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Ragil Widyorini · Jianying Xu · Kenji Umemura
Shuichi Kawai

Manufacture and properties of binderless particleboard from bagasse I: effects of raw material type, storage methods, and manufacturing process

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Abstract Binderless particleboards were manufactured from sugarcane (*Saccharum officinarum* L.) bagasse by steam-injection pressing and by using hot pressing as a reference method. The inner layer (core/pith) and the outer hard fibrous layer (face/rind) of bagasse were used as raw materials. The effects of bagasse type, manufacturing process, and storage method on the mechanical properties of binderless particleboards were investigated. The results showed that the bagasse pith particles provided better board properties than bagasse rind particles. It seemed that bagasse pith particles were more easily deformed than bagasse rind particles, enlarging the bonding contact area. The severe conditions of steam-injection pressing caused delamination on the bagasse pith binderless boards with densities of 0.6 g/cm^3 or higher, and gave poor bonding quality. However, steam-pressed boards showed relatively higher board properties than hot-pressed boards. The storage method of sugarcane bagasse affected the chemical composition and the board properties. It was shown that the extent of self-bonding formation depends on the chemical and morphological properties of lignocellulosic materials, as well as on the manufacturing conditions.

Key words Binderless board · Bagasse pith · Bagasse rind · Steam-injection pressing

Introduction

Sugarcane (*Saccharum officinarum* L.) stalk can be separated into the tough fibrous material called rind (approximately 50% of the total dry weight of stalk), the juice that contains pith cells and internal fiber called pith, and the thin outer wax-laden skin called dermax.[1] Bagasse, a waste product of sugarcane processing, is now considered to be one of the most promising nonwood lignocellulosic raw materials. Large quantities of this waste are still left unused or burnt in developing countries. The surplus bagasse is usually used as a fuel source for sugar processing.

Bagasse normally contains residual sugars, depending on the cane variety, its maturity, harvesting method, and the efficiency of the sugar milling plant. The residual sugars may cause problems in resin-bonded board manufacturing,[1] because sugars may not be chemically compatible with the conventional resin binders and may interfere with the bonding.[2] Therefore, the removal of pith/core and residual sugars is usually important to produce good quality panel products.[1,2]

Considering that bagasse is a sugar-containing lignocellulosic material, Shen[2] developed bagasse binderless composites using a hot pressing system at an elevated temperature of 180°C or higher. Shen claimed that the bagasse composite products could be produced without the removal of pith and residual sugars.

Mobarak et al.[3] investigated the manufacturing of molded binderless boards from bagasse pith, depithed bagasse (rind), and whole bagasse using a hot pressing system under various pressing pressures of 15.7–25.5 MPa and temperatures of 175°–185°C. The densities of these binderless molded products were relatively high, about 1.34 to 1.36 g/cm^3. The results showed that the bagasse pith provided high bending strength compared with the depithed bagasse. Unfortunately, no data concerning the internal bond strength was given in this study.

Steam treatment has been known to be an effective method for improving the dimensional stability of wood-based composites.[4–8] Okamoto et al.[4] reported that the dimensional stability of the binderless medium density fiberboard (MDF) made from mixed softwood and hardwood fibers was improved by using steam-injection pressing, although the internal bonding (IB) was very low. Xu et al.[5] developed binderless particleboard from kenaf

R. Widyorini (✉) · J. Xu · K. Umemura · S. Kawai
Research Institute for Sustainable Humanosphere, Kyoto University, Gokasho, Uji 611-0011, Japan
Tel. +81-774-38-3670; Fax +81-774-38-3678
e-mail: ragil@rish.kyoto-u.ac.jp

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core using steam-injection pressing. The IB strength of these binderless boards was relatively excellent, even at low steam pressures of 0.6–1.0 MPa. It was found that partial degradation of the three major chemical components of the kenaf core by the steam-injection pressing increased the bonding performance and dimensional stability of the binderless boards.[6]

The present research deals with the manufacturing conditions for binderless bagasse pith and rind particleboards by steam-injection pressing, as well as the evaluation of hot-pressed particleboards as reference. The effect of the storage method of bagasse pith on the board properties is also discussed.

