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Properties of kenaf core binderless particleboard reinforced with kenaf bast fiber-woven sheets

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Abstract Kenaf composite panels were developed using kenaf bast fiber-woven sheets as top and bottom surfaces, and kenaf core particles as core material. During board manufacture, no binder was added to the core particles, while methylene diphenyldiisocyanate resin was sprayed to the kenaf bast fiber-woven sheet at 50 g/m^2 on a solids basis. The kenaf composite panels were made using a one-step steam-injection pressing method and a two-step pressing method (the particleboard is steam pressed first, followed by overlaying). Apart from the slightly higher thickness swelling (TS) values for the two-step panels when compared with the one-step panels, there was little difference in board properties between the two composite panel types. However, the two-step pressing operation is recommended when making high-density composite panels ($>$0.45 g/cm^3) to avoid delamination. Compared with single-layer binderless particleboard, the bending strengths in dry and wet conditions, and the dimensional stability in the plane direction of composite panels were improved, especially at low densities. The kenaf composite panel recorded an internal bond strength (IB) value that was slightly low because of the decrease of core region density. The kenaf composite panel with a density of 0.45 g/cm^3 (one-step) gave the mechanical properties of: dry modulus of rupture (MOR) 14.5 MPa, dry modulus of elasticity (MOE) 2.1 GPa, wet MOR 2.8 MPa, IB 0.27 MPa, TS 13.9%, and linear expansion 0.23%.

Key words Kenaf composite panel · Kenaf bast fiber-woven sheet · Kenaf core particle · One-step pressing · Two-step pressing

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Introduction

Kenaf binderless particleboards were successfully manufactured by steam-injection pressing in our previous studies.[1,2] Although the board properties were good for low-density binderless boards, the boards recorded modulus of rupture (MOR) values that were low relative to the high internal bond (IB) values, and thus the uses of binderless board in some applications may be limited.

Various methods can be applied to improve the bending strength of wood-based panels. For example, overlaying is quite an effective method.[3–5] Overlaying panels improves the board appearance and properties, resulting in high-value products.[4] Overlaying involves the lamination of various sheet materials such as veneer, paper, and vinyl film to particleboard.[5]

Kenaf bast fiber comprises roughly 40% of the kenaf stalk dry weight. It provides extremely high strength with a tensile strength of 480 MPa and Young's modulus of 18 GPa, more than three times that of softwood fiber.[6] Ohnishi et al.[7] developed high-strength oriented medium-density fiberboard from kenaf bast fibers. Considering the high strength of kenaf bast fiber and the standpoint of overall utilization of the whole stalk, kenaf bast fiber seems to be a potential overlay material for making kenaf composite panel. In this study, kenaf composite panels, i.e., kenaf core binderless particleboards overlaid with kenaf bast fiber-woven sheet were manufactured to improve the bending performance of the boards, and the properties were evaluated.

Materials and methods

Woven sheet of kenaf (*Hibiscus cannabinus* L.) bast fiber and kenaf core particles were used as raw materials. The kenaf bast fiber sheet was woven with the yarned fiber bundles with 3.7 and 3.9 fiber bundles per centimeter in parallel and perpendicular directions, respectively. The kenaf bast fiber-woven sheet was 1.22 mm thick, weighed 325 g/m^2, and had a moisture content of 10%. Kenaf core particles used were the same as in the previous studies,[1,2] that is, kenaf core stalks (air-dried density of 0.14 g/cm^3) about 1.2 m long were cut into chips 5 cm in length and further processed into particles with a target thickness of 0.5 mm using a knife ring flaker. The moisture content of the particles was 12%.

Preliminary experiment

Currently there are two basic processes for overlaying particleboards. One is a two-step process, where the particleboard is first manufactured, followed by overlaying of surface materials. The other method is a one-step direct method where the surface materials and particle mat are consolidated to the final thickness in a one-step pressing operation. In the latter case the particles tend to fill any voids in the surface material.

Considering ease of handling, the one-step pressing method was applied to our preliminary experiment, although it was found the board with a relatively high density was easy to delaminate due to the pressure of steam trapped inside the high-density composite panels. Even the board with 0.45 g/cm^3 density showed slight delamination.

