# Effect of furnish type and high-density raw material from mill residues on properties of particleboard panels

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**Title :**

# Effect of furnish type and high-density raw material from mill residues on properties of particleboard panels

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Furnish type; high-density wood; mill residues; particleboard properties

## Abstract

The purposes of this study were to examine the use of furniture mill residues containing high-density raw materials in particleboard production and to evaluate the effect of mixing several types of furnish on board performance. Wood wastes collected from the furniture industry in Japan containing matoa (*Pometia pinnata*), Douglas-fir (*Pseudotsuga menziesii*), and sugi (*Cryptomeria japonica*) with different particle shape were prepared as raw materials for use in the manufacture of experimental particleboards. Seven board type and three mixed boards were manufactured with three replications. Methylene diphenyl diisocyanate (MDI) resin was applied at 6% content in mat preparation. The pressing conditions were temperature of 180°C, initial pressure of 3 MPa, and pressing time of 5 minutes. The target density was 0.72 g/cm$^3$. This study showed that matoa particleboard had properties suitable for use in interior applications, although its properties were considered inferior compared with other particleboards. Improvement of matoa particleboard could be achieved by mixing with higher quality wood particles such as those from sugi or Douglas-fir. The furnish type used in this study affected board performance. All residues from furniture mills have the potential to be used for particleboard production, even when they contain different furnish types and wood species.

## Introduction

The particleboard (PB) industry in Japan developed in the 1960s using plywood mill residues as the main raw material. Since then, domestic plywood production has decreased from 8 million $m^3$ in 1980 to 3 million $m^3$ in 2000, and procuring raw materials has become a critical issue in the PB industry in terms of maintaining and expanding production. In the 1990s, recycled wood generated from demolition and construction was used to supplement the shortage of plywood residues [1]. About 20% of PB production in Japan was generated using wood from demolition sources in 1992 [2], and the use of recycled wood in the industry accounted for 80% of total production in 2010.

Despite this situation, the residues generated in the furniture and fixtures industry have not yet been used for PB production. One reason for this is that residues from the furniture and fixtures industry contain high-density hardwood, which is not considered suitable as a raw material in PB production [3]. The density or specific gravity is an important factor in determining which species are used in the manufacture of composition board products, where lower density woods will produce boards with strength properties superior to higher density species [4]. A study by Setunge et al. [5] showed that 100% utilization of hardwood residues is feasible for PB production, but it has not been possible to achieve a quality comparable to that of softwood PB. Gamage et al. [6] reported that hardwood PB had better mechanical and physical properties when the surface resin content and pressing times were higher.

In this study, the availability of residues from the furniture and fixtures industry for PB production was determined. The target product was PB for interior application particularly a thick board used for flooring system. One hardwood and two softwood species were selected as raw materials in this work. Matoa (*Pometia pinnata*), one of the high-density hardwood species, has the potential to be used as a raw material for PB production. Moslemi [7] and Maloney [4] explained the negative effects of high-density raw materials on the mechanical properties of PB. Therefore, to minimize the negative effects of high-density particles, PB needs to be produced by combining low-quality particles such as matoa with high-quality particles from softwood species such as sugi or Douglas-fir. Besides the density of wood species, the shape and size of particles can also affect PB quality. Moslemi [7] stated that the performance of particleboard is a reflection of particle characteristics. Both the slenderness ratio (length/thickness) and the flatness ratio (width/thickness) of particles are important. Hammer milling, which produces relatively low-quality particles compared with the commonly used knife-ring flaking operation, was used to fabricate laboratory-scale boards. The main purposes of this study were to examine the utilization of high-density raw materials in particleboard production and the possibility of using residues from the furniture industry and to evaluate the effect of mixing several types of particles as raw material on board performance.