Materials and methods

Raw materials

In order to investigate the effect of storage method, the raw materials were prepared in three different ways as follows:

1. After harvesting, the sugarcane (*Saccharum officinarum* L.) stalk was directly separated by a cane separator to obtain the inner layer (pith) and the outer layer (rind). The pith was sent to the sugar milling process to extract the sugar juice. To eliminate the effect of particle size, the bagasse rind was further processed into particles using a hammer mill and then screened to pass 2 mm. The bagasse pith particles (C1) and rind particles (F1) were then air-dried.
2. After harvesting, the sugarcane stalk was separated by the cane separator. The pith was sent to the sugar milling process to extract the sugar juice, and then kept in a refrigerator (for about 5 months) to prevent fermentation. The pith particles obtained were called C2.
3. The sugarcane stalk was stored for 3 weeks before being treated by the cane separator. The pith was sent to the sugar milling process to extract the sugar juice, and was then air-dried (C3).

The moisture contents of pith particles (C1, C2, and C3) and rind particles F1 were about 13%.

Chemical analysis of sugarcane bagasse

All samples were extracted successively with a mixture of ethanol and benzene (1:2, v/v) for 24 h by refluxing, and then with distilled water at 85°C for 3 h. The analyses of extractives were carried out in duplicate. Lignin and holocellulose contents were determined by the Klason and Wise methods, respectively. α-Cellulose content was determined by extraction of the holocellulose with 17.5% NaOH solution. All the chemical analyses were carried out in triplicate.

Manufacture of binderless board

The dimensions of the binderless boards were 230 × 230 × 12 mm. The rind F1 and pith C1 particles were hand-formed using a forming box into homogeneous single-layer mats. The mats were pressed using a steam-injection press, which was sealed with a 12-mm-thick stainless steel frame. Steam was injected into the mats after the press had closed to the final board thickness and the pressing pressure reached the desired level set at 6.0 MPa. The mats were pressed with steam pressure of 1.0 MPa (183°C) with pressing times of 0.75–15 min. After that, the steam was then released from the particlemats by using a vacuum system for 3 min. During pressing, the temperatures of both the upper and lower platen were kept at 190°C, which is a little higher than steam temperature, to avoid steam condensation.

The target densities, material type, treatment type, and pressing times used in this experiment are shown in the Table 1. The target densities of each board manufactured using bagasse pith C1 and rind F1 were set at four levels, ranging from 0.5 to 0.8 g/cm^3. In addition, the binderless boards prepared by hot pressing were subjected to a temperature of 190°C for 10 min. In order to investigate the storage method, bagasse pith C2 and C3 binderless boards were manufactured under these conditions: steam-injection pressing (1.0 MPa for 10 min) and hot pressing (190°C for 10 min). The target board density was 0.7 g/cm^3.

Evaluation of physical properties of binderless board

Prior to evaluation of the mechanical properties and dimensional stability, the binderless boards were conditioned at room temperature for about 10 days. They reached a moisture content of 6%–9%. The properties of binderless boards were evaluated in accordance with the Japanese Industrial Standard for Particleboards.[9]

Two specimens of 230 × 25 × 12 mm were prepared for each board for their static bending test. The three-point bending test was conducted over an effective span of 180 mm at a loading speed of 10 mm/min. Three test specimens of 50 × 50 × 12 mm were prepared for each board for IB tests, and two specimens of the same size of each board were prepared for thickness swelling (TS) and water absorption (WA) tests after 24 h water immersion at 20°C.

