Effects of Density Profile on Bending Strength of Commercial Particleboard

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Abstract

Face layer density is widely known to be important for increasing bending strength (i.e., modulus of rupture [MOR]), whereas outer core layer density is not regarded as such. This study reports the importance of the outer core layer density for commercial particleboards. The core and face layers were manufactured with coarse and fine particles, respectively. The coarse particles increased MOR because of the long wood fibers retained in the particle, whereas fine particles did not increase MOR because of the absence of long wood fibers. Long wood fibers in the outer core layer, as opposed to face layers, increase MOR. Moreover, the sampling position of the density profile specimen was important for the MOR. The MOR was influenced with the density profile specimens obtained near the center of the MOR specimen; thus, the low-density part near the center of the MOR specimen exerted a large influence by significantly decreasing the MOR.

Commercial particleboards (i.e., boards) are more common than laboratory boards; however, studies on their properties are lacking. A previous study reported the means and standard deviations of the bending strength (i.e., modulus of rupture [MOR]), of two types of commercial boards (Korai et al. 2012). The calculated coefficients of variation (CV) were 11.3 and 7.29 percent. Moreover, Dettmer and Smith (2015) calculated the CV of the MOR of commercial boards, which ranged from 7.7 to 22.4 percent. When compared with the CV of other industrial materials such as metal, these values show a large variation. The CV of the commercial board, like that of other industrial materials, should be reduced. Although the same type of commercial board is manufactured from the same lot, the MOR variation is large and is presumably caused by nonuniformly applied adhesive, nonuniform mat moisture content, and nonuniform mat formation. The majority of these factors cannot be studied before and after hot pressing. Only the density profile after hot pressing can be studied to investigate MOR variation. The density profile of commercial boards is presumably varied as well as the MOR, but it is not extensively investigated. Density profile variation may be one of the causes of MOR variation. Therefore, the present study aimed to investigate the density profile variation.

Several studies reported an increase in MOR with increasing face layer density (Kawai and Sasaki 1986; Wong et al. 1998, 1999). Such studies used the density profiles of single-layer boards manufactured in laboratories with coarse particles (Fig. 1 [Kawai and Sasaki 1986; Wong et al. 1998, 1999]). Most studies on the relationships between MOR and density profile used a single-layer particleboard for the laboratory board. In contrast, a commercial board has three layers—face–core–face (Stark et al. 2010). The core and face layers are manufactured with coarse and fine particles, respectively (Fig. 1). Moreover, the density profiles of single-layer and three-layer boards considerably differ. Thus, the relationship between the face layer density and MOR of these boards may also considerably differ; however, this difference has not yet been investigated. For example, Strickler (1959), Kawai and Sasaki (1986), and Wong et al. (1998, 1999) studied the density profiles of single-layer boards and investigated their relationship with the MOR. Although their findings are interesting and valuable, they are inapplicable to three-layer boards. Moreover, a limited number of studies have explored the relationships between the density profiles and MOR of commercial boards. Thus, in the present study, the relationships between the density profiles and MOR are investigated

Experimental

MOR measurement

The boards used were bonded with methylene diphenyl diisocyanate resin, manufactured in a Japanese factory with the thickness and density of 9.1 mm and 0.78 g/cm^3, respectively. The core and face layers of these boards were manufactures with coarse and fine particles, respectively (Fig. 1). The boards were categorized as type 18 according

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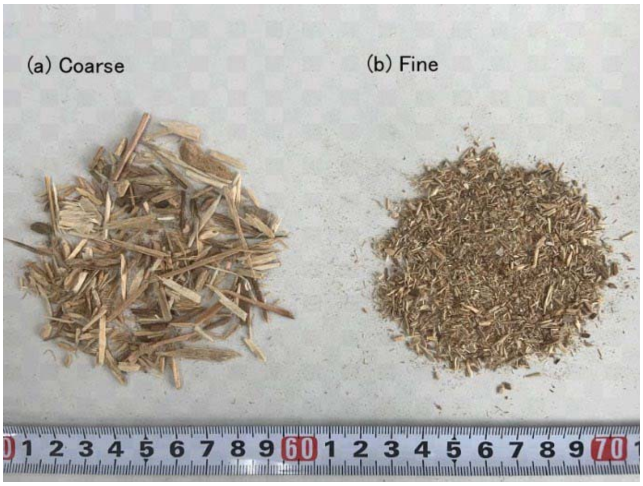


