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ORIGINAL ARTICLE

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Water resistance properties of kenaf core binderless boards

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Abstract Binderless boards were prepared from kenaf core under various manufacturing conditions and their water resistance properties were evaluated. The board properties evaluated were retention ratios of modulus of rupture (MOR) and modulus of elasticity (MOE), internal bonding strength after water treatment (IB), thickness swelling (TS), water absorption (WA), and linear expansion (LE). These values were then compared with those of boards bonded with urea–formaldehyde (UF), urea melamine formaldehyde (UMF), and phenol–formaldehyde (PF) resins, and their water resistance properties were assessed. We found that pressing temperature was one of the most important conditions for the improvement of water resistance properties. The retention ratios of MOR, MOE, and IB of kenaf core chip binderless boards (pressing temperature 200°C, target density 0.8 g/cm^3, and the three-step pressing of 6 MPa for 10 min, then 4 MPa for 3 min, and 2 MPa for 3 min) were 37.1%, 49.9%, and 55.7%, respectively, compared with values for UMF-bonded boards of 22.5%, 27.1%, and 40.7%, and values for PF-bonded boards of 42.8%, 41.8%, and 54.1%, respectively. The results showed that the water resistance properties of binderless boards were higher than those of UMF-bonded boards and almost as high as those of PF-bonded boards.

Key words Self-bonding · Binderless board · Water resistance property · Kenaf core

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Introduction

Synthetic resins play an important role in the utilization of biomass resources including wood. However, there are some negative side effects: health risks caused by the emission of volatile organic compounds from the resin, or problems concerning issues such as waste disposal or recycling. In addition, synthetic resins are generally the most expensive raw materials for the manufacture of wood-based materials such as particleboards.[1,2] One possible solution to these problems is to reduce or exclude synthetic resin. In this regard many researchers have investigated the production of binderless boards from various origins.[2–6] Other approaches have been to pretreat the raw materials with steam (e.g., steam explosion process) before the manufacture of binderless boards,[3–9] or to use injection molding of wood powder using very high pressure.[10] In contrast, in this study, in order to achieve a simplified manufacturing process, only the milling process was applied to the raw materials.[11]

In a previous study,[11] we manufactured binderless boards from kenaf core powder, without any steam explosion process, and studied their mechanical properties. The best board properties were achieved with a raw material grain size of 53 μm, pressing temperature 180°C pressure 5.3 MPa, time 10 min, board thickness 5 mm, and target density 1.0 g/cm^3.[11] Although the steam explosion method was not applied, problems still remain concerning the manufacturing conditions: the reduction of density and the use of coarser raw materials still needs to be considered. In addition, it was observed that the performance of binderless boards was high under the initial dry conditions but decreased once they were exposed to wet conditions. This means that the performance of binderless boards should not be evaluated only by the initial properties found under dry conditions, but should also consider the self-bonding properties under wet conditions.

In this study, we focused on the water resistance properties of binderles boards in order to assess the self-bonding properties. The objectives were first to evaluate water resis-

Table 1. Screen analysis for three particle types prepared from kenaf core

Particle type	Aperture size[a] (mm)									
	+3.35	+2.00	+1.70	+1.00	+0.500	+0.355	+0.250	+0.180	+0.150	−0.150
Powder-1[b]	0	0	0	0	0	0	0	0	0	100
Powder-2	0	0	0	2.0	19.3	20.6	24.6	13.4	4.8	15.4
Chip	1.4	45.9	26.6	14.1	9.6	1.5	0.7	0.1	0	0

Data given as percent mass of total sample for each particle type
[a] Plus sign indicates that the particles were retained on the sieve; minus sign indicates that the sample passed through the sieve
[b] Average element size 53 μm

Table 2. Manufacturing conditions for kenaf core binderless boards in preliminary study

Manufacturing conditions	Raw material	Pressing Conditions			Target density (g/cm^3)
		Temperature (°C)	Time (min)	Maximum specific pressure (MPa)	
B	Powder-1[a]	180	10	5.3	0.8
B_1			10 (4 → 3 → 3)[b]	6 → 4 → 2[b]	
B_2			10	3	
B_3			10	1	
B_4			10	0.5	

[a] For details of Powder-1, see Table 1
[b] A three-step pressing schedule was adopted

tance properties of boards where density reduction and coarser material application were taken into consideration during the manufacturing process. These were more practical conditions than those examined in our previous study.[11] The water resistance properties of the newly produced binderless boards were also compared with those of boards bonded with synthetic resins.