Results and discussion

Chemical properties of raw materials

The chemical compositions of sugarcane bagasse samples according to storage method and bagasse type are shown in Table 2. The pith C1 and rind F1 particles showed no great differences in chemical composition, except that the hemicellulose content of C1 particles was relatively high compared with that of F1 particles. Compared with C1 and C2 particles, C3 particles contained the more hot water-soluble components and less hemicellulose. It seemed that fermen-

Table 1. Manufacturing conditions for bagasse binderless particleboards

Raw materials	Target board density (g/cm^3)	Treatment	Process condition	Pressing time (min)					
Bagasse pith C1	0.5	SP	1 MPa			3	6	10	
	0.6		1 MPa	0.75	1.5	3	6[a]	10[a]	15[a]
	0.7		1 MPa		1.5[b]	3	6[a]	10[a]	
	0.8		1 MPa			3[b]	6[b]		
	0.5	HP	190°C					10	
	0.6		190°C					10	
	0.7		190°C					10	
	0.8		190°C					10	
Bagasse rind F1	0.5	SP	1 MPa			3	6	10	
	0.6		1 MPa	0.75[a]	1.5	3	6	10	
	0.7		1 MPa		1.5[a]	3	6		
	0.8		1 MPa			3[a]	6		
	0.5	HP	190°C					10	
	0.6		190°C					10	
	0.7		190°C					10	
	0.8		190°C					10	
Bagasse pith C2	0.7	SP	1 MPa					10	
	0.7	HP	190°C					10	
Bagasse pith C3	0.7	SP	1 MPa					10	
	0.7	HP	190°C					10	

SP, Steam-injection pressing; HP, hot pressing system
[a] The board was slightly delaminated
[b] The board was totally delaminated

Table 2. Chemical composition of sugarcane bagasse

	AB extractives	HW extractives	Klason lignin	α-Cellulose	Hemicellulose
Pith particles (C1)	2.2	16.2	18.9	30.9	28.4
Rind particles (F1)	4.9	18.5	20.8	31.1	22.6
Pith particles (C2)	1.9	7.8	21.7	35.7	29.5
Pith particles (C3)	3.7	26.1	16.6	29.4	21.6

Data given as percentages based on dry weight of material
AB, Alcohol–benzene; HW, hot water

tation had occurred during storage. The color of the C3 particles was pink, supporting this conclusion. Fermentation occurs as an exothermic process, thus causing a rapid increase in temperature.[1] At the same time, the residual free sugars ferment to acetic acid.[1] This combination causes severe damage to hemicelluloses and cellulose fiber quality, as well as severe losses in storage.[1] Therefore, the fermentation process has to be controlled to preserve the quality of bagasse and to minimize losses in storage.

Binderless board conditions after pressing

Some of the steam-pressed C1 binderless boards were slightly delaminated after pressing, while others were totally delaminated as shown in Table 1. On the other hand, hot-pressed binderless boards were sound. One of the reasons may as follows: pith C1 binderless boards with higher densities have higher compaction ratios (i.e., 6.4 for a 0.60-g/cm^3 target density board), making it difficult for the steam inside the board to escape, thereby causing poor bonding strength. It seemed that delamination had already occurred during the pressing treatment. In addition, C1 particles contained a large amount of hot water-soluble components, which indicated high residual free sugars. The degradation of the chemical components and residual free sugars into low molecular weight compounds will release water during treatment.[2] Therefore, by injecting the high-pressure steam for longer pressing times, excess steam would be produced and substantial degradation of the chemical components would occur in the board. It is well known that intensive degradation of chemical components during treatment might decrease the board properties.[10]

Steam-pressed rind F1 binderless boards with short pressing time (i.e., 0.75 min for a 0.60-g/cm^3 target density board) were delaminated, whereas steam-pressed boards with longer pressing times were not. There were differences between rind and pith binderless boards in the occurrence of delamination. This may be due to the effects of the chemical and physical properties of the raw materials. It was