Figure 1.—Coarse (a) and fine (b) particles used for core and face layers, respectively, in this study.

to the Japanese Industrial Standards (JIS 2003). Two hundred eighty-eight MOR specimens of 50 mm × 210 mm were prepared from the two commercial boards of 910 mm × 1820 mm, which were obtained from the same lot. In addition, 127 MOR specimens were randomly selected from 288 MOR specimens that were prepared from the two commercial boards. Furthermore, MOR was determined according to JIS (JIS 2003).

Density profile measurement

An X-ray densitometer (DA-X 5000, GreCon, Germany) was used for measuring the density profile. Density profile specimens were obtained from the MOR specimens. Figure 2 shows their sampling positions within the MOR specimen. Two adjacent density profile specimens (specimens A and B) of 50 mm × 50 mm were obtained from one MOR specimen after MOR measurement. Figure 3 shows how each layer was defined in the density profile. Layers 1 to 3 (L1 to L3) were manufactured with fine particles (Fig. 1b), and the face layers (thickness, 0 to 1.7 and 7.4 to 9.1 mm) were identified. Layers 4 to 9 (L4 to L9) were manufactured with coarse particles (Fig. 1a), and the core layer (thickness, 1.7 to 7.4 mm) was identified. Density was measured at intervals of 0.1 mm along the specimen thickness, and the mean density of each layer was calculated. For example, the L1 density was obtained by averaging the densities measured at thicknesses of 0.2 to 0.7 and 8.4 to 8.9 mm. In addition, the gross density of specimens A and B were measured.

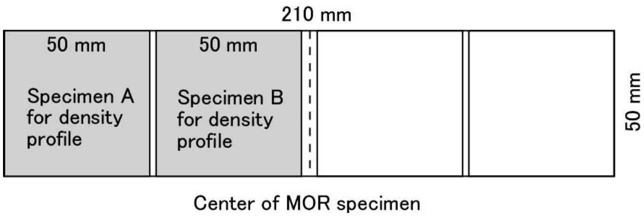


Figure 2.—Sampling positions of specimens A and B within the MOR specimen. This is the top plane of the MOR specimen. MOR is modulus of rupture.

