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Formation of the density profile and its effects on the properties of particleboard

E.-D. Wong, M. Zhang, Q. Wang, S. Kawai

Summary Two types of particleboards bonded with an isocyanate resin, one with uniform vertical density profile (homo-profile), and the other with conventional U-shaped profile, were fabricated to various density levels using lauan *(Shorea* spp.) particles. The fundamental relationships between the density profile and the board properties were determined, and the results are summarized as follows:

1. In homo-profile boards, the moduli of rupture (MOR) and elasticity (MOE), internal bond (IB) strength, and screw withdrawal resistance (SWR), are highly correlated to the board mean density.
2. The bottom limit of the board density is estimated to be ca. 0.25 g/cm^3, based on the correlation regressions between mechanical properties and mean density.
3. At equal mean density level, the MOR and MOE of the conventional particleboards are higher than the homo-profile boards, due to the higher density near the faces. However, the reverse is true for IB, owing to the presence of the low density core in the former.
4. The net impact of peak density on MOR and MOE is greater at higher mean density level while raising the core density results in more pronounced improvement in IB at lower density.
5. In addition to the compaction ratio, the dimensional stability of the board is also affected by the peak area and mat moisture content.

Introduction

Most of the particle and fiber-based boards are produced using thermosetting resin adhesives, and hot pressing is usually applied to achieve accelerated and complete curing of the binder, besides densifying the boards to the desired thickness and density level. During the hot pressing process, the interaction among heat, moisture and pressure gives rise to non-uniform deformation of the elements, which results in an uneven density distribution along the thickness direction of the board. Typically, this density profile resembles a 'U-shape', with

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E.-D. Wong (✉), M. Zhang, S. Kawai
Wood Research Institute, Kyoto University, Uji, Kyoto 611, Japan

Q. Wang
Hokushin Co. Ltd. 17-2, Mokuzai-Cho Kishiwada 596, Japan

the peak density near the board surfaces, and the lowest density in the core region.

Though the effects of the density profile on the board properties have often been pointed out qualitatively, the real phenomena of density profile formation, and its specific effect on the board performance remain ambiguous. The presence of this vertical density gradient has been reported to result in higher bending strength, but lower internal bond and interlaminar shear (Kelly 1977). A steep density gradient in low-density particleboard could cause shear failure to occur before the specimen fails in bending, hence reducing the modulus of rupture (Kawai and Sasaki 1986). Accordingly, thickness swelling and water absorption are also adversely affected by a great difference in the peak and core densities.

In earlier researches, conclusions were drawn regarding the general qualitative effects of furnish characteristics, e.g., configuration, compressibility, moisture content and its distribution, and hot pressing conditions, including type, temperature, closing speed, pressure and duration, on the formation of density profile in particleboards (Suchsland and Woodson 1986; Strickler 1959).

This study investigates the specific relationships among the mean density, vertical density profile, and the physical and mechanical properties of particleboards. The quantitative understanding of the above correlations is fundamental and vital for the attempts in simulating the density profile for boards with desired properties for specific end-uses. Subsequently, it would be possible to monitor the board properties through proper manipulation of the processing factors, using the existing facilities within economic limits.

Materials and methods

Raw materials

Lauan (*Shorea* spp.) particles with an air dry density of 0.4 g/cm^3 were prepared using a knife-ring flaker and screened to exclude the fines. The distribution of the particles based on screening test is as shown in Table 1. The particles were then conditioned to about 10% moisture content (MC). The particles used were relatively fine and uniform, with about 80% of 0.13–0.61 mm thickness, 0.3–1.4 mm width and 4–8 mm length, in order to achieve uniform board properties.

A polymeric isocyanate resin, UL4811, formulated by Gun-ei Chemical Industries Corp. was used as binder at a resin content of 8% based on the oven dry weight of the particles. Based on the isocyanate resin, 20% of acetone was added as resin diluent for better resin distribution.

Table 1. Distribution of particle furnish based on mesh analysis

Mesh No.	x > 4	4 > x > 9	9 > x > 20	20 > x > 32	32 > x
Mesh opening (μm)	x > 4760	4760 > x > 2000	2000 > x > 840	840 > x > 500	500 > x
Particle geometry (mm)	–				
Length	–	11–21	5–13	4–8	–
Width	–	1.4–2.5	0.6–1.4	0.3–0.7	–
Thickness	–	0.26–0.64	0.29–0.61	0.13–0.33	–
Weight (g)	Negligible	3.3	16.9	12.1	4.8
Percentage (%)	Negligible	9	45	33	13

Particleboard fabrication

Two major types of particleboards were produced, namely, particleboards with a flat, uniform vertical density distribution along the board thickness, termed as 'homo-profile' particleboards hereafter, and conventional particleboards with U-shaped vertical density profile.