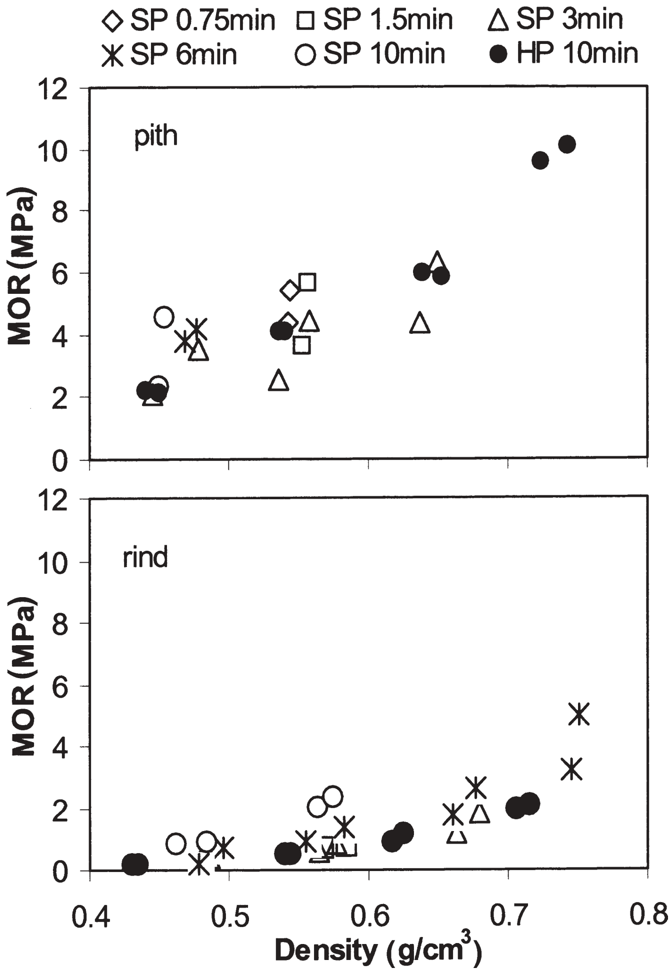

Fig. 1. Effects of board density, pressing time, and pressing method on the modulus of rupture (MOR) of bagasse pith C1 and rind F1 binderless particleboards. *SP*, steam pressure was 1.0 MPa; *HP*, hot-pressing system at 190°C

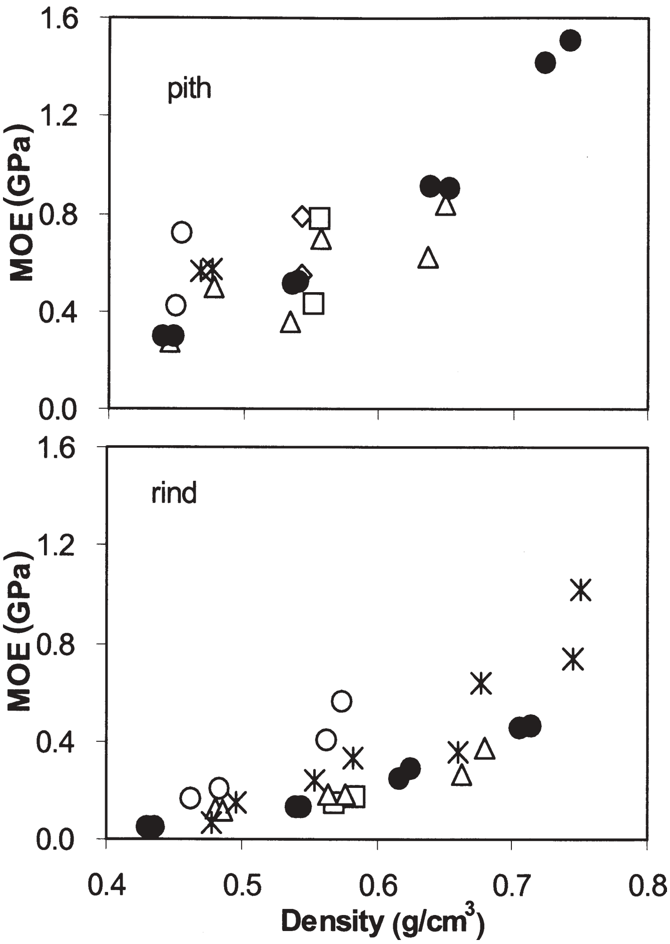

Fig. 2. Effects of board density, pressing time, and pressing method on the modulus of elasticity (MOE) of bagasse pith C1 and rind F1 binderless particleboards

obvious that a certain pressing time was required to produce the board.