Materials and methods

Materials

Kenaf core, from kenaf (*Hibiscus cannabinus* L.) grown in Indonesia, was reduced to powder (Powder-1 and Powder-2) by using a flour mill (model ACM-10; Hosokawa Micron, Japan). Kenaf core chip (Chip) was also prepared by reducing the same kenaf core until it passed through a 6-mesh sieve. The particle size distributions of Powder-1, Powder-2, and Chip were determined by screen analysis using 100 g of each sample as shown in Table 1. They were used for board manufacturing without classification. The moisture contents of Powder-1, Powder-2, and Chip were 8%–9%. We did not apply any further pretreatment, such as the steam explosion method, to the raw material before board manufacture.

Influence of pressing pressure and time on binderless boards

In our previous study in which manufacturing conditions for kenaf core binderless boards were investigated, the maximum pressing temperature was 180°C under the one-step pressing schedule for 10 min at a pressure of 5.3 MPa because of the risk of explosions caused by vapor.[11] Therefore, as a preliminary study, the influence of pressing schedules was examined.

Binderless boards were prepared from Powder-1. The boards were hand-formed in a forming box into homogeneous single-layered mats and then manually prepressed using a lid that fitted the internal dimensions of the forming box. After the forming box was removed, rectangular corrugated cardboard sheets were stacked around the mats to minimize their diffusion and any damage caused during the press closing process. Then the mats, with their top and bottom surfaces covered with aluminum foil, were pressed with a hot pressing machine under various manufacturing conditions, B and B_1–B_4 described in Table 2. The board size was 300 × 300 mm, with a thickness of 5 mm, and the press closing time was 5 s. Metal bars (distance bars), 5 mm thick, were used to achieve the correct board thickness. Once the boards were manufactured, the following parameters were assessed according to JIS A 5905-1994 (Fiberboards) regulations: modulus of rupture (MOR), modulus of elasticity (MOE), internal bonding strength (IB), thickness swelling (TS), and water absorption (WA).

Board preparations for water resistance evaluation

Binderless boards

Binderless boards were manufactured from Powder-1, Powder-2, or Chip (Table 1) using the same technique described in the previous section. The manufacturing conditions used for the boards are listed as A–F in Table 3. The board size, thickness, and the press closing time were the same as described in the previous section.

Table 3. Manufacturing conditions for kenaf core binderless boards used to evaluate water resistance properties

Manufacturing conditions	Raw materials[a]	Pressing conditions			Target density (g/cm^3)
		Temperature (°C)	Time (min)	Maximum specific pressure (MPa)	
A	Powder-1	180	10	5.3	1
B[b]	Powder-1	180	10	5.3	0.8
C	Powder-2	180	15	5.3	0.8
D	Powder-2	200	10 (4 → 3 → 3)[c]	6 → 4 → 2[c]	0.8
E	Chip	200	10 (4 → 3 → 3)[c]	6 → 4 → 2[c]	0.8
F	Powder-2	200	10 (4 → 3 → 3)[c]	6 → 4 → 2[c]	0.7

[a] For details of Powder-1, Powder-2, and Chip, see Table 1
[b] The same as in Table 2
[c] A three-step pressing schedule was adopted

Table 4. Manufacturing conditions for the kenaf core particleboards with synthetic resins

Manufacturing conditions	Resin type	Target resin content (%)	Target density (g/cm^3)	Pressing conditions		
				Temperature (°C)	Time (min)	Maximum specific pressure (MPa)
G	UF	10	1.0	180	10 (4 → 3 → 3)[a]	5 → 3 → 1[a]
H	UF	10	0.8			
I	UF	5	1.0			
J	UF	5	0.8			
K	UMF	5	0.8			
L	PF	5	0.8			

UF, urea–formaldehyde resin; UMF, urea melamine formaldehyde resin; PF, phenol–formaldehyde resin
[a] A three-step pressing schedule was adopted