Homo-profile particleboard

A series of control particleboards with flat and uniform density profile were manufactured to different mean density levels ranging from 0.3 to 1.1 g/cm^3. The dimensions of the particleboards were 12 × 300 × 300 mm.

A total of six hand-formed mats were cold-pressed to the targeted thickness of 12 mm in one pressing process. The press platens were then heated up to 160 °C, in order to achieve complete curing of the resin. It took about 1 h and 45 min to raise the platen temperature to 160 °C. The boards were removed from the press immediately after the platens reached 160 °C.

Conventional particleboards

In addition to the homo-profile boards, conventional particleboards were fabricated at 0.5 and 0.7 g/cm^3 density levels, by hot pressing at 160 °C for 3 minutes. The press closing speed was 3 to 4 mm/s from mat thickness to the distance bar. The apparent particle mat density was 0.13–0.18 g/cm^3. The maximum specific press pressure was about 30 kgf/cm^2. The dimensions of the boards were 12 × 350 × 400 mm. In order to produce particleboards with varied density profiles, the MC of the particles and their distribution in the mat were manipulated, as summarized in Table 2. In the Uniform MC category, the MC was uniform throughout the mat, at 5, 10 and 20% levels. For the Distributed MC category, the face MC was higher than the core, and the proportions of the face and core particles were varied. The overall mat MC levels of the boards are as shown in Table 2.

Evaluation of particleboards

Upon removal from the hot press, the particleboards were conditioned for 1 week under controlled temperature and relative humidity of 20 °C and 65 ± 5%, respectively. The unsanded boards were then tested in accordance with the Japanese Industrial Standard for Particleboards (JIS A5908, 1994).

Table 2. Particle moisture content and their distribution in the mat

Code	MC (%)	Particle proportion[1]	Overall mat MC (%)
Uniform MC			
5MC	5	–	5
10MC	10	–	10
20MC[2]	20	–	20
Distributed MC	face : core : face	face : core : face	
MC18/5–1/4/1	18 : 5 : 18	1 : 4 : 1	9
MC20/0–1/4/1	20 : 0 : 20	1 : 4 : 1	7
MC20/0–1/8/1	20 : 0 : 20	1 : 8 : 1	4

[1] Based on the oven dry weight of the particles
[2] Boards were found to have inferior strength, and were omitted in the subsequent analysis

The static bending test was conducted using three specimens of 40 × 200 mm from each board in a 3-point bending test over an effective span of 180 mm, at a loading speed of 10 mm/min.

Four internal bond (IB) specimens with dimensions of 50 × 50 mm were prepared from each board. Prior to IB testing, the vertical density gradient of these specimens was determined by means of gamma radiation transmitted through the sample across the thickness at an interval of 0.1 mm, using a density profiler (Institute of Geological & Nuclear Sciences, 1994).

Four test specimens 50 × 50 mm were prepared from each sample board for thickness swelling (TS) and water absorption (WA) tests. Besides the standard testing, the specimens were subjected to further dimensional stability evaluation under the following dry/wet conditioning cycle: soaking in ambient water (20 °C) for 24 h, oven drying at 60 °C for 72 h, soaking in 70 °C water for 24 h, oven drying at 60 °C for 72 h, 4 h boiling, oven drying at 60 °C for 72 h and finally conditioning at 20 °C and 65 ± 5% relative humidity till equilibrium.

The screw withdrawal resistance of the boards was evaluated using the visually intact portion of the tested static bending samples. Twelve screw withdrawal resistance tests were conducted for each sample board.

Results and discussion

Homo-profile particleboards

Density profile

From the density profile analysis, it was found that all of the particleboards produced using the cold pressing method had a uniform vertical density profile along the board thickness, irrespective of the board mean density levels. Figure 1 shows some examples of the density profiles of the homo-profile particleboards.

Bending properties

The moduli of rupture (MOR) and elasticity (MOE) of the homo-profile boards in relation to the mean density (MD) are shown in Fig. 2a. It could be misleading to correlate the bending strength and mean density based on the conventional boards, as it has been reported that the bending strength of particleboards with similar mean density, but different density profile, could differ by up to 80%

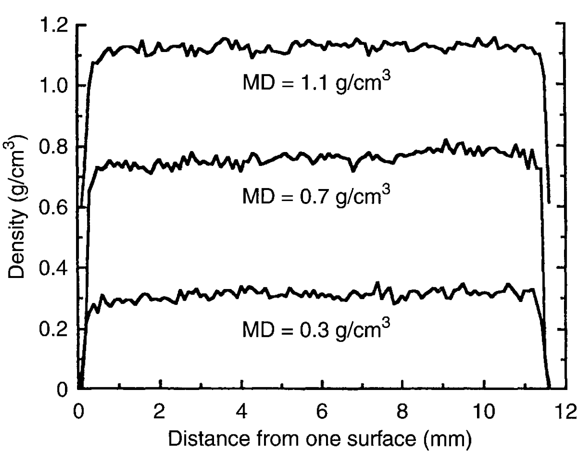

Fig. 1. Density profile of homo-profile particleboard at different mean density levels