## Materials and Methods

### Furnish preparation

Wood wastes from matoa (*Pometia pinnata*), Douglas-fir (*Pseudotsuga menziesii*), and sugi (*Cryptomeria japonica*) were used as raw materials to manufacture experimental PB. The species and furnish types for the fabrication of boards are listed in Table 1. The raw materials of M-, Mt-, D- and S-board were first chipped employing a hammer mill and screened using a sieve of 4-mm mesh to remove the larger particles. Mt-board was produced from a hammer-milled particles obtained from matoa slabs (trimmed) in a commercial mill, which possibly contain low quality parts such as pith, compression failure and same decay. Ms- and Ds-board were produced from matoa and Douglas-fir planer shavings. To obtain a relatively high-quality particle for comparison, Douglas-fir lumbers were waferized by a disk flaker and then hammer milled to reduce the particle size (Dk-board). C1-board comprised of M-, D- and S-type particles, whereas C2-board was composed of the particles used in M- and D-board with the same proportion of each particle type. C3-board used five types of furnish containing two shavings (Ms- and Ds-type particles); hence, this type of board simulated a particleboard made from all the wood residues produced in the furniture and sawmill industry. As for reference, Fig. 1 provides representatives of furnish type used in this study. Particles were dried in a laboratory dry kiln at 60ºC to a final moisture content of around 10%. The particle-size distribution of each furnish type was determined with a sieve shaker into six different size classes as shown in Table 2. The dimensions (length, width, and thickness) of 300 randomly selected particles of  representative particles type (M-, D- and Dk-type) were measured manually using calipers for determining its slenderness and aspect ratio.

## Panel manufacture

Methylene diphenyl diisocyanate (MDI) adhesive, Cosmonate M-201W obtained from Mitsui Chemical Co.Ltd., was applied in a rotating drum blender fitted with a pneumatic spray gun [8]. MDI was applied at 6% based on oven dry weight. The mat moisture content before pressing was controlled to be approximately 12%. Particle mats were created manually without orientation. Seven board type and three mixed boards were manufactured for experimental PB with three replications. The dimensions of PB were 320 × 340 × 10 mm. The target density of pressed board was 0.72 g/cm³. The mat was hot pressed for 5 minutes at a press temperature of 180 ºC and an initial pressure of 3 MPa. After pressing, the edges of the pressed panels were trimmed to the final size of 280 × 280 mm and then the actual board density was measured. The actual board density ranged from 0.69 to 0.72 g/cm³.

## Testing methods

Physical and mechanical properties of the boards were determined according to Japanese Industrial Standards (JIS) A 5908 [9]. The properties evaluated were the modulus of rupture (MOR) in static bending and the internal bond strength (IB). Six specimens of each board type measuring 280 x 50 mm were used for MOR test, whereas seven specimens of each board type measuring 50 x 50 mm were used for IB test. Three samples were selected randomly for the linear expansion test. Prior to testing, all specimens measuring 280 × 50 mm were conditioned in climate chamber having temperature of 60ºC for 22 h to have a constant moisture conditions and initial dimensions. Linear expansion (LE) of the samples was measured using a dial gauge comparator [10] at intervals during treatment under humid conditions at 40°C and 90% RH for 120 h, followed by dry conditions at 60°C for 120 h [11]. Estimation of the properties for C1, C2 and C3 was calculated based on the weight proportion of each constituent. Thickness swelling (TS) test consisted of immersion in water at 20°C during 24 hours. Four specimens with dimension of 50 x 50 mm were used. Vertical density profiles (VDP) of the specimens were also measured using a commercial density profiler (DA-X; GreCon) based on an X-ray system. Specimens with dimensions of 50 × 50 mm were used.

## Results and Discussion

### Particle Classification

Sieve screen weight data analysis was used to characterize the shape of particles, as previously performed by Sackey and Smith [12]. The mean weight percentage of each particle size is shown in Table 2. For each type of particle, the largest mass fraction was collected in the 10-mesh sieve, which had an opening of 2.0 mm. M-board type particles were mainly distributed in three fractions: 15% in the 5(+) sieve, 64% in the 10(+) sieve, and 16% in the 20(+) sieve. These three fractions constituted 95% of M-board type particles screened. Approximately 90% of Dk-board particles were in two fractions, the 5(+) and 10(+) sieves. There were no large differences in the ratios between M- and Mt-board particles, which originated from the same source. Among the seven particle types, Ms-board particles were distributed more widely in these fractions. About 5% was collected on the 40-mesh screen and 6% passed through the 40 mesh. The slenderness ratio of M-, D-, and Dk-type particles were 13, 14, and 40, respectively, whereas those aspect ratio were 7, 7, and 9, respectively.