Particleboards

Particleboards were prepared from kenaf core chip (Chip, Table 1) using urea–formaldehyde (UF) resin (TX-202, Oshika, Japan) with added ammonium chloride (2% of resin weight) and urea melamine formaldehyde (UMF) resin (B-201, Oshika) or phenol–formaldehyde (PF) resin (PX-341, Aica Kogyo, Japan). The different manufacturing conditions used in this study were designed based on the resin-use guidelines in order to maximize their bond quality, and are shown as G–L in Table 4. The manufacturing conditions for the particleboards (Table 4) were different from those for the binderless boards (Table 3), but the purpose of this experiment was to evaluate the bond properties achieved by synthetic resins fixed under the most suitable manufacturing conditions for each resin. The board size, thickness, and the press closing time were the same for all boards, as described in the previous paragraph. As a reference, a commercial medium-density fiberboard (MDF; using UMF resin, with a board thickness of 5mm and a board density of 0.8g/cm^3) was also evaluated.

Evaluation of water resistance properties

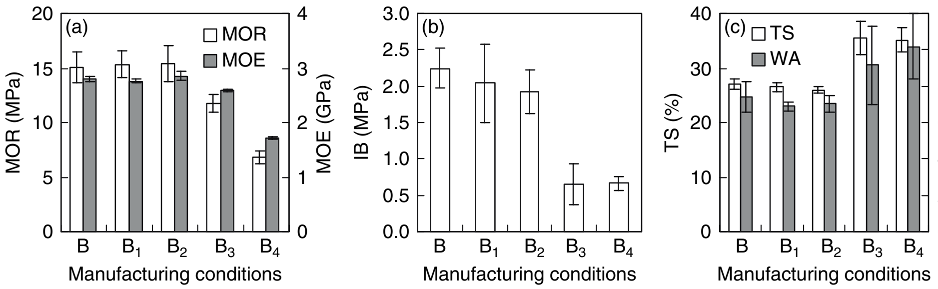
The following properties were measured from the manufactured boards according to JIS A 5905-1994 (Fiberboards) standards; MOR and MOE in dry and wet conditions, IB, TS, WA, and linear expansion (LE). MOR and MOE in wet conditions were determined after soaking the boards in water at 70°C for 2h and then in water at 20°C for 1h. TS and WA were examined after 24h of water soaking and then the boards were dried (20°C and 65% relative humidity for more than 1 week until equilibrium) and their IB strength was defined as "IB after water treatment". The MOR, MOE, and IB retention ratios (calculated by using their average values), and TS, WA, and LE were used as indicators for the water resistance properties of binderless boards. More than seven specimens were used at every testing.

Results and discussion

Effects of pressing pressure and time

Figure 1 shows the properties of the kenaf core binderless boards manufactured under the different pressing schedules B–B_4 described in Table 2. The performances of boards manufactured under B_3 and B_4 conditions were inferior to B, B_1, and B_2 boards, indicating that insufficient pressing pressure affected the board properties. However, no obvious differences were observed between B, B_1, and B_2, which suggests that differences in pressing pressure were less important above a minimum threshold, taking into account the fact that the actual board density (±0.02g/cm^3 from the target density) and the press closing time (5s) was almost identical. In addition, the results also indicated that a three-step or one-step pressing schedule could be selected without

Fig. 1a–c. Properties of kenaf core binderless boards manufactured under various pressing times and pressures. **a** Modulus of rupture (MOR) and modulus of elasticity (MOE); **b** internal bond strength (IB); **c** thickness swelling (TS) and water absorption (WA). For details of the manufacturing conditions, see Table 2