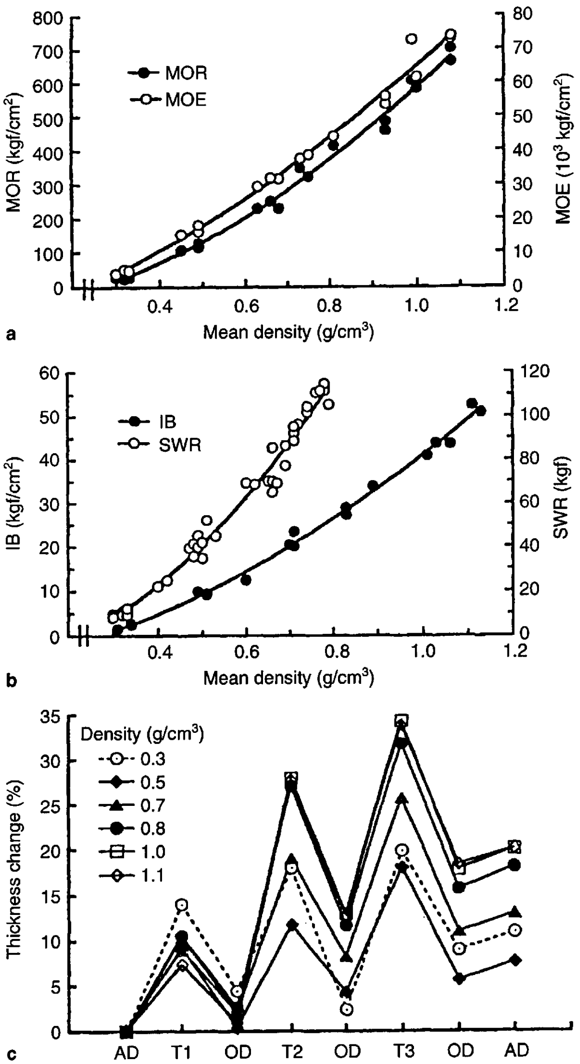

Fig. 2a–c. Properties of homo-profile particleboards as related to the board mean density (MD) Notes: (a) MOR = $-75 + 164MD + 495(MD)^2$, $R = 0.995$; MOE = $-12+41MD + 35 (MD)^2$, $R = 0.994$; where MOR = modulus of rupture, MD = mean density, MOE = modulus of elasticity, (b) IB = $-7 + 16MD + 32(MD)^2$; $R = 0.997$; SWR = $-15 + 24 MD + 176(MD)^2$, $R = 0.992$; where IB = internal bond, SWR = screw withdrawal resistance. The SWR for boards with MD greater than 0.8 g/cm^3 could not be measured, as the head of the nail was damaged, and 'slipped' from the holder when the pulling force exceeded 120 kgf. (c)AD = airdry,Tl = 24 h immersion in cold water, OD = 72 h oven dry at 60 °C, T2 = 24 h immersion in 70 °C water, T3 = 4 h boiling

(Shen and Carroll 1970). For the homo-profile boards, since the density profiles of these boards are uniform along the board thickness, any change in the bending properties could be attributed solely to the difference in the board mean density, as long as the sample does not experience shear failure during the static bending test. The MOR and MOE are observed to be highly correlated to the mean board density in a curvilinear trend. MOR can be represented by MOR = $-75 + 164MD + 495(MD)^2$, (R = 0.995). For MOE, this relationship is expressed as MOE = $-12 + 41MD + 35(MD)^2$, (R = 0.994). Extrapolation of both the MOR and MOE curves reveals the lower limit of the board densities to be about 0.25 g/cm^3, below which the MOR and MOE would be negligible.

Internal bond (SB) strength

Figure 2b shows the relationship between the internal bond (IB) strength and the core density (CD) which is equivalent to the mean density in this case. In the homo-profile boards, except for the 0.3 and 0.7 g/cm^3 density boards, the others experienced failure near the core, despite the absence of the low core density. IB was highly correlated to the core, i.e., mean density of the homo-profile particleboards, as shown in Fig. 2b. This is because the higher compaction ratio results in greater inter-particle contact, consequently more effective bonding as the adhesive is spread over a greater particle surface area instead of filling the voids in-between the particles.

For homo-profile boards, the correlation between IB and the core density can be expressed as IB = $-7 + 16CD + 32(CD)^2$, (R = 0.997). Based on this expression, the bottom limit of the board density is about 0.27 g/cm^3, which is very close to the values derived from MOR and MOE. The lower limit of the compaction ratio is about 0.63, being slightly higher than that reported previously (Kawai and Sasaki 1993), probably due to the lower resin content.