Board manufacture

The dimensions of the composite panels were 300 × 300 × 12 mm, and target board densities were set at 0.35, 0.45, and 0.55 g/cm^3. The composite panels were made using both one-step and two-step pressing operations. In the one-step operation, the kenaf core particles were formed into particle mats without adding any adhesive. The kenaf bast fiber-woven sheets that were sprayed with a methylene diphenyldiisocyanate (MDI) resin adhesive covered on the top and bottom surfaces of the mats, and pressed into composite panels with a sealed steam-injection press. The press was sealed with a 12-mm-thick stainless frame. Steam was introduced into the press after it was closed and the pressing pressure reached the desired level with an initial pressure of 6 MPa. The mats were pressed under the steam treatment with a pressure of 1.0 MPa (183°C) and a treatment time of 10 min. The steam was then released from the press, which took about 30 s. During pressing, the temperatures of both the upper and lower platens were kept at 190°C, which was a slightly higher temperature than the steam temperature to avoid steam condensation. In the two-step operation, the binderless particleboard from kenaf core was made using steam-injection pressing under the same pressing conditions as the one-step operation, followed by coverage with kenaf bast fiber-woven sheets on the top and the bottom surfaces, and hot pressing at 190°C for 2 min to give the composite panel. In both the one-step and two-step cases, a vacuum system was used immediately after steam-injection pressing to release the steam before unloading to avoid board delamination. The vacuum time was 3 min for each board.

MDI adhesive used was UL 4811 formulated by Gun-ei Kagaku Kogyo. The kenaf bast fiber-woven sheet was sprayed at 50 g/m^2 solid basis using a spraying gun. Acetone equal to the resin weight was added to obtain a suitable quantity and viscosity for efficient spraying.

Measurement of strength properties of kenaf bast fiber-woven sheet

As a reinforcing material, the strength of the overlaid material should have a great influence on the properties of the composite panel. In order to have a better understanding of the strength characteristics of the kenaf bast fiber-woven sheet, the tensile strength and Young's modulus (MOE) of kenaf bast fiber-woven sheet were measured.

Two plies of woven sheet of 300 × 300 mm were laminated to the density range of 0.5–0.8 g/cm^3 (laminate thickness of 0.8–1.5 mm) by hot pressing at 190°C for 3 min, using MDI resin as an adhesive at 50 g/m^2 solid basis. The tensile strength and Young's modulus were then measured by tensile test.

The tensile tests of laminates of kenaf bast fiber-woven sheet were conducted on specimens of 70 × 17 mm, with the grip distance of 50 mm, at a loading speed of 1 mm/min.

Board evaluation

Prior to evaluation of the mechanical properties and dimensional stability, the kenaf composite panels were conditioned at room temperature for about 2 weeks. They reached a moisture content of 5%–7%. The properties of the kenaf composite panels were then evaluated in accordance with the Japanese Industrial Standard (JIS) for Particleboards (JIS A 5908, 2003).[8]

Five specimens measuring 12 × 25 × 220 mm were prepared from the each board for the static bending test in the dry condition. The longitudinal direction of the specimens was parallel to the kenaf bast fiber bundles. Two and three specimens were prepared from the parallel and perpendicular directions of each board, respectively. The static bending test was conducted using three-point bending over an effective span of 180 mm at a loading speed of 10 mm/min. Five 50 × 50-mm test specimens were prepared from each sample board for IB tests, and four specimens of the same size from each board were prepared for thickness swelling (TS) and water absorption (WA) tests after 24 h of water immersion at 20°C.

In addition to the standard testing, bending strength tests under wet conditions were also conducted under mild conditions considering the relatively poor wet bending strength of binderless particleboard. This involved soaking the specimens in water for 3 h at 20°C, and then conducting the test when the specimens were still wet. Two specimens were used for each sample board, with the dimensions of 12 × 50 × 220 mm. Prior to the bending test, the lengths of specimens were measured before and after water soaking, and the linear expansion (LE) of the boards were calculated.