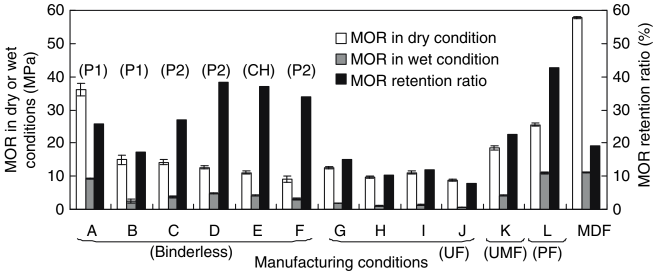


Fig. 2. MOR in dry and wet conditions and the retention ratio of boards manufactured under various conditions. *P1*, *P2*, and *CH* for boards *A–F* indicate Powder-1, Powder-2, and Chip, respectively, as shown in Table 1; *UF*, urea–formaldehyde resin; *UMF*, urea melamine formaldehyde resin; *PF*, phenol–formaldehyde resin; *MDF*, commercial medium density fiberboard with a density of 0.8 g/cm³. For details of manufacturing conditions A–F and G–L, see Tables 3 and 4, respectively

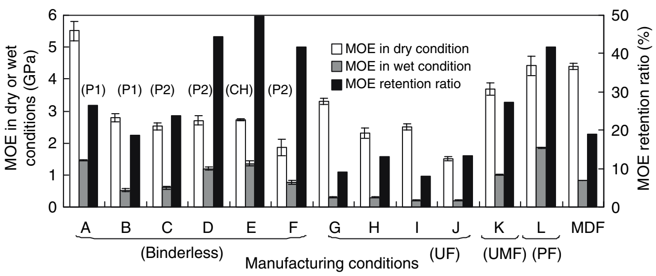


Fig. 3. MOE in dry and wet conditions and the retention ratio of boards manufactured under various conditions. For details of manufacturing conditions A–F and G–L, see Tables 3 and 4, respectively

affecting the board properties. Results from a previous study have also shown that the pressure and pressing time did not greatly influence board properties.[12] The influence of excessive pressing pressure may have been reduced by the metal distance bars used for thickness control during hot pressing.

Evaluation of the water resistance properties of binderless boards

Figures 2–6 show the water resistance properties (MOR, MOE, IB, TS, WA, and LE) of the kenaf core binderless boards and particleboards. The properties of the binderless

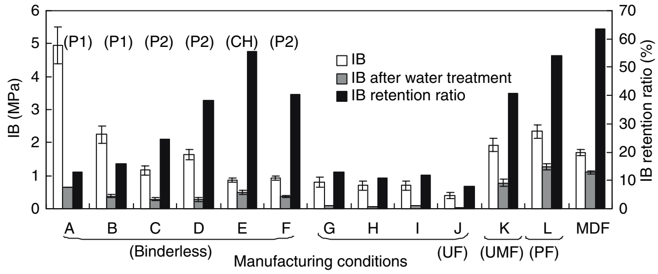


Fig. 4. IB, IB after water treatment, and the retention ratio of the boards manufactured under various conditions. For IB after water treatment, the IB values were determined after soaking in water (20°C) for 24 h and then drying. For details of manufacturing conditions A–F and G–L, see Tables 3 and 4, respectively

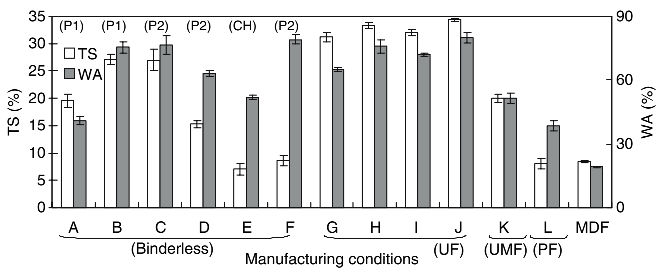


Fig. 5. TS and WA of boards manufactured under various conditions. For details of manufacturing conditions A–F and G–L, see Tables 3 and 4, respectively

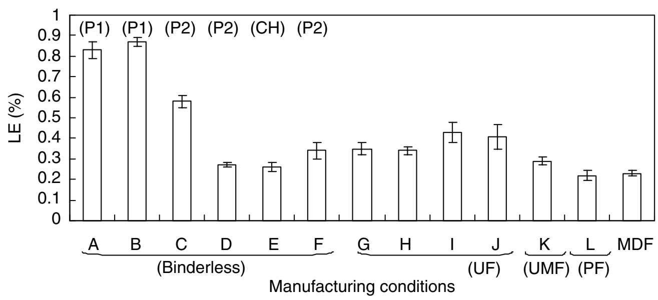


Fig. 6. Linear expansion (*LE*) of boards manufactured under various conditions. For details of manufacturing conditions A–F and G–L, see Tables 3 and 4, respectively