### Mechanical properties of the samples

Figure 2 illustrates the MOR values of the samples. The mean MOR for M-board was 13.4 MPa under dry air conditions, which meets the requirement for 13-type PB as specified by JIS [9]. Because there are several disadvantages in using M-type particles, this value was higher than we expected prior to board fabrication. It is known that high-density species are not good for particleboard production because of the resulting low compaction ratio. Furthermore, particles configured using a hammer-milling operation do not have good bending properties compared with ring-flaked particles. Despite these unfavorable conditions for M-type particles, the results indicated that panels made from M-type particles resulted in acceptable bending properties when using MDI resin. Such findings suggest the potential of matoa as a raw material for PB for use in interior applications. There was no significant difference between the MOR for M- and that for Mt-boards, even though Mt-board consisted of particles obtained from slabs when lumber was being prepared for furniture and fixtures.

Comparing the three main raw materials produced by hammer milling, D- and S-board had much larger MOR values than those of M-type panels. One of the reasons of this finding would be the lower density of conifers. The densities of particles used in M-, D-, and S-board were 0.64 g/cm$^3$, 0.41 g/cm$^3$, and 0.32 g/cm$^3$, respectively, and the corresponding compaction ratios were 1.13, 1.76, and 2.25. Maloney [4] stated that a compaction ratio of at least 1.3 is required to produce well-bonded boards. This suggests that M-board will not achieve good bonding quality compared with D- or S-board. There was a significant difference between the MORs of M- and D-board at the 5% confidence level, but no significant difference was found between the MORs of D- and S-board. It was observed that the MOR in PB produced from planer shavings was low, as also reported by Heebink et al. [13], when compared with those from hammer-milled.

The particles used in Dk-board were flakes created in the laboratory to allow a comparison with the other six particle types. As expected, the MOR value of Dk-board was much higher than those of the other board types, demonstrating how particle shape affects the mechanical properties of PB. It is well known that thin and long particles (i.e., strands or flakes) give higher bending properties. The MOR of Dk-board was about twice than that of D-board, whereas the slenderness ratio of Dk and D particles were 40 and 14, respectively. In this study, we used a hammer-milling operation for particle preparation, presuming a lower grade furnish; however, the effect of particle shape was confirmed by a comparison with Dk-board.

The MORs of the mixed boards (C1, C2, and C3) were around 15 MPa. From Fig 2, it can be seen that the mixed boards had higher MOR values than those of made from M-type particles. This implies that by mixing with a higher quality particle, the MOR of M-board can be enhanced. Based on the MOR values of each furnish type, we also estimated the MOR values of the mixed boards and compared these estimates with the observed MOR values. The observed MORs of mixed boards were similar to the estimated values, suggesting that the properties of a mixed PB can be determined from the properties of each constituent. This is in accordance with the study by Hu et al. [14], which predicted the bending properties of three-layered PB using the rule of mixture. Moya et al. [15] also made similar observations in a study to predict the bending stiffness of hybrid panels. Based on the statistical analysis using t-test, bending strength values of the samples had sufficient values suggesting that such waste material can have potential to be used for PB manufacture.

## Internal bond strength

Figure 3 illustrates the effects of particle shape and type on IB strength. The IB strength of M-board was 1.2 MPa, which was a surprising result. All board types exhibited high IB values, exceeding the requirement of 0.3 MPa for 13-type PB as specified by JIS [9]. S-board had the largest IB strength value among the six particle types from mill residue (M- to Ds-board particles) and was comparable to that of Dk-board, with a value of 2.0 MPa. One of the reasons for this high IB strength was the high bonding performance of the MDI resin used in the experiment [8, 16]. It was also found that a resin content of 6% was sufficient to provide the necessary internal bond properties for hammer-milled particles.