Results and discussion

The kenaf composite panels were successfully manufactured. However, the high density (0.55 g/cm^3) of composite panels made by the one-step pressing method showed slight delamination. The reason may be as follows: the boards with high densities have high compaction ratios (i.e., 3.9 for a board with a density of 0.55 g/cm^3), making it difficult for the steam inside the board to escape, while, in addition, in this study, the MDI adhesive formed a film on the board surfaces and prevented the steam from escaping, thereby producing high steam pressure inside the board. When the internal pressure of the steam in the particle mat is higher than the bonding strength of the board during unloading, delamination might occur. In this study, use of a vacuum system may have lightened the delamination, because it was not observed in panels with densities of 0.45 g/cm^3. However, use of the vacuum system did not completely solve the problem. No delamination was observed in the high-density composite panels made by the two-step operation.

The specimens that were delaminated were not evaluated further, and thus the number of test specimens decreased.

Bending strength

The effect of board density on the MOR of kenaf composite panels manufactured by one-step and two-step pressing methods is shown in Fig. 1. The MOR values of the composite panels from the one-step and two-step pressing operations increased with increasing panel density. The relationship between MOR and density of one-step composite panels was similar to that of the two-step composite panels. Compared to single-layer kenaf binderless particleboard, the MOR of the composite panel was improved, especially at the low density level. At a density of 0.3 g/cm^3, the MOR value was 8.0 MPa, 3.2 times higher than that of the single-layer binderless particleboard, which was only 2.5 MPa, whereas at a density of 0.6 g/cm^3, the MOR value of the composite panel was 20.9 MPa, 1.4 times that of the single-layer binderless particleboard. During bending testing, all the failures were caused by bending failure when the maximum bending moment was developed.

The increase of the MOR value of the composite panel is due to the relatively higher strength value of the kenaf bast fiber-woven sheet when compared with kenaf core particleboard. The tensile strength and Young's modulus of woven sheet at various densities are shown in Fig. 2. The tensile strength of kenaf bast fiber-woven sheet increases with increasing density. In kenaf composite panels, the thickness of the kenaf bast fiber-woven sheet was around 0.5 mm despite board density, and thus the density of the kenaf bast fiber-woven sheet was calculated to about 0.75 g/cm^3. The tensile strength was 36.3 MPa. The high strength of kenaf bast fiber-woven sheet serves in imparting strength to the kenaf composite panel. Because the weight ratio of the kenaf bast

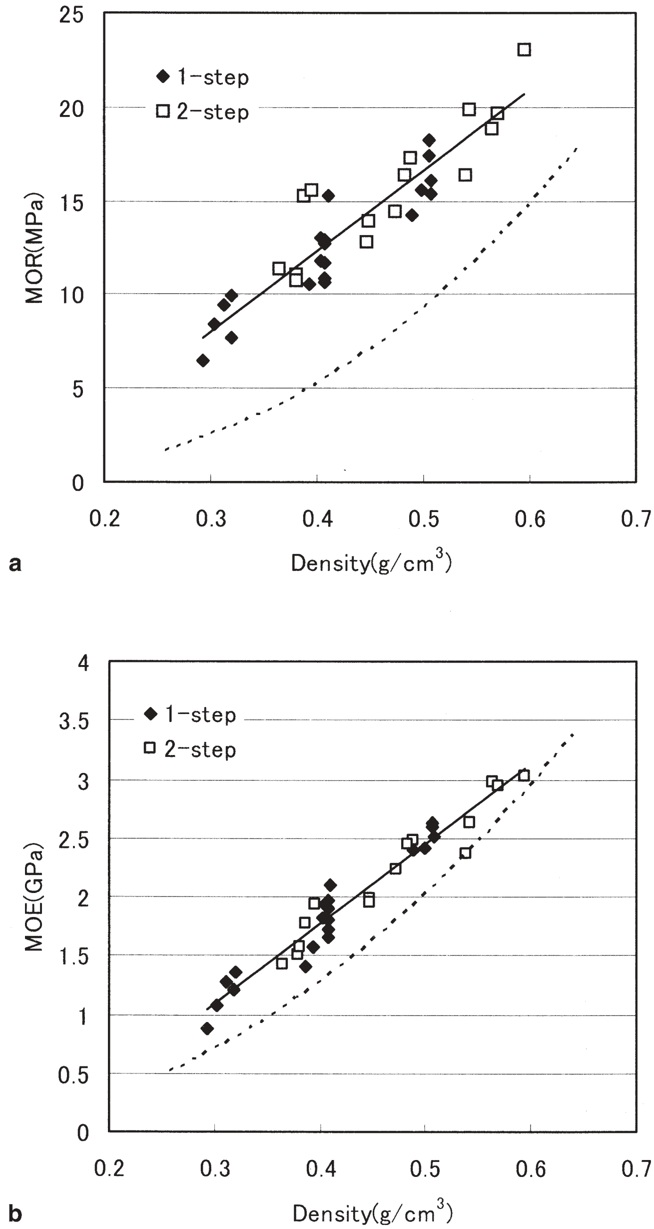
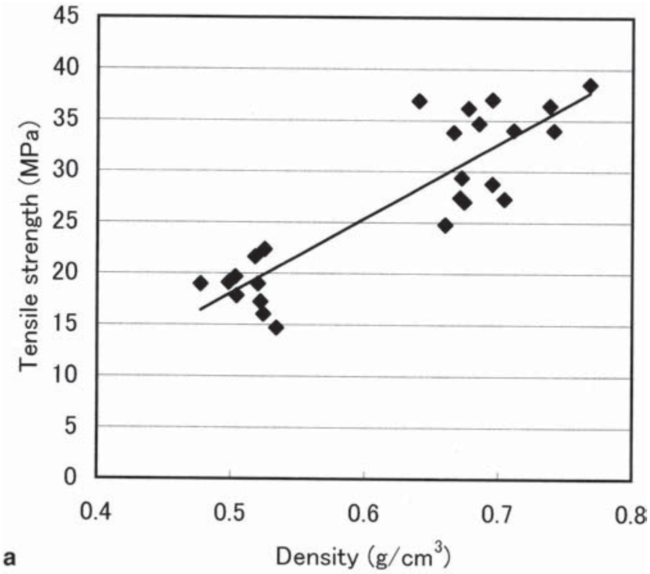