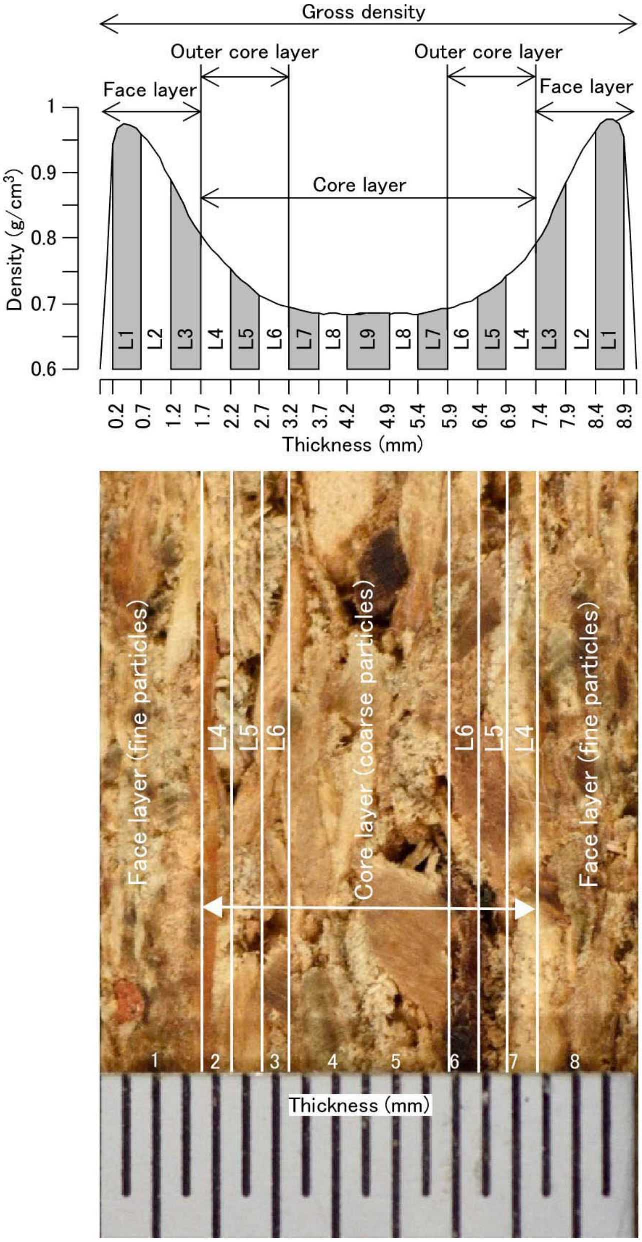


Figure 3.—Definition of layers 1 to 9 (L1 to L9) and gross densities in the density profile. This is the through-layer thickness plane of the density profile specimen.

Results and Discussion

Modulus of Rupture

Figure 4 shows the MOR histogram. The mean and standard deviation were estimated to be 23.9 and 1.69 MPa, respectively, a common trend for a normal distribution. The CV was calculated to be 7.07 percent. The same variation was obtained in other studies (Korai et al. 2012, Dettmer and Smith 2015).

Table 1 lists the correlation coefficients between the layer density and MOR. Specimen B exhibited a higher correlation than specimen A. Figure 5 shows the relationship between the gross density of specimens A (or B) and MOR. All these results indicated that specimen B is superior to specimen A in investigating the MOR because its

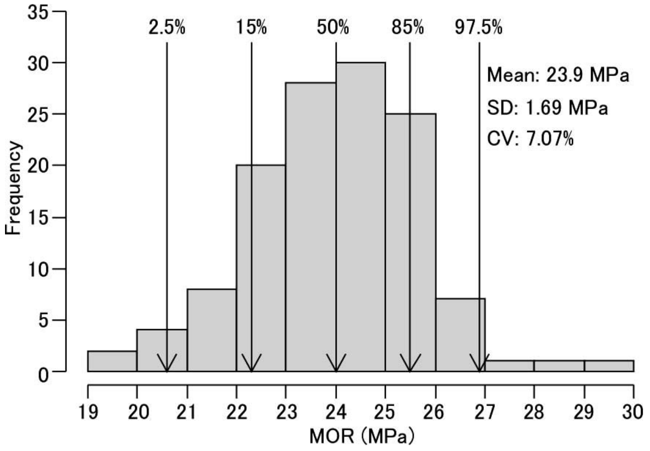


Figure 4.—Histogram of the MOR measured on 127 specimens and their 2.5, 15, 50, 85, and 97.5 percent points. MOR is modulus of rupture, SD is standard deviation, CV is coefficient of variation.

sampling position was near the center of the MOR specimen (Fig. 2). Thus, attention must be focused on the sampling position of the density profile specimen when investigating MOR based on density profile. The results indicated that the best sampling position was near the center of the MOR specimen. However, most studies have not considered this aspect.

The relationship between layer density of specimen B alone and MOR was analyzed in the following steps. The correlation coefficients of L1, L2, and L3 (face layer, Fig. 3) should be high in theory (Wong et al. 2003); however, they were low at 0.544, 0.472, and 0.507, respectively. Comparatively, unexpectedly high correlation coefficients of L4 (0.610), L5 (0.599), and L6 (0.548; outer core layer [Fig. 3]) were observed. Figure 6 shows the relationship between layer density (L1, L2, L3 L4, L5, and L6) of specimen B and MOR. Face and core layers were manufactured with fine and coarse particles, respectively (Stark et al. 2010). The size of coarse particles was significantly larger than that of fine particles (Fig. 1). Wood fibers in the fine particles were completely cut, yielding an absence of long wood fibers. MOR is that the maximum load that exceeds the proportional limit and permanent deformation in the face layers before breakdown. Long wood fibers increase the proportional limit and permanent deformation, increasing the MOR. In theory, high-density face layers increase the MOR, but very short fibers in even high-density face layers do not. Theoretically, outer core layers do not increase the MOR; however, long wood fibers in the outer core layer, as opposed to face layers, increase the MOR.