Screw withdrawal resistance

In previous works, no relationship was found to exist between density and screw withdrawal resistance of some commercial boards, mainly due to the masking effect of the variation in board structure, particle size, resin type, species and processing conditions (Kelly 1977). For homo-profile boards, the screw withdrawal resistance (SWR) was apparently related to the board density in a curvilinear trend as shown in Fig. 2b. This correlation is represented by SWR = $-15 + 24MD + 176(MD)^2$, (R = 0.992). As the board density, i.e., the amount of mass per volume, increases, the ability of the board to hold or resist the withdrawal of the screw was improved accordingly.

Thickness swelling (TS) and water absorption (WA)

Under the dry/wet cyclic conditioning, the particleboards generally experienced an increase in the thickness and weight after water soaking and boiling. The total thickness swelling (TS) of the board after immersion in water is attributed to the release of the compressive stresses, hygroscopic swelling of wood, and the deterioration of the inter-particle bonding.

Except for the 0.3 g/cm^3 boards, the degree of board TS generally increased with increasing board density, as shown in Fig. 2c, whereas the WA showed a reversed trend. In boards of 0.3 g/cm^3 density, the highly porous structure allows easy penetration and uptake of water, resulting in high water absorption which causes the board to swell, giving rise to relatively high TS. In addition, the lower bonding efficiency between the loosely packed particles also tends to deteriorate more easily under the dry/wet conditioning cycle. In the higher density board, the higher compaction ratio implies that more compressive deformation has been imparted onto the particles during hot pressing and the particles were under greater compressive set. Upon repeated exposure to the dry and wet conditions, the particleboards experienced an irrecoverable TS after each stage of oven-drying, despite the shrinkage of particles due to the loss of moisture. The irreversible TS could be attributed to the recovery of the compressive set of particles caused during hot pressing, stress release, as well as the deterioration of the inter-particle bonding, which was overcome by the spring-back effect and hence eventually failed to hold the particles together.

The WA of particleboards is highly correlated to the board density. Under higher compaction, the porosity of the board is reduced, resulting in a lower rate of water penetration into the board. Similar to TS, the degree of WA increased after each stage of conditioning, due to the deterioration of the inter-particle bonding and the gradual breakdown of the entire structure. The oven dry weight however, decreased gradually over the conditioning cycle, mainly because of the loss of some particle and chemical components.

Conventional particleboard

Density profile

As expected, the vertical density profile of the particleboards produced by conventional hot pressing generally resembles a 'U-shape', as shown in Fig. 3.

When no distance bars were used, higher initial press pressure would result in higher mean density, with most of the density gain in the form of greater densification in the mat surfaces compared to the core (Moslemi 1974). This can basically be applied to the boards pressed with distance bars to different final densities, where the initial pressure (before the top platen reaches the stops) experienced by the thicker mat for high density board was higher, due to the additional mass. Consequently, for boards fabricated with similar processing parameters, the contrast between the peak and core densities becomes more pronounced at higher mean density. The core region is flat and gentle in lower density board, but resembles an 'arc-shape' in higher density board. For boards of similar mean density, a difference in the face and core moisture content results in a relatively more slender and higher peak nearer to the surface, with a wider and lower core region, as indicated by the dotted lines in Fig. 3. The high MC on the faces enhances plasticizing of the wood particles, besides retarding the occurrence of pre-cure, giving rise to tight and hard faces near the surfaces. Theoretically, the

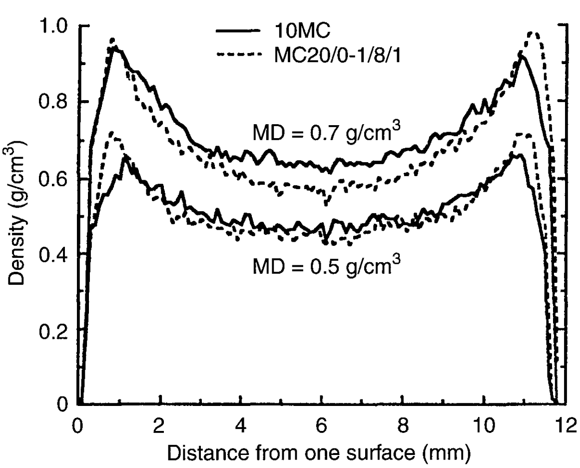

Fig. 3. Typical density profile of conventional particleboard at different mean density (MD) levels
Note: 10MC – uniform 10% MC, MC20/0-1/8/1 – face to core MC of 20 : 0% and particle ratio of 1 : 8 : 1

high moisture on the mat faces would change to steam and move into the core upon hot pressing, hence facilitating the transference of heat to the core. It has been calculated that about 12% MC needs to be converted to steam in order to fill all the voids in the particleboard during hot pressing (Strickler 1959). In this study, since the overall mean MC of the mats with varied moisture distribution ranged from 4 to 9%; the amount of the steam formed – hence the resultant steam vapor pressure – may not be sufficiently high to allow thorough and immediate penetration of heat throughout the core. Consequently, while the faces are plasticized and set at higher density, the core would still be resisting the pressure. When sufficient heat finally reaches the core, most of the wood particles would have been compressed and set near the faces, leaving no excessive wood in the core for further compression. As a result, a wide, low density zone is formed in the core region.