It was observed that Dk-board particles had higher quality as a furnish in terms of IB strength. The differences in IB strength between Dk-board particles and other hammer-milled particle was small compared with the differences in MOR shown in Fig. 2. Although a particle with a high slenderness ratio, such as a flake, enhances the bending properties of the board, it would not necessarily contribute to the enhancement of the internal bonding properties. According to a study by Wong et al. [17], IB strength was strongly correlated with core density, where the compaction ratio has an important role in producing greater interparticle contact. This explains why S-board had a higher IB strength than did D- or M-board has.

The results also indicated that the IB quality of the mixed boards was sufficiently high when MDI binder was used. The IB strengths of C1, C2, and C3 were 1.6 MPa, 1.3 MPa, and 1.5 MPa, respectively, which are much larger than the JIS requirement of 0.3 MPa. The mean IB strength for the three mixed boards corresponded to the ratio of S-type particles, which provided high IB strength to S-board. Particle-size mix also more strongly influences the IB strength than does particle density [18, 19]. We also estimated the IB strength of the mixed boards and compared it with the observed IB strengths based on the IB strength of each furnish type. The observed IB strength of mixed boards was higher than the estimated value, but the difference was not significant. This suggests that the properties of mixed PB can be asummed from the properties of each constituent.

## Vertical density profile

Figure 4 illustrates density profiles of the samples made from different furnish in terms of their effect on mechanical properties of the specimens. These profiles show two peak densities in the outer layers of the board, with the lowest density in the core layer. PB made from Douglas-fir (D-board) and sugi (S-board) showed a greater difference in the density profile between the surface and core region and had a sharper density gradient in the thickness direction than did M-board. This condition resulted in a higher MOR value for D- and S-board than that for M-board, as shown in Fig 2. Chen et al. [20] stated that the density profile is the combined result of temperature, moisture content, and pressure gradients in the furnish during pressing. Thus, the different wood species used in this study influenced the density profile, with the density of raw materials and the particle shape and size affecting the mat compaction and heat-transfer velocity during hot pressing. Miyamoto et al. [18] reported similar results, with board density and particle size also affecting the temperature behavior.

In terms of VDP, the peak and core density are regarded as the dominant factors affecting PB properties [21]. The difference between the peak density and the core density was 13% for M-board, 26% for D-board and 20% for S-board. This implies that PB made from higher density wood species will demonstrate a smaller difference in density between the surface and core region than will PB made from lower density wood species. The peak distance (i.e., the distance between the highest density layer and the board surface) was 1.36 mm, 1.06 mm and 1.10 mm for M-, D- and S-board, respectively. This is evidence that D- and S-board had a higher MOR than did M-board. The higher density in the surface layers correspondingly generates greater bending strength and greater resistance to absorption and swelling [22].

## Dimensional stability

This study also measured linear expansion (LE) because the target board was a thick PB used directly over a floor heating system, and we were concerned with dimensional stability in the linear direction. Medium-density PB is allowed to change linearly by a maximum of 0.35 percent due to atmospheric changes ranging from 50 to 90% relative humidity (RH), as required by ANSI 1999 [23]. Figure 5 illustrates the LE behavior of PB. The figure shows that furnish type affected the LE more significantly than wood species did, and planer shavings had the highest value. This suggests that particle length and thickness play important roles, as noted by Sackey et al. [24], who reviewed several studies and noted that LE increased with decreasing particle length and increasing particle thickness. However, our study showed that Dk-board had the highest LE value of all the hammer-milled particleboards. This might be due to high levels of moisture absorption in the surface of knife-milled board, which led to more expansion in the linear direction.

Figure 6 presents the total LE (dLE) for all types of boards tested, where dLE is defined as the difference between the LE at 120 h under humid conditions and the LE at 240 h under dry conditions. Thus, dLE can be considered the ultimate linear dimensional change, which would potentially occur under extremely severe conditions. The effect of particle type can be determined by comparing dLE values. No large differences among M-, Mt-, and D-boards were found, although the use of planer shavings resulted in boards with larger LE value. The dLE ratio of Ms-board to M-board was 1.7, and that of Ds-board to D-board was 1.9. Although Dk-board showed better qualities, the dLE value of Dk-board particles was relatively higher than were those recorded for the hammer-milled particle types used in M-, D-, and S-boards. The reason for this is not clear at this stage, but the result demonstrates that different particle shapes and sizes generate different LE values. This is in agreement with other studies, which have reported that LE is much more dependent upon particle geometry than on density [3, 16, 18].

