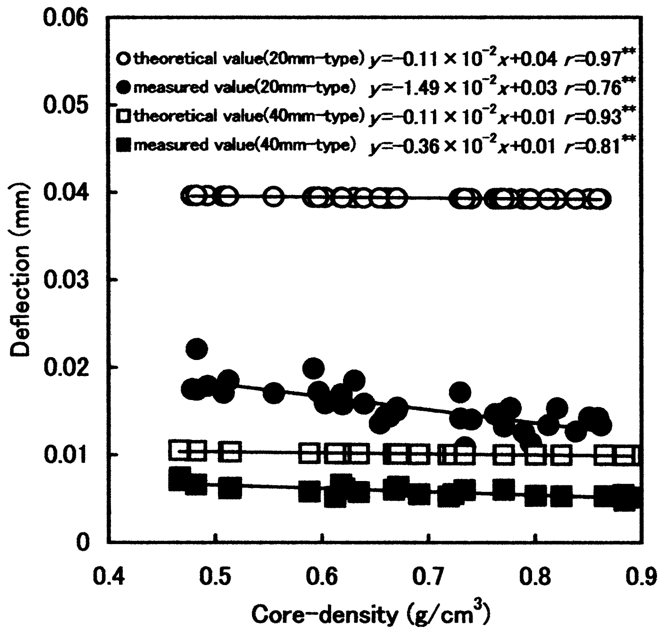

Fig. 6. Relations between the deflection and core-density of perpendicular specimens of M/C-board as the truss beam

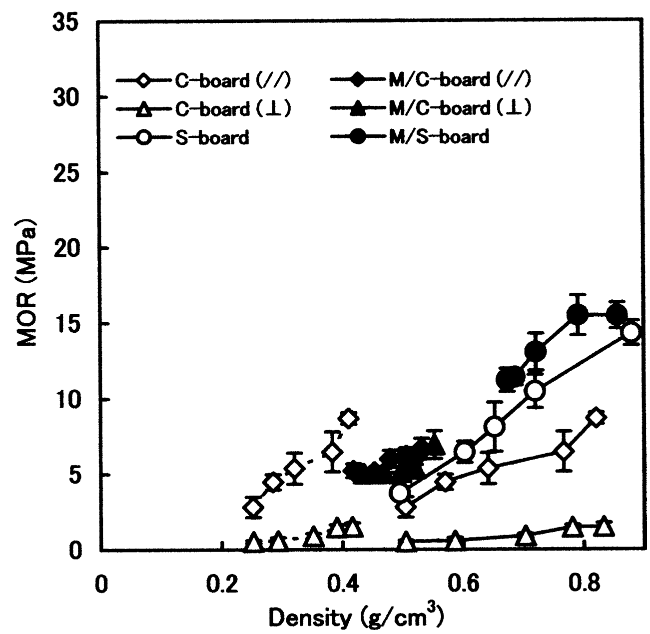

Fig. 7. Relation between MOR in the wet condition and the density of 20-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-boards (*dotted lines*) and M/C-boards were their apparent densities

Bending property in wet conditions

Figures 7 and 8 show the relation between the MORs under wet conditions and the density of each board. For the 20-mm-type C-board, the MOR under wet conditions decreased to 40%–55% of normal for the parallel specimen and 31%–60% for the perpendicular specimen. Similarly, the MOR of the 40-mm type decreased to 37%–87% for the parallel specimen and to 34%–61% for the perpendicular specimen. For S-board, the decreases in MOR were 15%–46% and 18%–50% for 20 and 40mm thickness, respectively. It is clear from these results that the decrease in the bending ability of C-board under wet conditions was larger than that of S-board. It was thought that the substantial