In the conventional U-shaped density profile, a definite correlation was found to exist among the peak, core and mean densities. This relationship however, is dependent on the processing condition of the boards as illustrated in Fig. 4. The high degree of correlation indicates that it is possible to estimate the peak and core densities with fairly high accuracy based on the mean density, under specific processing conditions. Figure 4 also reflects that at a similar mean density level, particleboards fabricated from mats with different MC distribution have a more pronounced density profile, i.e., comparatively higher peak, but lower core density, compared to those with uniform MC distribution. Among the boards manufactured from mats with different MC distribution, mats with a greater difference in face/core MC, e.g., 20/0%, result in a more contrasting density profile compared to that of 18/5%. When the face to core MC ratio remains unchanged, a reduction in the proportion of high MC face particle causes the peak to be more slender, shifting closer to the surface, as in the case of face/core/face particle ratio of 1/8/1 compared to 1/4/1 (OD basis), at similar face/core MC of 20/0%.

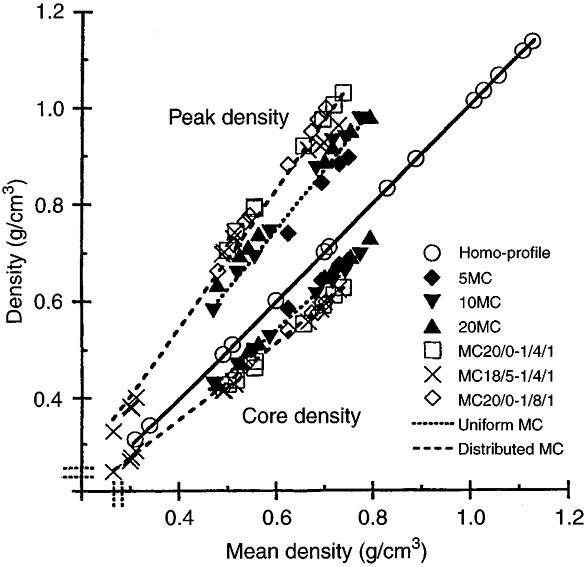

Fig. 4. Correlation between peak density (PD), core density (CD) and mean density (MD) in different types of particleboard
Notes: Uniform MC ($PD = 8.1 \times 10^{-3} + 1.2MD$, $R = 0.981$; $CD = 7.3 \times 10^{-3} + 0.9MD$, $R = 0.994$); Distributed MC ($PD = -0.02 + 1.4MD$, $R = 0.992$; $CD = 2.3 \times 10^{-2} + 0.8MD$, $R = 0.998$)

Bending properties

Figures 5 and 6 show the MOR and MOE of conventional boards compared to the homo-profile boards. The MOR and MOE of conventional boards are generally higher than the homo-profile boards, owing to their difference in the vertical density profile. However, the differences between the MOR/MOE of the conventional boards and the homo-profile boards were less significant than expected from the results of density distribution illustrated in Fig. 4. The properties of homo-profile particleboard, namely, bending strength, IB, screw withdrawal resistance and dimensional stability, are largely dependent on the board mean density. In conventional boards, variation in the density gradient might have a profound effect on the above properties. This specific impact is, however, masked by the influence of mean board density. Further, the effect of the pre-cured low-density layer near the very surface of the specimens on the MOR and MOE also needs to be further verified in the future studies.

The correlations between the peak density and the MOR and MOE at fixed mean density levels were determined. In this analysis, the peak densities were calculated based on the regression correlation between the peak and mean density for each individual fabrication condition. The peak density (PD) has relatively higher effect on both the MOR and MOE at higher mean density (MD) level, as indicated by the steeper gradient of the regression lines in Figs. 7 and 8.