For M-board, the dLE was 0.45%, and the corresponding moisture content change (dMC) from the wet condition to the dry condition was 12.3%. Thus, the LE per unit moisture change (LE/MC) for M-board was 0.033. The moisture change (dMC) for all board types ranged from 11.5% to 12.6%, and the LE/MC of the boards with hammer-milled particles ranged between 0.030 and 0.040. The mixed boards (C1, C2, and C3) also had LE/MC values ranging from 0.030 to 0.040. These values were comparable to or lower than those of commercial boards.

Thickness swelling, the change in thickness of the board, is also a parameter of dimensional stability. Figure 7 illustrates the TS value of PB from several furnish types. It can be seen that seven furnish types resulted PB with TS value lower than 12 %, as required by JIS [9], whereas TS value of mixed boards (C1, C2, and C3) exceed the JIS requirement. The TS values seem conversely with the LE value. There were no significant differences among M-, Mt-, D- and S-board, but those were different to Ms-, Ds- and Dk-board. It implies that particle type more influenced TS rather than wood species did. Planer shavings and knife-milled particles are thinner than hammer-milled particles. It causes to swell greater after 24 h water soaking. That the mixed boards resulted higher TS value, it might be due to unstable inter-particles bonding between different wood species inside the panel during water soaking that caused the panels easy to swell.

## Conclusions

Residues from the wooden furniture industry have not yet been optimally used for PB production because they consist of a wide range of particle geometries and different wood species. In this study, the availability of all residues from the furniture and fixtures industry, including the use of high-density raw material such as matoa, was assessed for PB production. Experimental PB were produced using all possible raw materials.

This study showed that matoa particleboard had properties rendering it suitable for use in interior applications, although its properties were considered inferior compared with the other particleboards. Improvement of matoa particleboard could be achieved by mixing with higher quality wood particles such as sugi or Douglas-fir particles and by using MDI resin. The use of sugi resulted in better quality matoa particleboard than did use of Douglas-fir in terms of bending properties, internal bond strength, and linear expansion.

The furnish type used in this study affected board performance. PB made from knife-milled Douglas-fir particles was the best performer in terms of strength and linear expansion, but for the same particle size, sugi performed best, followed by Douglas-fir and matoa. The use of all residues from the furniture industry resulted in PB properties that met JIS requirements.

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## Legend to Figures

**Fig. 1.** Representative furnish type used in this study. M: matoa hammer-milled, D: Douglas-fir hammer-milled, Dk: Douglas-fir knife-milled.

**Fig. 2.** Modulus of rupture (MOR) of particleboard made from various furnish type and wood species. Error bar indicates the standard deviation.

**Fig. 3.** Internal bond (IB) strength of particleboard made from various furnish type and wood species. Error bar indicates the standard deviation.

**Fig. 4**. Vertical density profiles of particleboards. M: matoa board, D: Douglas-fir board, S: sugi board.

**Fig. 5.** Linear expansion (LE) of particleboards made from various furnish type and wood species. Treatment under humid conditions of 40°C and 90% RH for 120 h, followed by dry conditions of 60°C for 120 h.

**Fig. 6.** Total linear expansion of particleboards made from various furnish type and wood species. dLE: difference between LE at 120 h under humid conditions and LE under dry conditions.

**Fig. 7.** Thickness swelling (TS) of particleboards made from various furnish type and wood species. Error bar indicates the standard deviation.

**Table 1.**

Wood species and furnish type for the laboratory-made particleboards

| Board name | Species and furnish type |
|---|---|
| M | Matoa; hammer-milled |
| Mt | Matoa slabs (trimmed); hammer-milled |
| D | Douglas-fir; hammer-milled |
| S | Sugi; hammer-milled |
| Ms | Matoa; planer shavings |
| Ds | Douglas-fir; planer shavings |
| Dk | Douglas-fir; knife-milled |
| C1 | M, D, and S mixture |
| C2 | M and D mixture |
| C3 | M, D, S, Ms and Ds mixture |