The outer core layers, particularly L4, are important for MOR increase, but this has not been well-established hitherto. This factor must be considered when discussing the density profile for increasing the MOR of three-layer boards. Hence, the theory of the density profile of the three-layer boards should be changed entirely.

Density profile

Figure 4 shows the 2.5 15, 50, 85, and 97.5 percent points of the MOR distribution. Figure 7 shows the density profiles of specimen B in 2.5, 15, 50, 85, and 97.5 percent points. One density profile was randomly selected when several density profiles existed at the same percentage point. Primarily, the MOR increased with increasing L4 density. The low and high MOR indicated the U- and V-shaped density profiles, respectively. The V-shaped density profile increased the MOR because of the high L4 density.

L4 (Fig. 7c) exhibited the highest density but not the highest MOR. This finding was presumably due to the asymmetrical density profile. The left L4 density was higher than the right; thus, the MOR in Fig. 7c was lower than that in Fig. 7e. This asymmetrical density profile presumably resulted from the nonuniform factors described in the introduction. In addition, the highest MOR (Fig. 7e) presumably resulted from the highest L1 density. In contrast, L1 density (Fig. 7a) exhibited the third-highest but the lowest MOR. This result is presumably due to the lowest L4 density. Although the L1 and L4 densities are important for increasing the MOR, the L4 density was more important than L1 density.

Layer density variation between adjacent specimens A and B

If the layer density of the adjacent specimens A and B had been similar, their correlation coefficients (Table 1) would have also been similar. However, the correlation coefficients of specimen A were lower, indicating a difference in the layer density between the two. This section investigates the layer density variation between specimens A and B. Table 2 lists the correlation coefficients of the layer densities between specimens A and B. Figure 8 shows the relationships between the L1 (or L4) density of specimens A and B as examples. L1 exhibited the lowest correlation coefficients. L1 was the outermost face layer, so it was sanded. The local surface was sanded deeply or shallowly, resulting in large variation of L1 density. Thus, sanding resulted in the lowest correlation coefficient. Specimen A was near specimen B, but their correlation coefficients were not high. Therefore, the layer density of specimens A and B were not similar, resulting in large layer density variation.

Gross density exhibited the highest correlation coefficient (Table 2). Figure 8 shows the relationships of gross density between specimens A and B. Table 3 lists the CV for comparing their layer density variations. The CV of the L1 to L9 densities was mostly higher than that of the gross density, indicating former large variation. Figure 9 shows the L4 and gross densities histograms to investigate the difference between L4 and gross density variations. The

Table 1.—Correlation coefficients between layer density[a] and modulus of rupture.

Layer	L1	L2	L3	L4	L5	L6	L7	L8	L9	Gross
Specimen A	0.390	0.279	0.370	0.509	0.518	0.446	0.307	0.151	0.103	0.411
Specimen B	0.544	0.472	0.507	0.610	0.599	0.548	0.442	0.279	0.235	0.599

[a] See Fig. 3 for layer density.