The properties of the partially and totally delaminated specimens were excluded from the results of board properties.

Bending strength

The effects of material type, board density, and pressing method, on the modulus of rupture (MOR) of binderless boards produced using various pressing times are shown in Fig. 1. The results show that the pith C1 binderless boards have higher MOR values than the rind F1 boards for both pressing methods. Mobarak et al.[3] found similar trends, in which bagasse pith-molded products provided high bending strength compared with bagasse-depithed products. In the pith area, the parenchyma cells are very large and thin walled.[3] It seems reasonable to conclude that the pith particles were more easily deformed and packed more closely than the rind particles, thus enlarging the self-bonding area.

The MOR value of the bagasse particleboards increased with increasing board density, which is a similar trend to that observed for conventional particleboards. The MOR value was 2.2 MPa for hot-pressed board from C1 particles with a density of 0.45 g/cm^3, whereas it was 9.9 MPa for a board density of 0.75 g/cm^3. Compared with the hot-pressed boards, the MOR values of steam-pressed boards that were made with pressing times longer than 3 min were higher.

The effects of the board density, pressing method, and material type on the modulus of elasticity (MOE) of binderless boards produced using various pressing times are shown in Fig. 2. Following the results for MOR, the pith C1 binderless boards provided higher MOE values than the rind F1 boards. Compared with hot-pressed boards, steam-pressed boards gave a high value in a relatively short pressing time.

Figure 3 shows the effects of pressing and storage methods on the MOR of bagasse pith binderless particleboards at a corrected density of 0.65 g/cm^3. The results show that the MOR values of steam-pressed boards were higher than those of hot-pressed boards. The steam-pressed C1 board

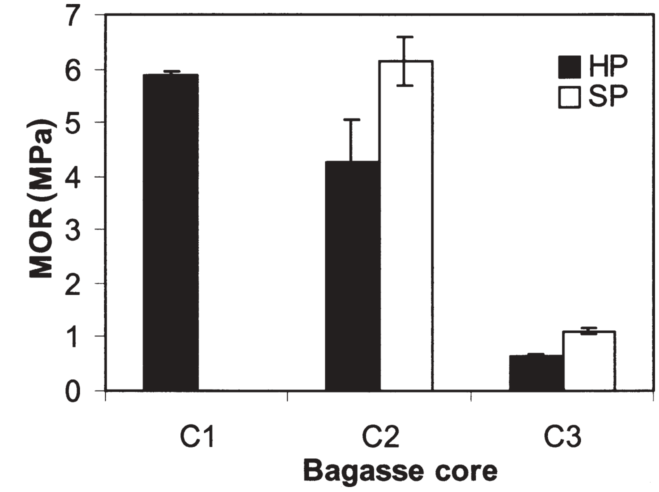

Fig. 3. Effects of storage and pressing methods on the MOR of bagasse pith binderless particleboards. The board density was a corrected value of 0.65 g/cm^3. *Vertical lines* through the bars represent the standard deviation from the mean. The pressing time was 10 min. *SP*, steam pressure was 1.0 MPa; *HP*, hot-pressing system at 190°C

was delaminated, whereas the C2 board was not. This might be due to the high hot water-soluble content of the C1 particles, as discussed earlier. The boards from C3 particles provided the lowest MOR compared with the boards from C1 and C2 particles for both pressing methods. It seemed that some degradation occurred during the storage period, as mentioned earlier, degrading the quality of C3 particles and resulting in poor bending strength of the particleboards.