**Table 2.**

Weight percentage of each particle size class (%)

| Furnish type | Mesh size [a] | | | | | |
|---|---|---|---|---|---|---|
| | 5 (+) | 10 (+) | 20 (+) | 30 (+) | 40 (+) | 40 (-) |
| M | 15.3 | 64.0 | 15.6 | 3.2 | 1.6 | 0.3 |
| D | 20.6 | 56.3 | 12.8 | 3.7 | 3.6 | 3.0 |
| S | 34.7 | 55.8 | 7.7 | 1.1 | 0.5 | 0.2 |
| Mt | 15.8 | 62.3 | 15.6 | 3.4 | 1.9 | 1.0 |
| Ms | 15.1 | 40.2 | 28.1 | 7.8 | 4.9 | 6.0 |
| Ds | 37.0 | 39.6 | 16.2 | 4.1 | 2.2 | 1.0 |
| Dk | 40.8 | 51.3 | 6.2 | 1.1 | 0.5 | 0.2 |

[a] Mesh size opening: (+) particles retained on the sieve; (-) particles pass through the sieve. Each mean is the result of n = 3 sample bags with each bag containing 50 g furnish.

**Fig.1**

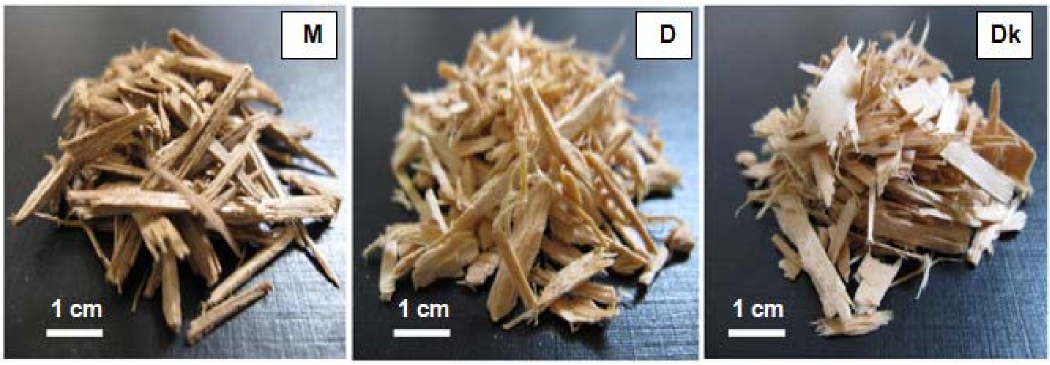
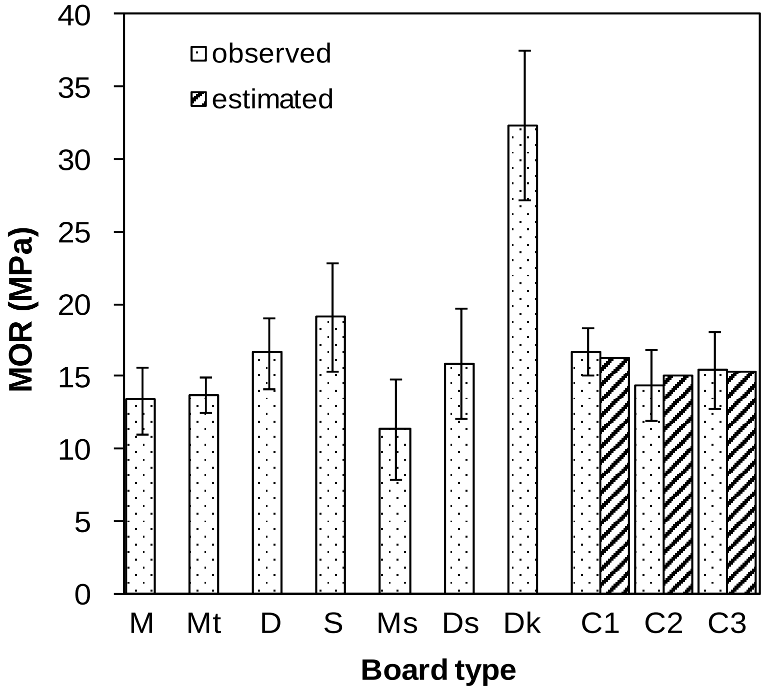