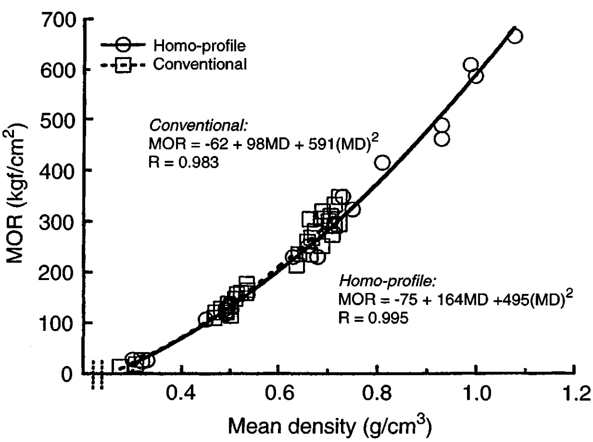

Fig. 5. Correlation between modulus of rupture (MOR) and mean density (MD) in homo-profile and conventional particleboards

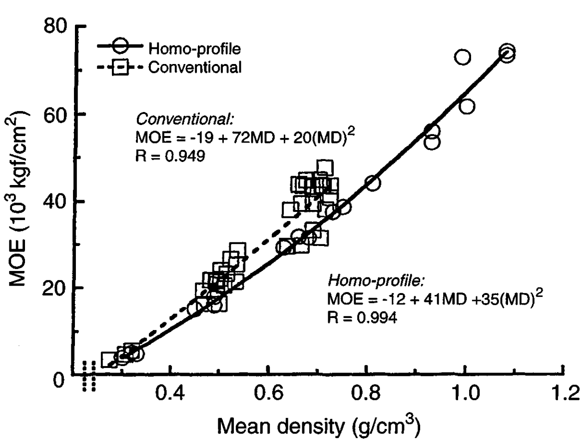

Fig. 6. Correlation between modulus of elasticity (MOE) and mean density (MD) in homo-profile and conventional particleboards

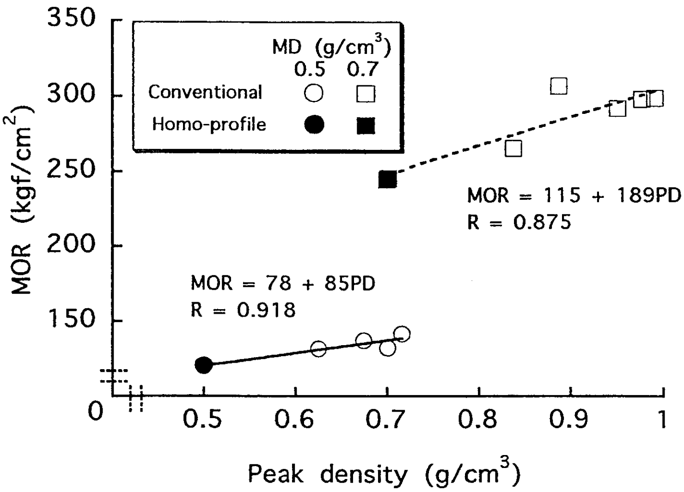

Fig. 7. Correlation between modulus of rupture (MOR) and peak density (PD) in homo-profile and conventional particleboards at equal mean density (MD) level

This reflects the curvilinear correlations between the MOR/MOE and the mean density based on the homo-profile boards. The boards fabricated from mats with 18% face and 5% core MC were found to have relatively lower MOE, but not MOR, compared to the other boards with similar peak density, at both 0.5 and 0.7 g/cm^3 mean density levels, as indicated in Fig. 8. A comparison of the density profiles reveals that the peaks in the MC18/5-1/4/1 boards were formed further away from the surface, due to the exceptionally slower closing speed. This suggests that MOE is more sensitive to the shape and location of the peaks in the profile, compared to MOR. These exceptionally low values were considered

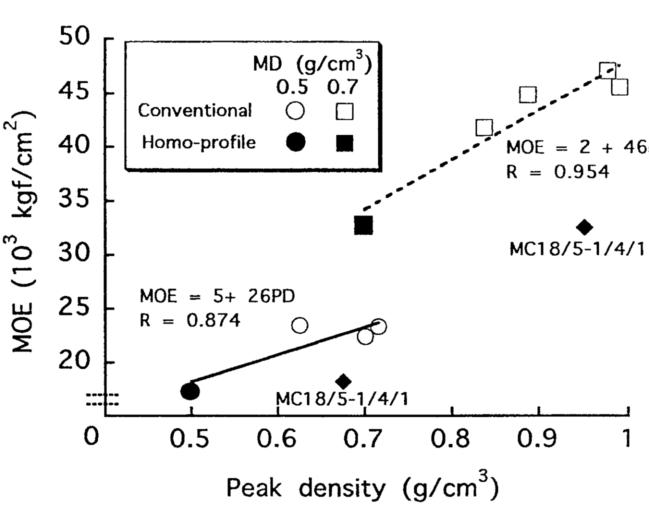

Fig. 8. Correlation between modulus of elasticity (MOE) and peak density (PD) in homo-profile and conventional particleboards at equal mean density (MD) level
Note: MC 18/5-1/4/1 are excluded in the above regressions

outliers, and were not included in the above regression analysis between MOE and peak density.