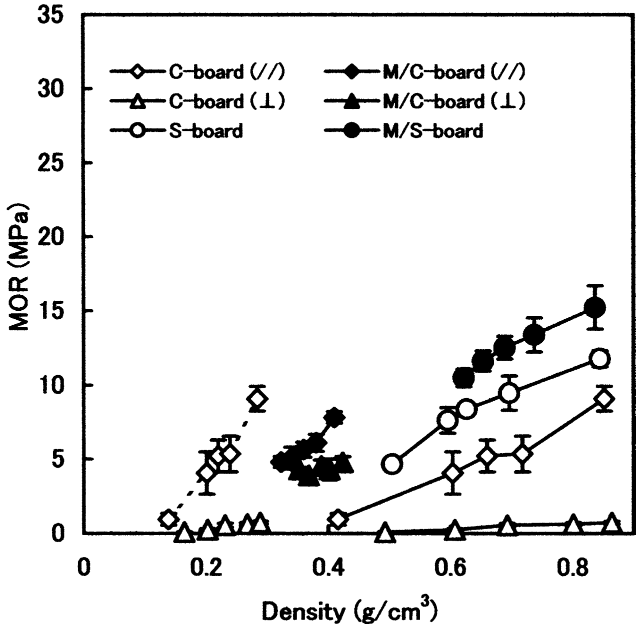

Fig. 8. Relation between MOR in the wet condition and the density of 40-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-boards (*dotted lines*) and M/C-boards were their apparent densities

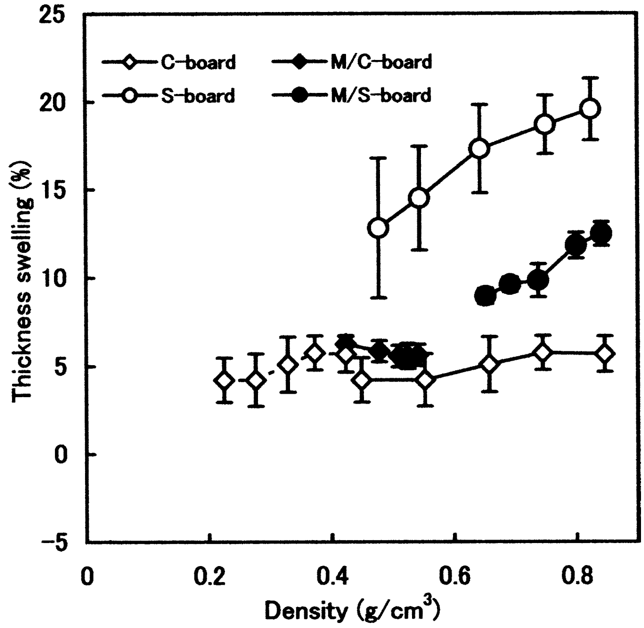

Fig. 9. Relation between thickness swelling and density of 20-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-board (*dotted line*) and M/C-board were their apparent densities

material of C-board was half that of S-board for the 20-mm type and one-third that of S-board for the 40-mm type.

In the case of M/C-board, the MOR decreased in the 20-mm type to about 62%–70% for the parallel specimen and to about 67%–76% for the perpendicular specimen. For the 40-mm type, the decrease was 64%–74% for the parallel specimen and 61%–75% for the perpendicular specimen. The decrease in MOR of M/C-board was greater than that of C-board. For M/S-board, the decrease in MOR was 47%–60% for the 20-mm type and 49%–57% for the 40-mm type; these decreases were greater than those for S-board.

Based on these findings, it can be seen that the MDF of the surface was broken more rapidly than was the core of the C-board. The MOR of M/C-board under wet conditions, unlike that in the normal condition, did not depend partially on the board density. Observation of the breaking point in the M/C-board after the wet bending test showed that most of the M/C-board was broken down at the MDF as face material. It seems that the MOR of M/C-board under wet conditions depended on the strength of the MDF. By changing the surface material, it is possible to improve the MOR of M/C-board because the corrugated particleboard of the core layer was not the part destroyed.