Internal bond strength

The effects of board density, pressing method, and material type on the IB strength of bagasse binderless boards are shown in Fig. 4. Trends similar to those of MOR and MOE were observed for the IB, especially for low densities. At a density of 0.45 g/cm^3, the IB value of hot-pressed board from C1 particles was 0.1 MPa, and at the density of 0.75 g/cm^3 it was 0.2 MPa. The IB values of steam-pressed boards that were manufactured with pressing times longer than 3 min were higher than hot-pressed boards. This shows that steam-injection pressing requires shorter pressing times than hot pressing to obtain about the same IB strength. The IB values of C1 binderless particleboards were lower than those of kenaf core binderless boards[5] at the same board densities, and slightly higher than other binderless boards, such as those from steam-exploded fibers of oil palm frond[10,11] and steam-injected wood MDF.[4]

The boards from C1 particles provided IB values that were higher than the boards from F1 particles. This may be partly attributed to the higher hemicellulose content of C1 particles than that of F1 particles. Generally, degradation of the hemicellulose is believed to play an important role in self-bonding.[2] Ellis and Paszner[12] also found that the board strengths were directly proportional to the pentosan content of the raw materials used.

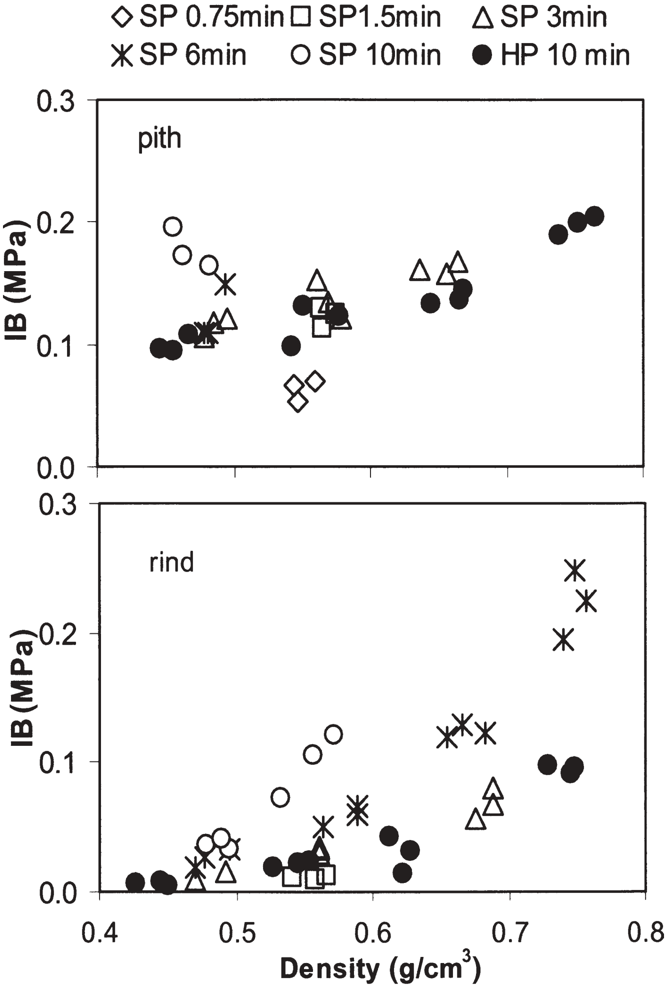

Fig. 4. Effects of board density, pressing time, and pressing method on the internal bonding (IB) of bagasse pith C1 and rind F1 binderless particleboards. *SP*, steam pressure was 1.0 MPa; *HP*, hot-pressing system at 190°C

Figure 5 shows the effect of pressing time on the IB of the binderless boards. The figure shows the corrected IB values for a board density of 0.55 g/cm^3. It is obvious that the IB values increase with increasing pressing time. Delamination was observed in the binderless boards from bagasse pith that were pressed for more than 6 min. It seemed that severe degradation of the chemical components had already occurred, as discussed previously. Suzuki et al.[10] reported that steam-exploded oil palm frond fiber at a steam pressure of 3 MPa showed signs of great damage to lignin macromolecules, and poor-quality binderless boards were manufactured.

