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ORIGINAL ARTICLE

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Manufacture and mechanical properties of binderless boards from kenaf core

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Abstract Binderless boards were prepared from finely ground powders of kenaf (*Hibiscus cannabinus L.*) core under varying manufacturing conditions. This research was designed to investigate their mechanical properties and evaluate the various manufacturing conditions: pressing temperature and time, pressing pressure, board density, board thickness, grain size of raw materials, and addition of furfural. The mechanical properties (i.e., modulus of rupture and elasticity, internal bonding strength) of boards increased with increasing board density and met the requirement for 15 type medium-density fiberboard (MDF) by JIS A 5905-1994. Thickness swelling and water absorption of boards exceeded the maximum permitted levels for 15 type MDF and S20 grade hardboard by JIS A 5905-1994, which indicates the low water-resistant property of binderless boards. In contrast to that in usual wood-based materials, internal bonding strength showed significant correlations with other board properties: modulus of rupture and elasticity, thickness swelling, and water absorption. We confirmed experimentally that the best manufacturing conditions proved to be as follows: pressing temperature 180°C, time 10min; pressing pressure 5.3MPa; board thickness 5mm; board density 1.0g/cm^3; average grain size 53μm; and powder with no furfural content.

Key words Self-bonding · Binderless board · Kenaf core

Introduction

Kenaf is grown as an annual fiber crop by a few countries, mainly in the Southeast Asian region. It grows quickly and can attain a height of 3.6–4.2m during a growing season. The stalk contains two types of fiber: an outer "bast" and an inner "core." There is renewed interest in the utilization of kenaf bast fibers as automotive nonwoven material.[1–3] The core however, has no utility in the automotive applications and is often discarded. Kenaf core is considered to be one of the new sustainable lignocellulosic raw materials if we use it effectively. Therefore, in this study we manufactured binderless boards from kenaf core and evaluated their mechanical properties.

It is well known that wood-based fragments can be formed into boards just by hot pressing, without the addition of any resin or adhesives, by means of activating chemical components of the board constituents. This phenomenon, called self-bonding, may be attributed to hydrolysis of hemicellulose and softened lignin.[4,5] Kenaf core is deemed to be a suitable raw material for making binderless boards because of its high hemicellulose content.[6,7]

Adhesive is generally accepted to be the most expensive raw material in the manufacture of particleboard or hardboard.[8] Binderless board will become an important target of trials for effective utilization of biomass waste, especially in developing countries where people have no or limited wood resources and no adequate chemical industries but a surplus of agricultural residues.[9]

As reviewed by Johns and Woo[10] chemical treatment of fiber is effective in improving the internal bonding strength of hardboard. Here we examine the latest studies on binderless board. Binderless boards were developed from oil palm frond.[5,8] Xu et al.[11] reported on the mechanical properties of low-density binderless particleboards from kenaf core, such as sound absorption and thermal resistance. Most studies on binderless board have concluded that these boards can be manufactured using steam explosion treatment. Although steam explosion was found to

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Part of this paper was presented at the 52nd Annual Meeting of the Japan Wood Research Society, Gifu, April 2002 be a useful pretreatment for the effective utilization of biowaste,[12] it requires special equipment and much energy. In this study, as a substitute pretreatment for steam explosion, kenaf core was processed through a flour mill and crushed into powder. Because kenaf core is soft and is easily crushed into powder, grinding is a potential pretreatment for raw materials for making binderless board. Therefore, the possibility of producing binderless board from finely ground powder of kenaf core was investigated.

Materials and methods

Materials

Kenaf (*Hibiscus cannabinus L.*) was harvested from a plantation in Indonesia in October 1999. The harvested stems were decorticated to separate the core from the bark, thereby obtaining kenaf core without any retting process. The core was then dried under the conditions of 70°C for 80 h (8 h/day for 10 days) and was crushed using a flour mill (model ACM-10; Hosokawa micron, Japan) into 53-μm powder and 3.3-mm chips (grain sizes), with about 8%–9% and 13% moisture contents, respectively. They were stored in unsealed vinyl bags in the laboratory.