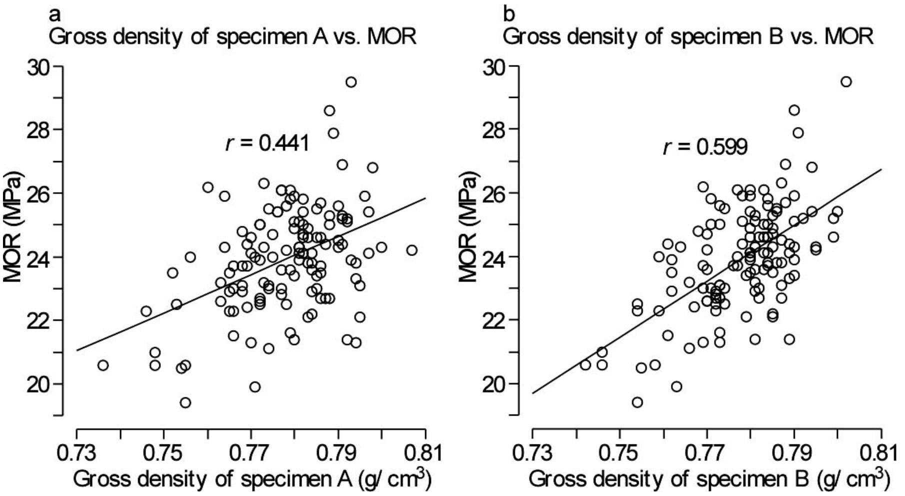


Figure 5.—(a) Relationship between the gross density of specimen A and MOR. (b) Relationship between the gross density of specimen B and MOR. See Fig. 2 for specimens A and B. MOR is modulus of rupture, r *is correlation coefficient.*