boards were evaluated and compared with the synthetic-resin-manufactured boards in order to assess the self-bonding properties of the binderless boards. Because the concept of the retention ratio is not stipulated in the JIS A 5905 standards, the bond achieved by the synthetic resins was used as a control to evaluate the bond achieved by self-bonding in the binderless boards. Even though the manufacturing conditions for the binderless boards and particleboards were not identical, the effect of any difference in manufacturing on MOR, MOE, and IB could be canceled by calculating the retention ratios of these mechanical properties. Similar calculations to negate the effect of different manufacturing conditions are not possible for TS, WA, and LE, but they are also important indicators of water resistance properties and so their results were also examined.

MOR and MOE retention ratios

The effect of manufacturing conditions on the MOR and MOE properties of binderless boards are shown in Figs. 2 and 3 (entries A–F). In dry conditions the values of MOR and MOE generally decreased with decreasing board density (A, density = 1.0 g/cm^3; F, density = 0.7 g/cm^3, Table 2), which was consistent with the results in our previous study.[11] The MOR values of the boards A, B, and C–F qualified for MDF 30 type, 15 type, and 5 type defined in JIS A 5905, respectively. In contrast, in wet conditions there was little effect of board density on MOR and MOE, indicating that the increase in pressing temperature between treatments A–F (from 180°C to 200°C, Table 2) caused an improvement of the water resistance properties despite the reduction in density. The evaluation of the results is based on the following two assumptions: the influence of the difference between one-step and three-step pressing was negligible (supported by the results of the preliminary study above); the effect of particle size increase was to reduce the quality of board properties.[11] Therefore, although the comparison of manufacturing conditions A–F sometimes involved changes to more than one variable, the favorable influence of the pressing temperature could be inferred.

In this connection, further interpretation of the water resistance properties was conducted based on the MOR and MOE retention ratios (Figs. 2, 3). The MOR retention ratio was higher in treatment A than in treatment B, which had a lower board density (Table 2), indicating that the water resistance was lowered. However, MOR and MOE retention increased when the pressing time was extended (C > B) and when the temperature was elevated (D > B), in spite of the use of Powder-2, which was coarser than Powder-1. These results indicated that the pressing temperature was more effective than the pressing time in improving the water resistance properties, taking into account the two assumptions mentioned above.

It has been reported that the flow of moisture inside mats could be affected by the particle geometry.[13] However, all particles used in this study were quite small (Table 1) and thus the difference in the raw material may not have affected the temperature effect at the center of the mat during pressing.[13,14] It has also been found[14] that the difference in the particle size does not affect the density profile of boards of the same bulk density. In addition, the press closing time, which can affect the vertical density profile,[15] was identical (5 s) and the actual board density was almost the same as the target density (±0.02 g/cm^3). It can therefore be presumed that the binderless boards in this study, manufactured under the same pressing temperature and target density conditions, should have very similar vertical density profiles and experience similar core layer temperatures during pressing.

Under manufacturing conditions D–F, where Powder-2 or Chip was used and the lower density mats were pressed at 200°C, water resistance properties were improved, which was attributed to the increased pressing temperature. The MOR and MOE retention ratios of the D–F binderless boards were higher than the boards bonded with UF resin (G–J) and UMF resin (K and MDF) and were almost as high as the PF resin boards (L). This indicated that binderless boards could show higher water resistance than the boards bonded with UF and UMF resin if the appropriate manufacturing conditions were adopted.

This self-bonding property was significantly affected by the chemical changes to the binderless board during hot pressing because no resin was applied during the binderless board manufacture. It has been reported that degradation of chemical components occurs during hot pressing.[16–18] Water-soluble fractions increased as a result of the degradation of hemicellulose.[16] In contrast, Sekino et al.[19] reported that changes in hemicellulose reduced the hygroscopicity and improved the dimensional stability. With lignin, even though some lignin experienced degradation,[17,18] an increase in the condensed structure with increasing pressing temperature was reported,[7,17,18] which might contribute to the water resistance properties. However, little is known about the relationship between the chemical changes of binderless boards during hot pressing and changes in board performance. More detailed work is necessary to evaluate board properties based on chemical analyses.