**Fig.2**



40
35
30
25
20
15
10
5
0
MOR (MPa)
observed
estimated
M
Mt
D
S
Ms
Ds
Dk
C1
C2
C3
Board type

**Fig.3**

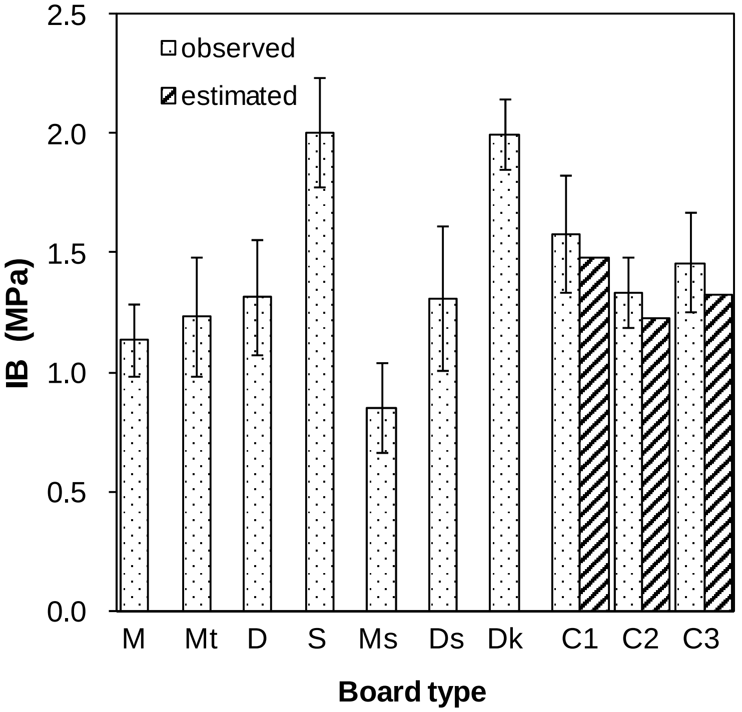

2.5
2.0
1.5
1.0
0.5
0.0
IB (MPa)
observed
estimated
M
Mt
D
S
Ms
Ds
Dk
C1
C2
C3
Board type

**Fig.4**

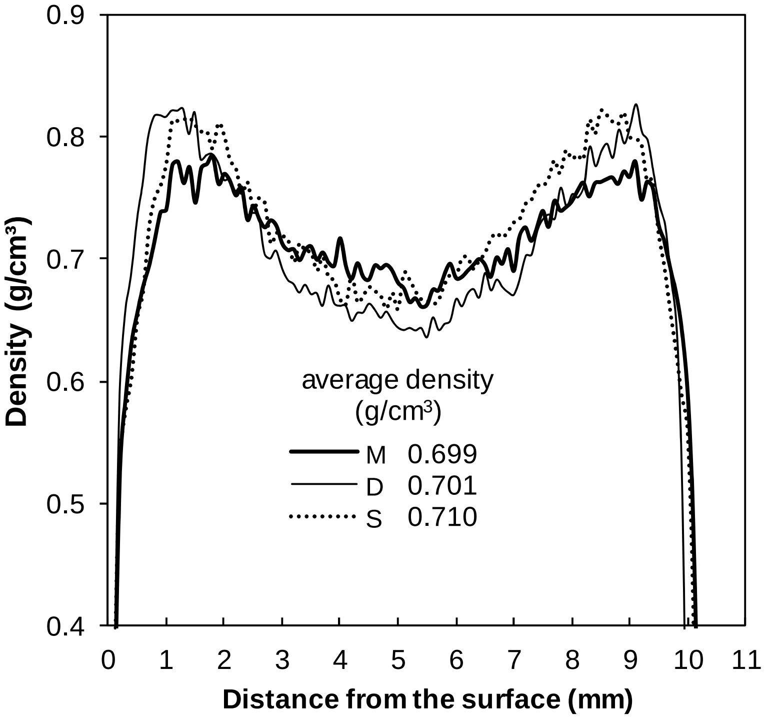

0.9
0.8
0.7
0.6
0.5
0.4
Density (g/cm³)
0
1
2
3
4
5
6
7
8
9
10
11
Distance from the surface (mm)
average density
(g/cm³)
M 0.699
D 0.701
S 0.710