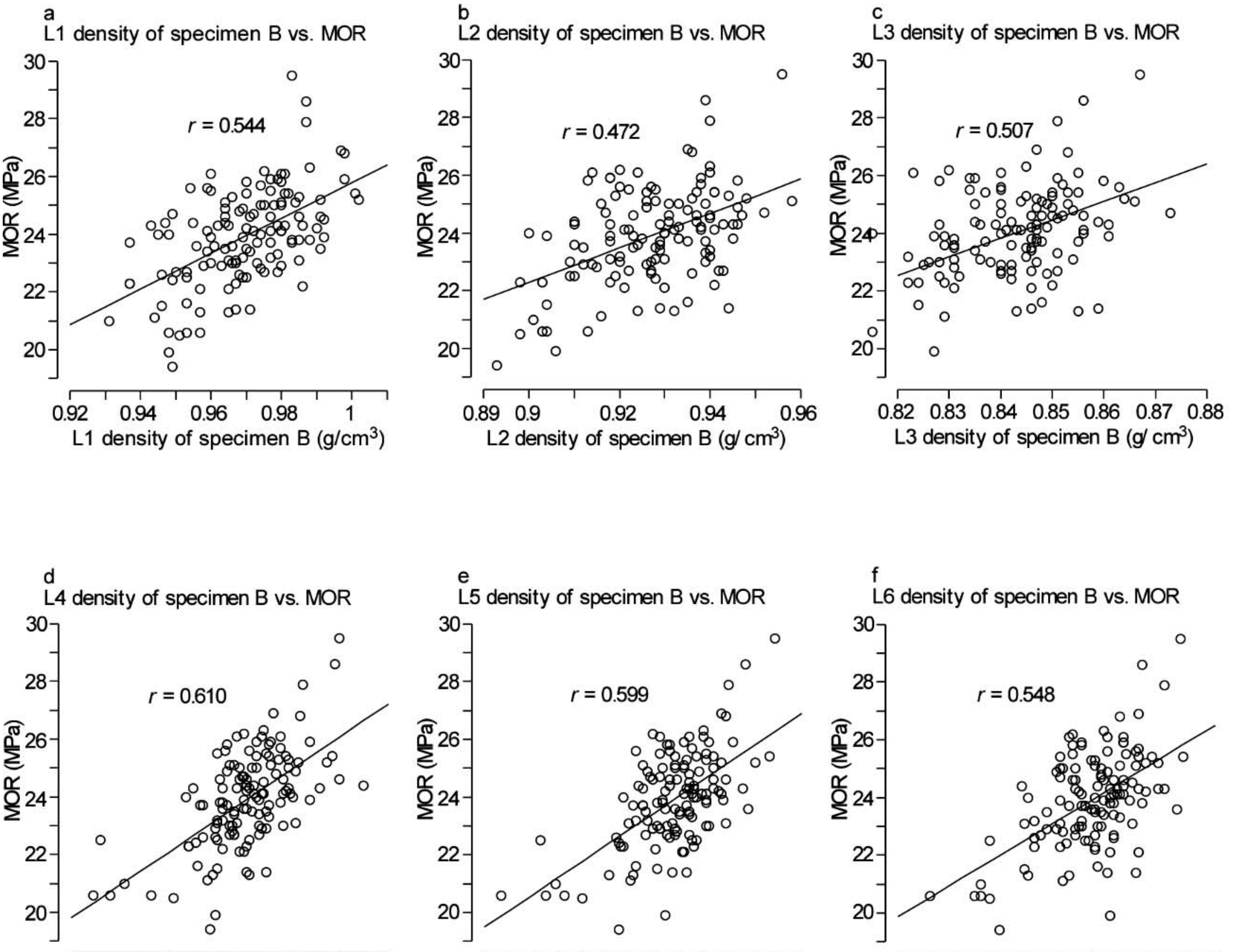


Figure 6.—Relationship between the layer density of specimen B and MOR. (a) L1 density of specimen B vs. MOR. (b) L2 density of specimen B vs. MOR. (c) L3 density of specimen B vs. MOR. (d) L4 density of specimen B vs. MOR. (e) L5 density of specimen B vs. MOR. (f) L6 density of specimen B vs. MOR. See Fig. 2 for specimen B. See Fig. 3 for L1, L2, L3, L4, L5, and L6. MOR is modulus of rupture. r *is correlation coefficient.*

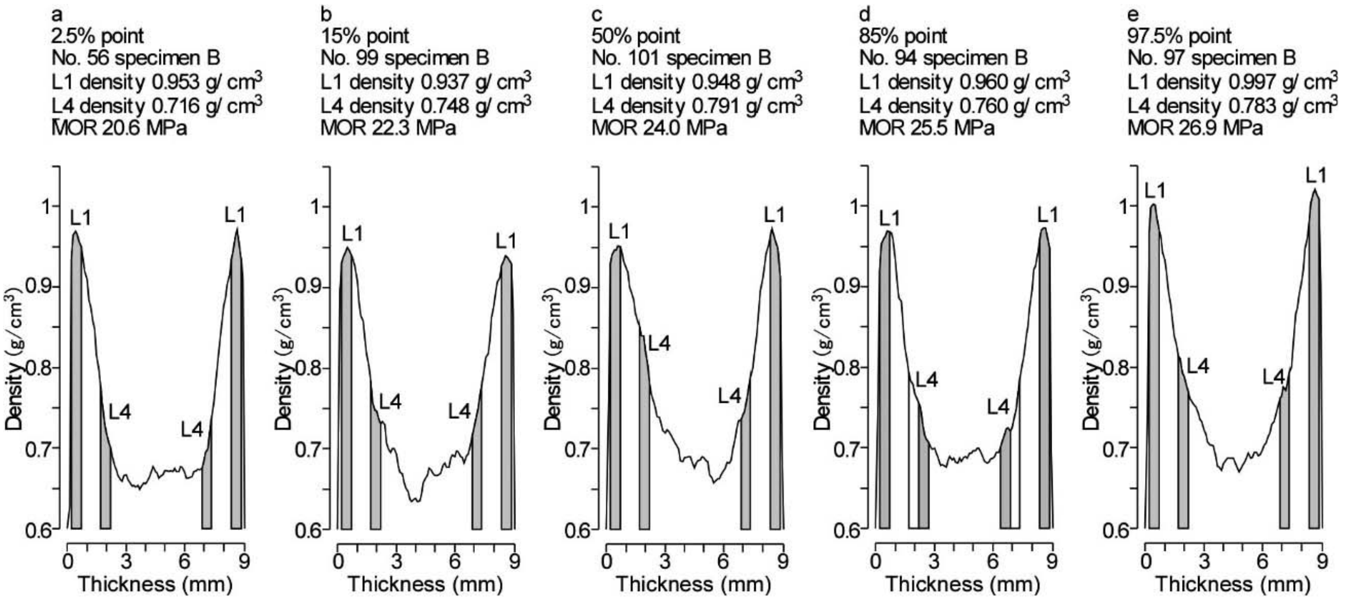


Figure 7.—Density profiles of specimen B. (a) 2.5 percent point. (b) 15 percent point. (c) 50 percent point. (d) 85 percent point. (e) 97.5 percent point. See Fig. 3 for percent point. See Fig. 2 for specimen B. No. is sampling number of the MOR specimen. See Fig. 3 for L1 and L4 densities. MOR is modulus of rupture.