Figure 6 shows the effects of pressing and storage methods on the IB of bagasse pith binderless particleboards at a corrected density of 0.65 g/cm^3. Trends similar to that of MOR were observed for the IB. The values of steam-pressed boards were higher than those of hot-pressed boards. The bagasse pith C3 particleboards showed the lowest IB values of the boards prepared with bagasse pith. Considering these results, the storage method is an impor-

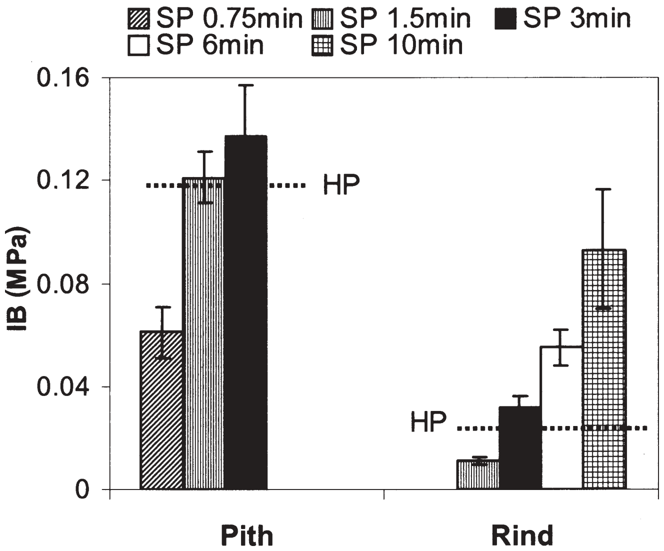

Fig. 5. Effect of pressing time on the IB of bagasse pith C1 and rind F1 binderless particleboards. The board density was a corrected value of 0.55 g/cm^3. *Dotted lines* represent IB values of hot-pressed boards (*HP*) at 190°C for 10 min. *SP*, steam pressure was 1.0 MPa

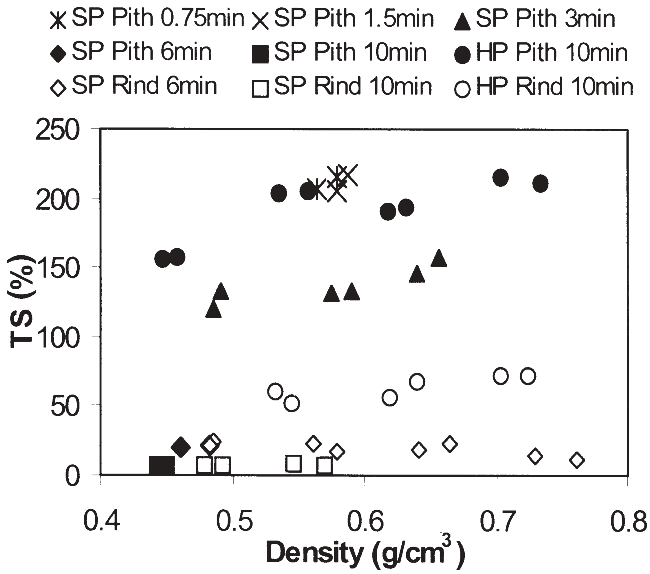

Fig. 7. Effects of board density, steam-pressing time, and hot-pressing system on the thickness swelling (TS) values of bagasse pith C1 and rind F1 binderless particleboards. Steam-injection was 1.0 MPa; *HP*, hot pressing system at 190°C