Fig. 1. Effects of board density and pressing method on **a** modulus of rupture (*MOR*) and **b** modulus of elasticity (*MOE*) of kenaf composite panel. The *broken lines* are the regression lines based on the results for single-layer binderless particleboard from previous studies[1,2]

fiber-woven sheet to the core layer decreases with increasing density of the kenaf composite panel, the improvement in the MOR value in high-density composite panels was not so evident when compared with the low-density composite panel.

At the densities of 0.42 and 0.54 g/cm^3, the MOR values of kenaf composite panel can meet the requirements of type 13 and type 18 particleboard, respectively, according to JIS A5908-2003.

As shown in Fig. 1, the MOE values of both one-step and two-step composite panels increased almost linearly with increasing board density. The MOE values of one-step composite panels did not show much difference with those of two-step composite panel. At a density of 0.3 g/cm^3, the



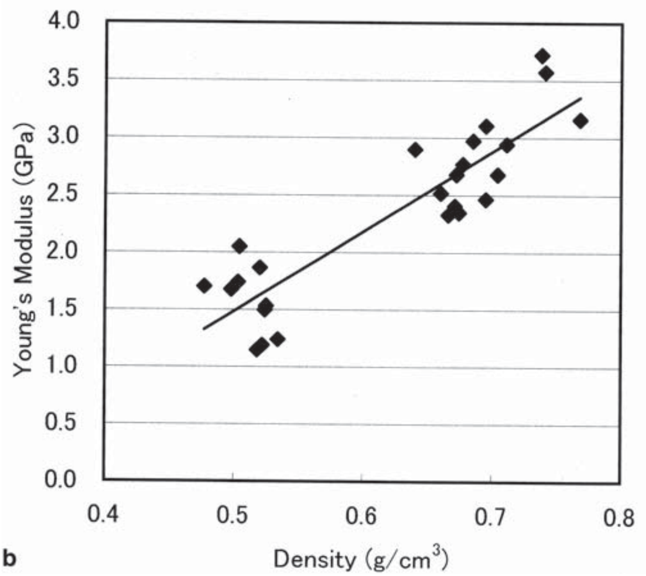


Fig. 2. **a** Tensile strength and **b** Young's modulus of kenaf bast fiber-woven sheet laminate