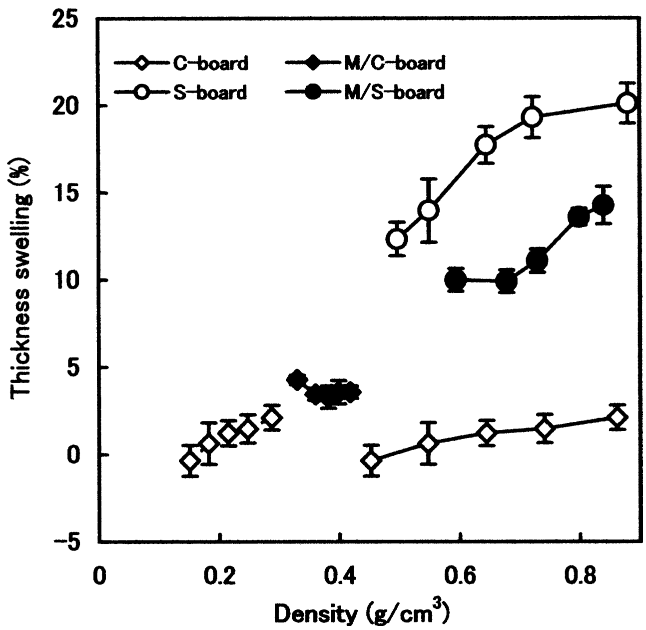

Fig. 10. Relation between the thickness swelling and density of 40-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-board (*dotted line*) and M/C-board were the apparent densities

Thickness swelling

Figures 9 and 10 show the relations between the TS and the density of 20-mm- and 40-mm-type boards. During measurement of TS, the thickness of the C- and M/C-boards was the apparent thickness including the mid-air part.

The TS of C-boards was 4.2%–5.7% for the 20-mm type and −0.4%–2.1% for the 40-mm type, and the TS of S-boards was 12.8%–19.6% and 12.3%–20.1%, respectively. The TS of M/C-board was 5.6%–6.2% for the 20-mm type and 3.3%–4.3% for the 40-mm type; and the TS of M/S-boards was 8.9%–12.5% and 9.9%–14.2%, respectively. The TS of C-board and M/C-board was superior to that of S-board and M/S-board and conformed to the value (12%) set by JIS A 5908. Moreover, the TS of MDF was 10%; we discovered that the TS of MDF decreased in the produced

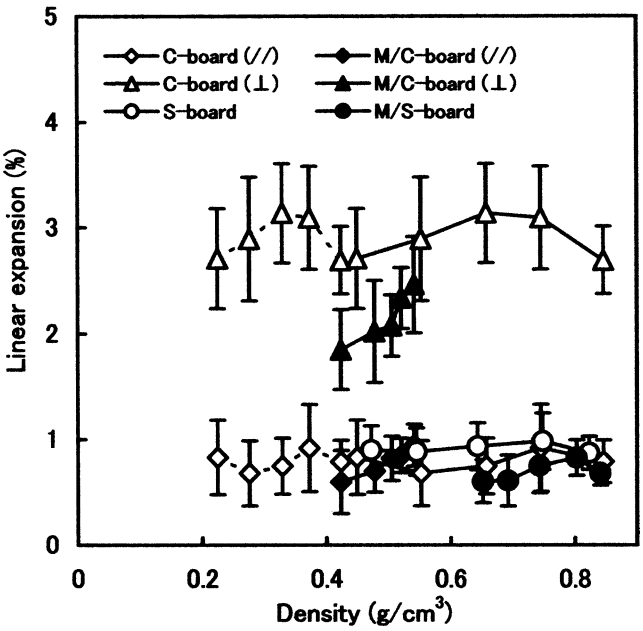

Fig. 11. Relation between linear expansion and density of 20-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C boards (*dotted lines*) and M/C-boards were their apparent densities