Table 2.—Correlation coefficients between layer density[a] of specimens A and B.

Layer	L1	L2	L3	L4	L5	L6	L7	L8	L9	Gross
Correlation coefficient	0.577	0.688	0.647	0.767	0.789	0.656	0.669	0.712	0.722	0.849

[a] See Fig. 3 for layer density.

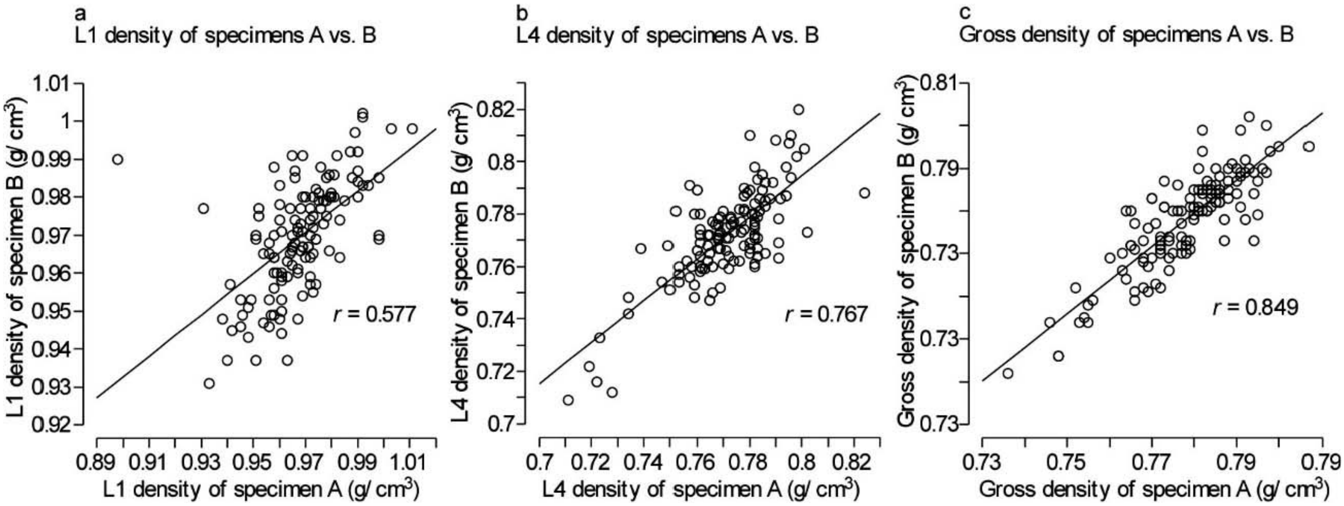


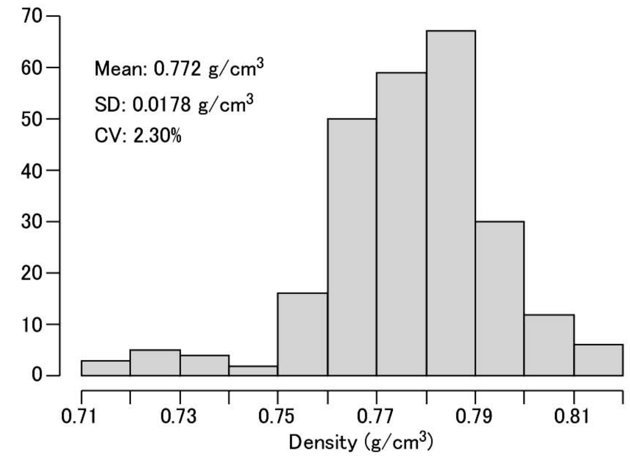
Figure 8.—Relationship between the layer density of specimens A and B. (a) L1 density of specimens A vs. B, (b) L4 density of specimens A vs. B, and (c) gross density of specimens A vs. B. See Fig. 2 for specimens A and B. See Fig. 3 for L1, L4, and gross density. r *is correlation coefficient.*

Table 3.—CV of layer density[a] of specimens A and B.