**Fig.5**

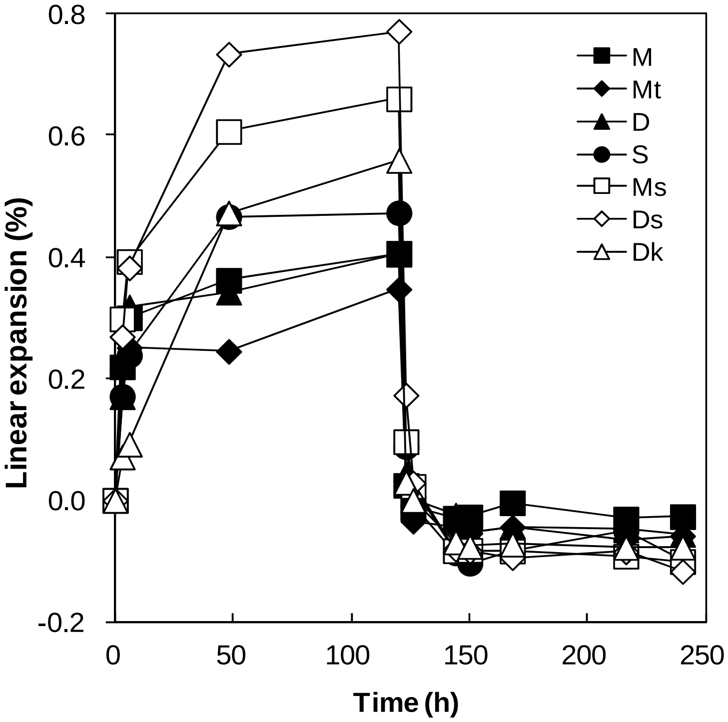

Linear expansion (%)
0.8
0.6
0.4
0.2
0.0
-0.2
0
50
100
150
200
250
Time (h)
M
Mt
D
S
Ms
Ds
Dk

**Fig.6**

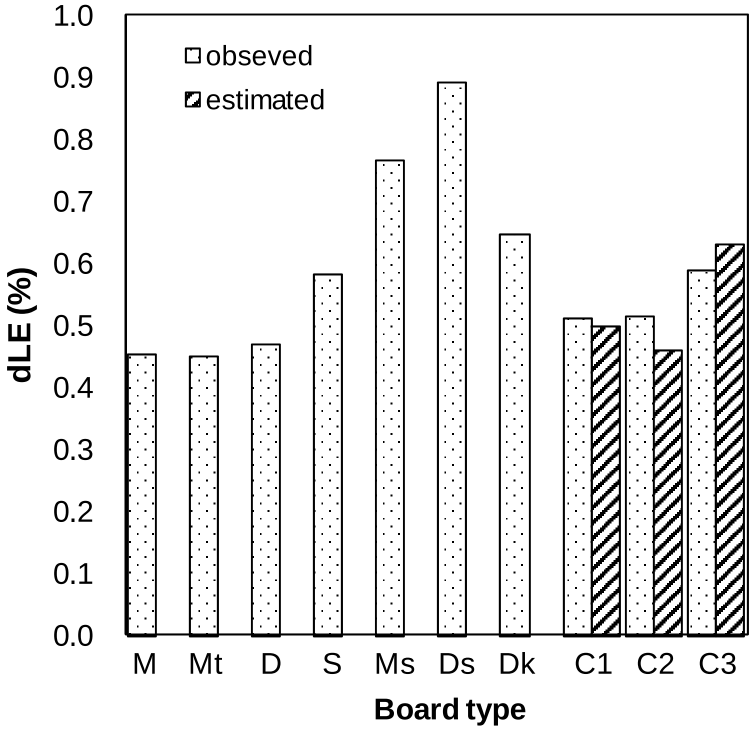

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
dLE (%)
obseved
estimated
M
Mt
D
S
Ms
Ds
Dk
C1
C2
C3
Board type

**Fig.7**