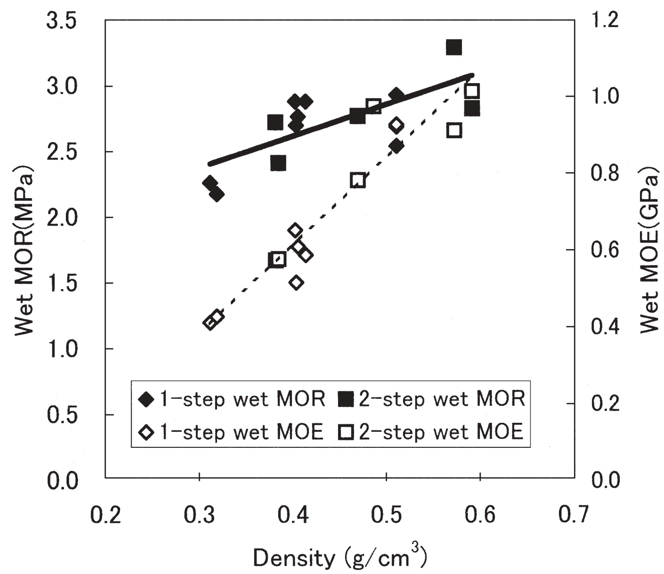


Fig. 3. Effect of board density and pressing method on wet MOR and wet MOE of kenaf composite panel

MOE value of kenaf composite panel was 1.1 ± 0.27 GPa (average value ±95% confidence intervals) according to the regression line of MOE values, which is 1.5 times that of the single-layer binderless particleboard, which was 0.70 GPa. The difference in MOE values between the composite panel and single-layer binderless particleboard decreased with increasing board density. At a density of 0.6 g/cm^3, the ratio of the MOE of composite panel to that of single-layer binderless particleboard is only 1.1. This is because the MOE value of kenaf bast fiber-woven sheet in composite panel keeps almost the same value, i.e., 3.2 GPa at a density of 0.75 g/cm^3. For the low-density composite panel, the MOE of the core layer was low, with the surface layer imparting rigidity to the board. Thus, the MOE of the composite panel increased. However, when the density of the composite panel increased, the MOE values of the core layer may have approached or even surpassed the MOE value of the surface layers, and the MOE value would then not be improved. Higher MOE values of kenaf composite panel could be obtained by increasing the density and the thickness of the kenaf bast fiber-woven sheet.

The increase in the wet MOR value was not so significant when the board density increased. As shown in Fig. 3, the wet MOR increased from 2.3 MPa to 3.1 MPa when the board density increased from 0.3 to 0.6 g/cm^3. Compared with the single-layer binderless particleboard, the wet MOR of low-density composite panel was apparently improved; at a density of 0.35 g/cm^3, the wet MOR of composite panel was 4.7 times that of the single-layer binderless particleboard, whereas at a density of 0.55 g/cm^3 the value was only 1.4 times higher. Compared with conventional binder-bonded board, the kenaf composite panel still recorded low wet MOR values for the poor wet strength of the binderless core layer, and the residual strength decreased with increasing board density. At a density of 0.3 g/cm^3, the residual strength was 30%, whereas it was 15% at a density of 0.6 g/cm^3. The wet MOE also increased with increasing board density.

During wet bending testing, almost all specimens experienced preceding horizontal shear failure in the core because of the decrease of bonding strength in the wet condition.

Internal bond strength

It is well known that most failure occurs in the low-density core region during the internal bonding test. Figure 4 shows the IB values of the kenaf composite panels. In the density range of 0.3–0.6 g/cm^3, the composite panels showed IB values of 0.13–0.41 MPa, which were slightly less than those of single-layer binderless particleboards. This may be caused