Layer	L1	L2	L3	L4	L5	L6	L7	L8	L9	Gross
Specimen A	1.64	1.62	1.83	2.27	2.39	2.22	2.13	2.45	2.77	1.60
Specimen B	1.54	1.44	1.58	2.35	2.44	1.99	2.03	2.25	2.56	1.48

[a] See Fig. 3 for layer density. CV is coefficient of variation.

a. L4 density



b. Gross density

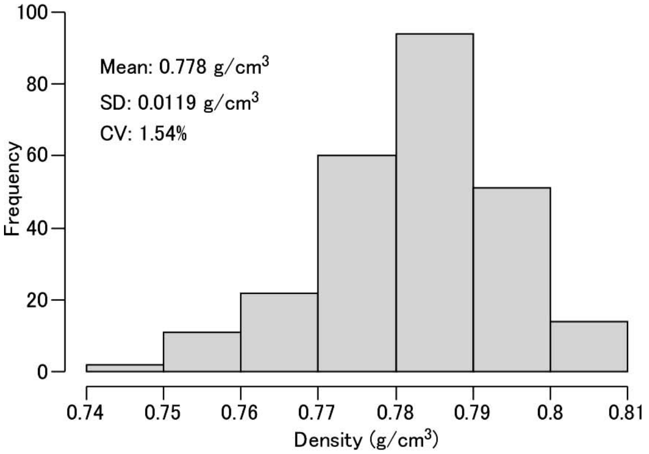


Figure 9.—(a) Histogram of the L4 density measured on 254 specimens A and B. (b) Histogram of the gross density measured on 254 specimens A and B. See Fig. 2 for L4. SD is standard deviation, CV is coefficient of variation.

gross density was normally distributed, resulting in low CV. In contrast, the L4 density was distributed to low density, resulting in high CV. The gradual drop to low density results in a large MOR reduction. The L4 density near the center of the MOR specimen influences the MOR; therefore, its sampling position is important. Alternatively, the low L4 density of a small part near the center of the MOR specimen decreased the MOR significantly. Moreover, the L4 density variation of this small part is one of the presumable causes of MOR variation. When MOR is measured, the gross density of the MOR specimen generally is measured (not the gross density of specimens A or B but the gross density of the 50 mm × 210 mm MOR specimen shown in Fig. 2). The distributions of gross density and density profile differ, so MOR should be investigated using both gross density and density profile.

Reconsideration of the MOR evaluation method

MOR is an essential index for evaluating mechanical properties according to JIS (JIS 2003). With a board thickness of 9.1 mm, the size of the MOR specimen is 50 mm × 200 mm. In contrast, the size of the commercial board is 910 mm × 1,820 mm (i.e., the MOR specimen is considerably smaller than the commercial board). One MOR specimen is obtained from many commercial boards as the representative commercial board. A MOR specimen with the low L4 density of a small part near the center of this specimen is possibly sampled in the JIS test. This specimen significantly decreased the MOR, which is unacceptable according to JIS. Consequently, many commercial boards manufactured from the same lot are unacceptable by JIS. The number of specimens with low L4 density can be best reduced through the reduction of nonuniform factors (as described in the Introduction). However, implementation of this reduction method in the present manufacturing systems is difficult. Therefore, rather than evaluating the MOR using a small specimen, 910 mm × 1,820 mm commercial boards should be evaluated using nondestructive testing methods.

Conclusion

Hitherto, compared with the outer core layer density, the face layer density is the primary parameter for increasing the MOR. The core layer was manufactured with coarse particles, whereas face layers were manufactured with fine particles. Long wood fibers are retained in the coarse particles; therefore, coarse particles increased the MOR, whereas fine particles did not do so because of the absence of long wood fibers. Long wood fibers in the outer core layer, as opposed to face layers, increase the MOR. Consequently, even the outer core layer density, particularly the L4 density, influenced the MOR. Moreover, attention must be focused on the sampling position of the density profile specimen. For MOR investigation, the best sampling position was near the center of the MOR specimen. Moreover, low L4 density of the small part near the center of the MOR specimen has a large effect on the considerable decrease in MOR. The L4 density variation of this small part is one of the presumable causes of MOR variation.

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