Internal bond (IB) strength

Figure 9 shows the high correlation between IB and mean density for both homo-profile and conventional boards. The IB of the latter is found to be lower than the former, due to its lower core density. Despite having equal mean density, the conventional board IB could differ by up to about 100 and 25%, at 0.5 and 0.7 g/cm^3 mean density levels, respectively as shown in Fig. 10. The degree of improvement in 0.5 g/cm^3 boards was almost twice as the one in 0.7 g/cm^3, as reflected in the gradients of the regression lines. This is most probably due to the steeper density profile in higher density board, where the arc-like core density

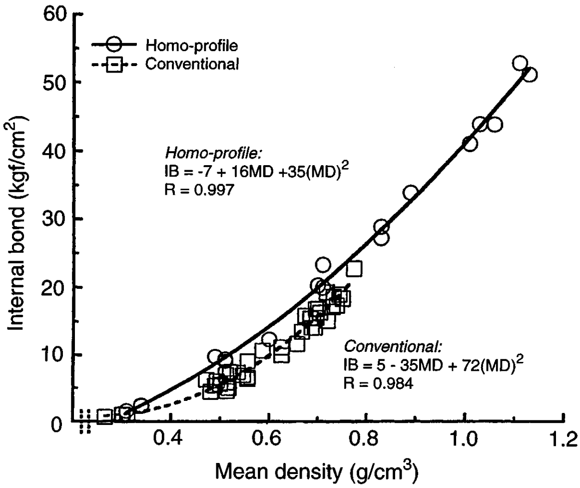

Fig. 9. Correlation between internal bond (IB) strength and mean density (MD) in homo-profile and conventional particleboards

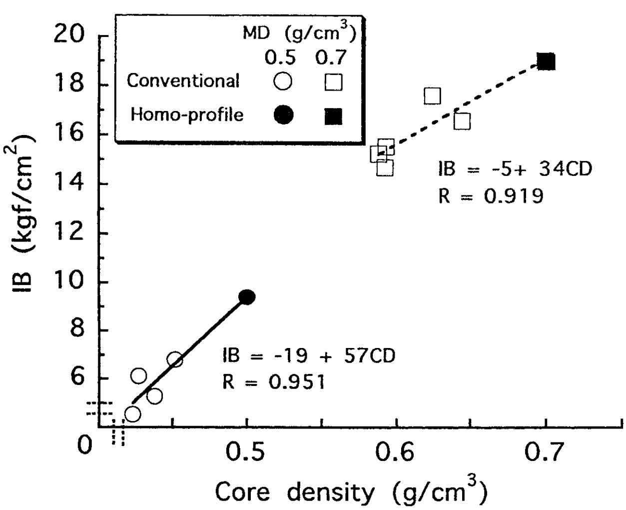

Fig. 10. Correlation between internal bond (IB) strength and core density (CD) in homo-profile and conventional particleboards at equal mean density (MD) level

profile presents a wider zone of low density/low strength core region, hence a higher possibility for failure to initiate in any weak point within the proximity.

Thickness swelling (TS) and water absorption (WA)

With reference to Fig. 11, the final spring-back (SB) of the boards, i.e., the final thickness swelling (TS) after the dry/wet cyclic conditioning was highly correlated to, but not completely dependent on the compaction ratio (CR). For homo-profile boards, SB increases with CR when CR is below 2.0. For CR exceeding 2.0, two distinct phenomena were observed, where the value of SB either rose further, or dropped drastically. In the former case, the set recovery of the particles under excessive compaction could have given rise to higher SB. In the case of the latter, structural failure might have occurred in the wood particles during the cold pressing process, due to the excessive pressure imposed onto the high density particle mat. Consequently, the internal stress of the board is being reduced, giving rise to lower spring-back. Homo-profile boards had the highest water absorption (WA). However, almost all of the conventional particleboards registered a higher degree of SB compared to the homo-profile boards at similar CR. Two other factors thought to be affecting the degree of SB are the U-shaped density profile, and the overall mean moisture content of the mat. Figure 11 shows that for boards manufactured from uniform MC mats, the dimensional stability of the boards improved with increasing overall mean MC, and vice versa. In higher MC mats, more vapor is generated during hot pressing, and the particles may be subjected to steaming treatment to a certain extent, resulting in improved dimensional stability.