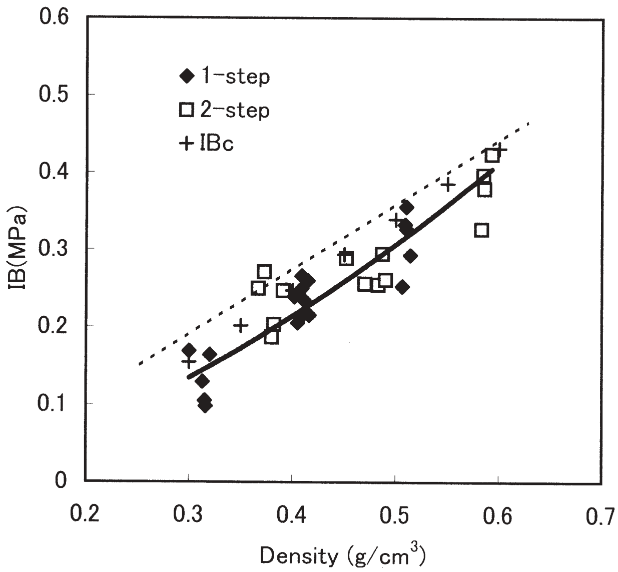


Fig. 4. Effect of board density and pressing method on the internal bonding strength (*IB*) of kenaf composite panel. The *broken line* is the regression line for 10-min steam treatment time based on the results for single-layer binderless particleboard in previous studies.[1,2] *IBc*, calculated IB value based on the core density of kenaf composite panel

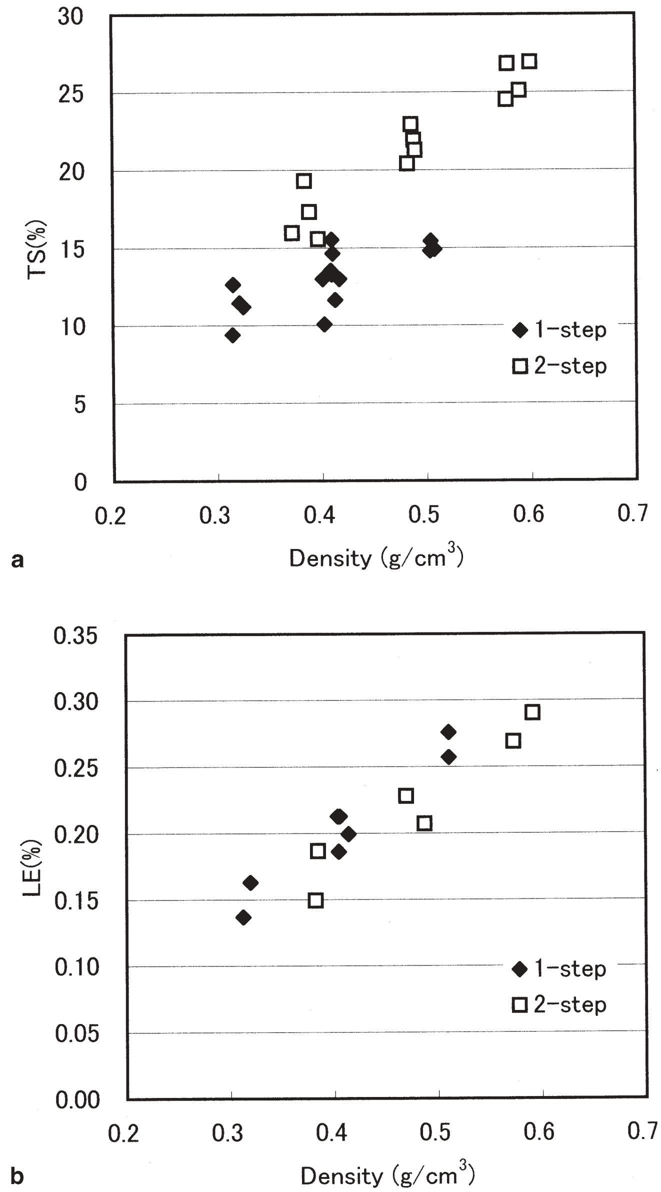


Fig. 5. Effect of board density and pressing method on **a** thickness swelling (*TS*) and **b** linear expansion (*LE*) of kenaf composite panel

mainly by the composite panels possessing relatively high-density surface layers and a low-density core, while the density profiles of the single-layer particleboards were relatively uniform. Thus, at a same mean density, the core density of the composite panel is lower than that of the single-layer binderless particleboard, and therefore produces the lower IB value. The differences between the mean density and core density of composite panels were 0.4, 0.3, and 0.1 g/cm^3 at the board densities of 0.3, 0.45, and 0.6 g/cm^3, respectively. The calculated IB values of composite panels based on the core density are also plotted in Fig. 4. It can be observed that calculated IB values showed the same trend as the observed IB values for composite panels. However, the observed IB values were slightly low, perhaps as a result of not only core density, but pressing method, board structure, etc. At a density of 0.50 g/cm^3, the IB value of kenaf composite panel can still meet the requirements for type 18 particleboard (0.3 MPa).