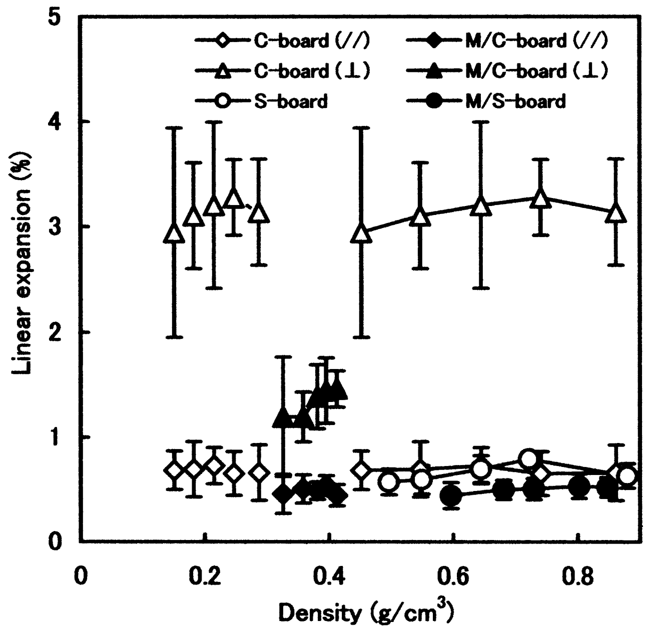

Fig. 12. Relation between linear expansion and the densities of 40-mm-type C-board, M/C-board, S-board, and M/S-board. The densities of C-boards (*dotted line*) and M/C-boards were their apparent densities

M/C-board. Because of the space in the C-board and M/C-board, the substantial material of these boards is smaller than that of S-board and M/S-board and is effective in controlling TS.[3,4]

Although the TS of S-board was improved by reinforcing it with MDF, the TS of C-board was not. It was reported that TS was closely related to linear expansion.[5] The TS of 40-mm-type C-board in the lowest-density sample (0.45 g/cm^3) showed a negative value. It was speculated that the reason for this was that expansion of the plane direction of the C-board was extremely high.

Linear expansion

Figures 11 and 12 show the relation between linear expansion (LE) and the density of the 20-mm- and 40-mm-type boards. As for the LEs of C-board (//), the values for the 20-mm and 40-mm types were almost equal to the LEs of S-board. However, the LE was higher for C-board (⊥) than for S-board. It is obvious that C-board was anisotropic in LE, and that the TS of C-board was influenced by the LE in the perpendicular direction.

The LE of C-board (//) showed insignificant dependence on board density. However, the LE of C-board (⊥) tended to increase with increasing board density; when the density of the core exceeded 0.75 g/cm^3, the LE of C-board (⊥) tended to decrease. Because of the corrugated shape, the residual stress from the forming process was liberated when C-board was soaked in water, and the LE of the perpendicular direction was increased. It was suggested that the spring-back that occurs in the thickness direction for conventional flat-type particleboard occurred in the perpendicular direction in C-board, as the LE of MDF was 0.5%. Although the LE in the perpendicular direction decreased by reinforcing the C-board with MDF, it was nonetheless higher than the LE of M/S-board. It can be concluded that improving LE in the perpendicular direction is a challenge for the future.

Conclusions

Corrugated particleboard was manufactured to provide a high-strength, low-density material. Because of the spaces in the board, the corrugated particleboard was less dense than that of flat-type particleboard. A composite board was produced by reinforcing both sides of the corrugated particleboard with MDF. The bending properties and dimensional stabilities of this composite board were investigated. Conclusions obtained from the experiment were as follows.

1. The MOR of corrugated particleboard was improved by reinforcement with MDF.
2. The MOR of composite board increased with board density only up to a certain density, beyond which the MOR was constant.
3. The decreased tendency of the deflection on the perpendicular specimen of the composite boards coincided well with the tendency of the theoretical value of the truss beam.
4. The thickness swelling of corrugated particleboard and the composite board was lower than that of flat-type particleboard.
5. The LE of corrugated particleboard was controlled somewhat by reinforcement with MDF. Considering the

practical case in which the board is used as a panel, it is necessary to improve the LE of composite board.

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