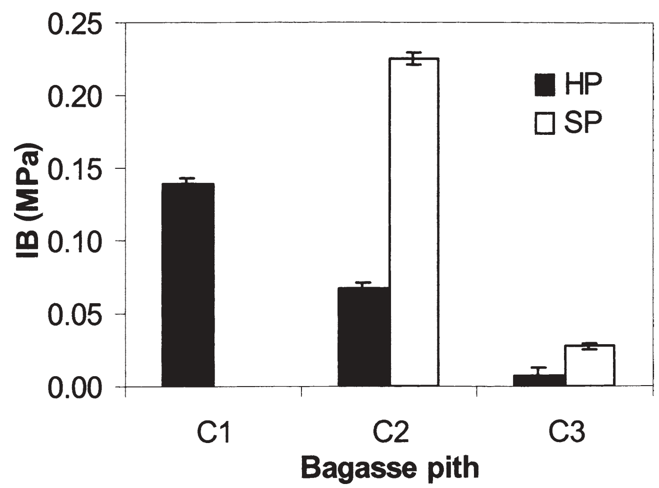

Fig. 6. Effects of storage and pressing methods on the IB of bagasse pith binderless particleboards. The board density was a corrected value of 0.65 g/cm^3. *Vertical lines* through the bars represent the standard deviation from the mean. The pressing time was 10 min. *SP*, steam pressure was 1.0 MPa; *HP*, hot-pressing system at 190°C

tant part of utilizing bagasse as a raw material of binderless products.

The surface of the steam-pressed boards was much darker than that of hot-pressed boards, indicating intensive changes in the chemical compositions of the lignocellulosic materials. In the previous study,[6] it was found that significant degradation of the chemical components of the kenaf core by mild steam-injection treatments (0.6–1.0 MPa) increased the bonding performance of the boards. This effect was not obtained by hot pressing, which degraded the chemical components of kenaf core much less effectively.[6] Compared with kenaf core particleboard, bagasse particleboard has inferior properties. It seems that the chemical compositions of raw materials affect the properties of binderless board, as does the manufacturing process. The chemical changes of bagasse during steam and heat treatments will be discussed in the next report, to clarify the self-bonding mechanism.

Dimensional stability

The TS values of C1 and F1 binderless particleboards are shown in Figure 7. The results show that no significant change was observed between the TS and board density, but the TS values are affected by the pressing time and pressing method. For steam-pressed C1 binderless boards, the TS value of a board with a density of 0.45 g/cm^3 with a 3-min pressing time was 125%, whereas the TS values decreased to 21% and 7% for 6-min and 10-min pressing times, respectively. The longer pressing time had a lower TS value, as reported in the previous studies.[3,6] Samples of steam-pressed F1 binderless boards manufactured at less than 3-min pressing time were broken into pieces after 24 h water immersion, and thus no TS values could be obtained. The WA values decreased with increasing board density because of the decrease of spaces in the boards.

Compared with the hot-pressed boards, the TS values of the steam-pressed boards were much lower. The low TS value might be attributed to the steam-injection pressing method, which has been proved to increase the dimensional stability of binderless boards.

Conclusions

Binderless particleboards were prepared from bagasse pith and rind using steam-injection pressing, and their mechanical properties were investigated. The effects of bagasse type, pressing condition, and storage method were evaluated. Binderless boards manufactured by hot pressing were also prepared. Based on the results obtained, the conclusions can be summarized as follows.

Bagasse pith particleboards provided properties that were superior to those of bagasse rind boards. The bagasse pith seemed more easily deformed than bagasse rind, thus enlarging the bonding area. The longer steam-injection time caused the delamination of the bagasse pith binderless boards, especially for the densities higher than 0.6 g/cm^3. It was suggested that excess steam, which had been produced in the boards, would cause severe degradation of the chemical components and provide poor board properties. However, the steam-pressed boards showed relatively higher properties compared with hot-pressed boards. The storage method also affected the chemical composition of the raw materials and the board properties. It was obvious that the storage method of bagasse is one of the important aspects of binderless product preparation. The extent of self-bonding formation depends on the chemical and morphological properties of lignocellulosic materials, as well as on the manufacturing conditions.

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