Dimensional stability

Figure 5 shows that the effect of board density on the TS value of composite panels made by both the one-step and two-step pressing operations. The TS values increased with increasing board densities in both cases. Compared with one-step composite panels, the two-step panels gave higher TS values. This may be the reason that core particleboards of two-step composite panels were densified again when overlaying the surface layers, and larger springback of the two-step panels were observed.

Linear expansion (LE) of both one-step and two-step composite panels increased with increasing board density, and in contrast to TS, LE of two-step composite panels showed somewhat lower values. The reason might be that the increase in thickness would restrain the increase in the lateral direction. This was often observed in previous studies[9,10] and was explained as an effect similar to the Poisson effect. The LE of composite panels showed low values. All specimens recorded values of less than 0.3%. Compared with single-layer binderless particleboards made in the previous study,[1] the composite panels showed lower values, especially at low-density levels. At a density of 0.3 g/cm^3, the LE value was less than half that of the single-layer binderless particleboard. The kenaf bast fiber-woven sheet may restrain the expansion of the core layer of composite panels.

Water absorption (WA) of the composite panels decreased with decreasing board density (Fig. 6). The WA of

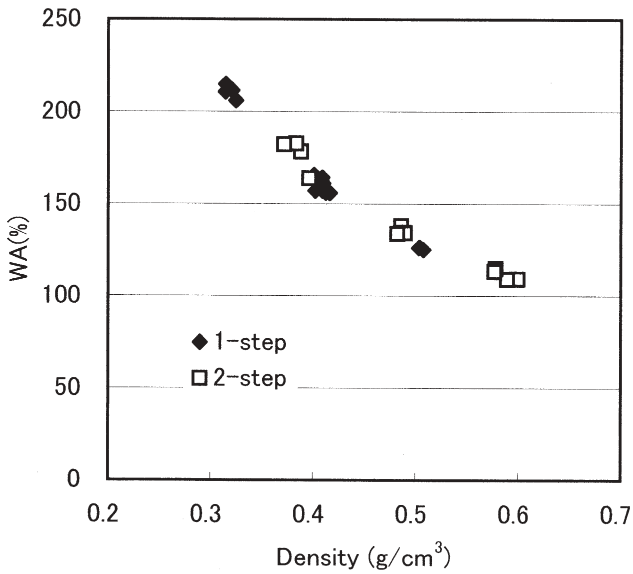


Fig. 6. Effect of board density and pressing method on the water absorption (*WA*) of kenaf composite panel

two-step composite panel did not show much difference with that of one-step composite panel. Compared with single-layer binderless particleboard, no significant change was observed for WA values.

It is worth mentioning that in this study only small amounts of adhesive were used in making boards. The core layers are free from binder, and only $50 g/m^2$ of resin was sprayed to the kenaf bast fiber-woven sheet. The average resin contents of the whole composite panel were only 3%, 2%, and 1.5% on the solid basis of the boards with the densities of 0.3, 0.45, and $0.6 g/cm^3$, respectively. Adhesive is generally accepted to be the most expensive raw material in the manufacture of composite panel. The development of binderless board and the composite panel with low resin content are doubtless economical and furthermore are environmentally friendly.

Conclusions

Kenaf bast fiber-woven sheet-overlaid composite panels were manufactured using both one-step and two-step pressing operations. The results are summarized as follows:

1. Except for TS, there is little difference in board properties between one-step and two-step pressed composite panels, although the two-step pressing operation is recommended when high-density composite panels ($>0.45 g/cm^3$) are manufactured in order to avoid delamination.
2. The bending strength under both dry and wet conditions, and the LE of kenaf composite panels were improved compared with single-layer binderless particleboard, especially at the low density levels.
3. TS of one-step composite panels did not show significant difference from the single-layer binderless particl board.
4. Compared to single-layer binderless particleboards, the kenaf composite panels showed IB values that were probably lowered due to the decrease in the core region density.
5. The kenaf composite panels with densities of 0.42 and $0.54 g/cm^3$ can meet the requirements for type 13 and type 18 particleboard, respectively, for both MOR and IB values.

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