Figure 12 illustrates the correlations between SB and the peak area for various particleboards at equal mean density levels. The peak area (PA) is estimated as

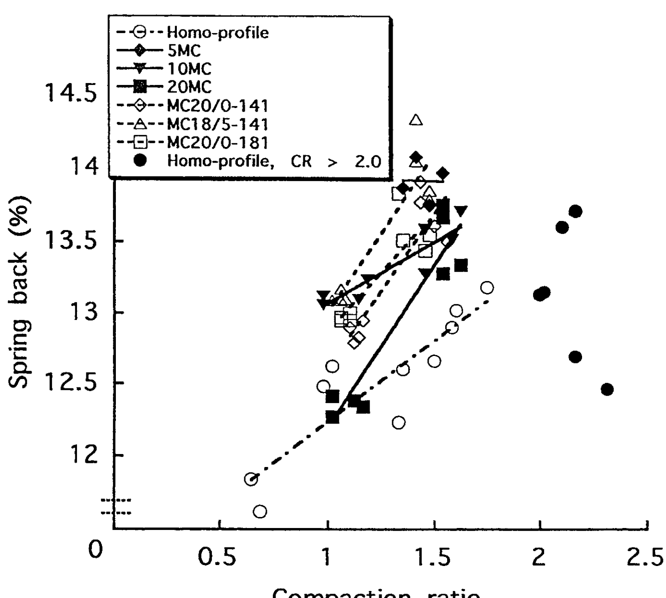

Fig. 11. Correlation between spring back (SB) and compaction ratio in homo-profile and conventional particleboards
Note: Homo-profile boards with CR > 2.0 are excluded in the above regression

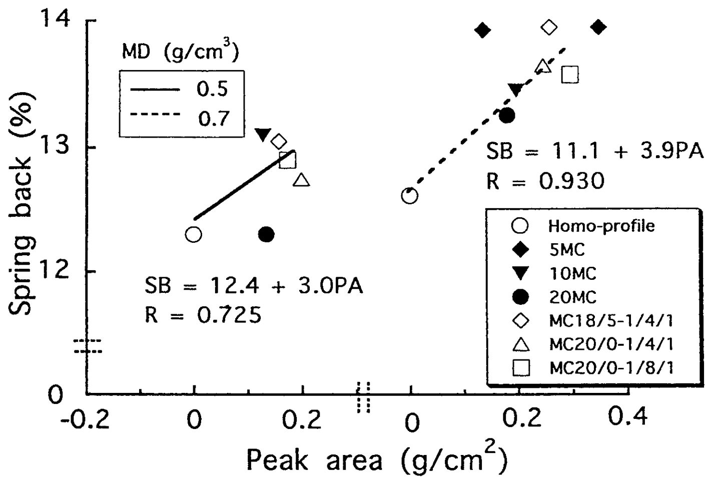

Fig. 12. Correlation between spring back (SB) and peak area (PA) in homo-profile and conventional particleboards at equal mean density (MD) level
Note: 5MC and 20MC are excluded in the above regressions. Peak area estimated as [(PD − MD) ∗ PB/2], where PB = width of peak base

PA = [(PD − MD) ∗ PB/2], where PD is the peak density (calculated based on the correlation between peak and mean density), MD is mean density, and PB is the width of the peak base, i.e., the distance between the intersections of the peak density and the mean density lines, based on the density profile chart. It can be seen in Fig. 12 that higher SB generally corresponds to greater PA. The higher SB registered by boards from MC18/5-1/4/1 is probably due to the presence of a thicker low density pre-cured layer on the surfaces, causing it to be more susceptible to deterioration under cyclic conditioning treatment.

Conclusions

This study basically established the fundamental relationships between the density profile and the board properties. Based on the evaluations of homo-profile and conventional particleboards, the results can be summarized as follows:

1. In homo-profile particleboards with leveled vertical density profile, the moduli of rupture (MOR) and elasticity (MOE), internal bond (IB) strength, and screw withdrawal resistance (SWR) are highly correlated to the board mean density in a curvilinear trend, with R values exceeding 0.99.
2. The bottom limit of the board density is estimated to be ca. 0.25 g/cm^3, based on the correlation regressions between MOR/MOE/IB and mean density.
3. In conventional particleboards, it is possible to predict the peak and core densities of the board based on the definite correlations existing between the peak, core and mean densities, with respect to the production conditions.
4. At equal mean density level, the MOR and MOE of the conventional particleboards are higher than the homo-profile boards, due to the higher density near the faces. However, the reverse is true for IB, owing to the presence of the low density core in the latter.
5. The net impact of peak density on MOR and MOE is greater at higher mean density level, while raising the core density results in greater improvement in IB in lower density board.

6. In addition to the compaction ratio, the dimensional stability of the board is directly correlated to the peak area and also influenced by the mat moisture content.

In general, a steeper density profile is advantageous for high density boards, since the bending strengths could largely be improved without serious reduction in IB. Where low density boards are concerned, a more gentle profile is preferred, as there is a bigger risk for the core density to dip below the bottom limit in steep profile, causing shear failure to occur before the board fails in bending.

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