IB retention ratios

The IB values of binderless boards were affected by raw material grain size (Fig. 4). The highest IB values were achieved in treatments A and B where Powder-1 was used while the lowest values were observed in treatment E where Chip was used. These results were consistent with the results in our previous study.[11] However, there was little effect of raw material on the values of IB after water treatment. A further important point is that the IB retention ratio of the binderless boards under conditions D–F was as high as that of the boards bonded with UMF resin (K). In particular the value of treatment E was also higher than that of the boards manufactured with PF resin (L). The IB retention ratio results also indicated that water resistance was improved when the pressing temperature was raised to 200°C. Under these production conditions the water resistance properties of the binderless boards were higher than those of the boards produced with UMF resin.

However, care should be taken when evaluating the IB retention ratio. For example, especially in the case of high density boards like treatment A, cracks sometimes occurred in the middle layer of the boards during the drying process due to the moisture content distribution. This greatly decreased the IB retention ratio and as a result the average IB retention ratio of treatment A was lower than that of treatment B.

TS and WA

The effect of the manufacturing conditions on TS for the binderless board treatments A–F (Fig. 5) is similar to that for MOR, MOE, and IB retention ratios discussed above. As discussed previously, the evaluation of TS does not involve calculations to cancel the influence of the differences in the manufacturing conditions between binderless boards and those manufactured with synthetic resins. However, the fact that TS showed the same tendency as the retention ratios suggested that the influence of differences in the manufacturing condition on TS was small and therefore TS could be used as an indicator of water resistance properties. TS values of binderless board treatments D–F were lower than those of the boards bonded with UF or UMF resin (G–K) and were similar to the PF resin-bonded boards (L). Therefore, the TS results also indicated that water resistance properties were improved by raising the pressing temperature from 180°C to 200°C, and, furthermore, the water resistance of binderless boards was higher than that of the boards using UMF resin and was almost as high as that of the boards bonded with PF resin.

In a previous study, the behavior of WA was found to be similar to that of TS.[11] However in the current study there were opposite trends for WA and TS when compared between different treatments (Fig. 5). Comparing treatment A with treatments D, E, or F, respectively, there was a decrease in TS at the same time as an increase in WA. There was a similar contrast between treatments B, C, or D and treatment F. In all these comparisons there was a reduction in density at the same time as an increase in water resistance properties. The reason for this difference may be that the decrease in TS was caused by an improvement in self-bonding properties, whereas the increase in WA was due to an increase in the voids resulting from density reduction. Therefore, it is reasonable to suppose that WA is often affected by the internal structure of the boards rather than by the bonding property itself, and is sometimes not suitable to be used as an indicator of the water resistance properties.

LE

The LE values of the boards manufactured under conditions D–F were lower than those of the boards of conditions A–C, indicating higher water resistance properties in D–F (Fig. 6). In addition, the LE values of the boards under conditions D and E were lower than those of the boards bonded with UMF resin (K).

It was found that the LE of binderless boards decreased with increasing board density, being consistent with previously reported results.[14] Some other studies have suggested that particle size as well as board density affect the LE of boards.[14] However, previous experimental results have been variable and therefore no clear conclusion can be drawn about the effect of the particle size on LE.[20,21] Therefore, in our study it was not possible to conclude the reasons for the high water resistance properties observed at the conditions D–F, because there were differences in both particle size and the pressing temperature. However, considering the results of the other properties mentioned above, it is likely that the pressing temperature condition might have contributed to the improvement of water resistance properties to some extent.

Conclusions

In this study, the water resistance properties of binderless boards were investigated to evaluate the self-bonding properties of such boards. Water resistance properties of binderless boards were investigated under different manufacturing conditions and then evaluated against boards bonded with synthetic resins. The main conclusions can be summarized as follows:

1. The water resistance properties of binderless boards were improved by increasing the pressing temperature from 180°C to 200°C. At 200°C, densities as low as 0.7 g/cm^3 could be achieved and large-particle-size raw materials could be used without any loss in water resistance properties. The pressing temperature was one of the most important conditions to accelerate self-bonding.
2. At 200°C pressing temperature, the water resistance properties of binderless boards were higher than for boards bonded with UF or UMF resins and almost as high as for boards bonded with PF resin.

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References

1. Fuwape JA, Oyagade AO (1993) Bending strength and dimensional stability of tropical wood cement particleboard. Bioresource Technol 44:77–79
2. Mobarak F, Fahmy Y, Augustin H (1982) Binderless lignocellulose composite from bagasse and mechanism of self-bonding. Holzforschung 36:131–135
3. Xu J, Han G, Wong ED (2003) Development of binderless particleboard from kenaf core using steam-injection pressing. J Wood Sci 49:327–332
4. Angles MN, Ferrando F, Farriol X, Salvado J (2001) Suitability of steam exploded residual softwood for the production of binderless

panels. Effect of the pre-treatment severity and lignin addition. Biomass Bioenerg 21:211–224
5. Velasquez JA, Ferrando F, Salvado J (2002) Binderless fiberboard from steam exploded *Miscanthus sinensis*: the effect of a grinding process. Holz Roh Werkst 60:297–302
6. Velasquez JA, Ferrando F, Salvado J (2003) Effects of kraft lignin addition in the production of binderless fiberboard from steam exploded *Miscanthus sinensis*. Ind Crop Prod 18:17–23
7. Suzuki S, Shintani H, Park SY, Saito K, Laemsak N, Okuma M, Iiyama K (1998) Preparation of binderless boards from steam exploded pulps of oil palm (*Elaeis guneensis* Jaxq.) fronds and structural characteristics of lignin and wall polysaccharides in steam exploded pulps to be discussed for self-bonding. Holzforschung 52:417–426
8. Laemsak N, Okuma M (2000) Development of boards made from oil palm frond II: properties of binderless boards from steam-exploded fibers of oil palm frond. J Wood Sci 46:322–326
9. Angles MN, Reguant J, Montane D, Ferrando F, Farriol X, Salvado J (1999) Binderless composites from pretreated residual softwood. J Appl Polym Sci 73:2485–2491
10. Takasu Y, Takahashi I (2005) Manufacture of self-bonding molding from woody material (in Japanese). APAST 15:4–7
11. Okuda N, Sato M (2004) Manufacture and mechanical properties of binderless boards from kenaf core. J Wood Sci 50:53–61
12. Van Dam JEG, Van Den Oever MJA, Keijsers ERP (2004) Production process for high density high performance binderless boards from whole coconut husk. Ind Crop Prod 20:97–101
13. Tomimura Y, Matsuda T, Suzuki I, Nagasawa S (1985) Strand boards and waferboards from Japanese coniferous thinnings and used structural timbers (in Japanese). Mokuzai Gakkaishi 31:1047–1052
14. Miyamoto K, Nakahara S, Suzuki S (2002) Effect of particle shape on linear expansion of particleboard. J Wood Sci 48:185–190
15. Miyamoto K, Suzuki S, Inagaki T, Iwata R (2002) Effects of press closing time on mat consolidation behavior during hot pressing and on linear expansion of particleboard. J Wood Sci 48:309–314
16. Widyorini R, Xu J, Watanabe T, Kawai S (2005) Chemical changes in steam-pressed kenaf core binderless particleboard. J Wood Sci 51:26–32
17. Okuda N, Hori K, Sato M (2006) Chemical changes of kenaf core binderless boards during hot pressing (I): influence of the pressing temperature condition. J Wood Sci 52:244–248
18. Okuda N, Hori K, Sato M (2006) Chemical changes of kenaf core binderless boards during hot pressing (II): their effect on the binderless board properties. J Wood Sci 52:249–254
19. Sekino N, Inoue M, Irle M, Adcock T (1999) The mechanism behind the improved dimensional stability of particleboards made from steam-pretreatment particles. Holzforschung 53:435–440
20. Kelly MW (1977) Critical literature review of relationships between processing parameters and physical properties of particleboard. General technical report FPL-10, U.S. Department of Agriculture Forest Service Forest Products Laboratory, Madison, WI
21. Hiziroglu S, Suchsland O (1993) Linear expansion and surface stability of particleboard. For Prod J 43:31–34