Board manufacture

For manufacture of binderless boards, powders and chips were hand-formed into homogeneous single-layered mats using a forming box. After forming, the mats were prepressed by hand, and their top and bottom surfaces were covered with aluminum foil. The mats were then pressed with a hot-press machine under various conditions: pressing temperatures of 140°, 160°, 180°, and 200°C; pressing times of 2, 5, and 10 min; pressing pressure 5.3 MPa; board thickness 5 and 10 mm; and targeted densities of 0.5, 0.8, and 1.0 g/cm^3. We conducted five experiments using combinations of these manufacturing conditions. Three to six boards were manufactured for each experiment. Details of the manufacturing conditions for each experiment are described below.

Conditions of pressing temperature and time

To test the effect of pressing temperature conditions, the hand-formed mats from powders were hot-pressed at 140°, 160°, or 180°C for 10 min (conditions A, B, and C). Then, to consider the possibility of shortening the manufacturing time because it is generally said that the pressing time is one of the most important factors in industrial board production, pressing conditions of 180°C for 5 min (condition D), 200°C for 2 min (condition E), and 200°C for 5 min (condition F) were investigated. Other manufacturing conditions were as follows: pressing pressure 5.3 MPa, board dimensions 300 × 300 × 5 mm, and targeted density 1.0 g/cm^3.

Conditions of board thickness

Another experiment was conducted to test the effect of the thickness of boards. The mats were prepared from powders and pressed at 180°C for 10 min under a pressure of 5.3 MPa. The boards were 5 and 10 mm thick, and their targeted density was 1.0 g/cm^3.

Conditions of board density

We investigated the effect of the board density on board properties. The mats from powders were pressed at 180°C for 10 min under a pressure of 5.3 MPa. The board thickness was 5 mm, and the targeted densities were 0.5, 0.8, and 1.0 g/cm^3.

Conditions of grain size of raw materials

To examine the effect of the grain size of raw materials, powders and chips were mixed in various proportions to prepare binderless boards. Three combinations with powder/chip ratios of 0%, 50%, and 100% were investigated. The hand-formed mats were pressed at 180°C for 10 min under a pressure of 5.3 MPa. The board thickness was 5 mm, and the targeted density was 1.0 g/cm^3.

Conditions of additional substances

An experiment was conducted to test the effects of furfural (2-furaldehyde) on board properties. Furfural is thought to be one of the factors involved in self-bonding. Powders were put into a rotating drum, where they were stirred and scattered; furfural was sprayed into it at 0%, 5%, 10%, and 15% based on the weight of the powders. After forming, the mats were pressed at 140°C, which is higher than the lignin-softening temperature at 12% moisture content (around 120°C[13]) and is lower than the boiling point of furfural (around 162°C). A three-step pressing schedule was used to avoid blistering because the addition of furfural caused a high moisture content in the mats. During the first step the mats were pressed under a pressure of 10 MPa for 4 min; and during the second and third steps they were pressed at 8 MPa for 3 min and 6 MPa for 3 min, respectively. The board size was 200 × 200 × 5 mm, with targeted density of 0.8 g/cm^3.

Evaluation of mechanical properties of boards

We measured the modulus of rupture (MOR) under dry and wet conditions, modulus of elasticity (MOE), internal bonding strength (IB), thickness swelling (TS), and water absorption (WA) according to JIS A 5905-1994 (Fiberboards). Bending tests were conducted with a concentrated load of 5 mm/min. The MOR in the wet condition was determined by measuring the MOR after soaking in 70°C water for 2 h and 20°C water for 1 h. The specimen size for bending tests was 50 × 200 mm with an effective span of 150 mm. The sample size for the IB, TS, and WA tests was 50 × 50 mm. More than seven specimens were tested for the MOR in the dry condition, MOE, IB, and TS; more than four specimens were tested for WA; and three were tested for MOR in the wet condition.

Results and discussion

Before we discuss the manufacturing conditions and the mechanical properties of the binderless boards, it is useful to show their appearance. The binderless boards pressed at relatively low temperature around 140°C had almost the same color as the original kenaf core, and those at high temperature (around 180°C) were light brown. All the boards had smooth surfaces, and especially the boards made at 180°C had tight edges and glossy sections like plastics. All the boards generated peculiar sweet smells during the hotpressing process, which indicates the hydrolysis of chemical components.

Table 1 shows the manufacturing conditions and the mechanical properties of all the binderless boards investigated in this study. More details are discussed below.

Effects of pressing temperature and time

We begin by comparing the conditions of A–C to consider the effects of pressing temperature conditions. Figures 1 and 2 show the MOR in dry and wet conditions and the MOE of the binderless boards at different IBs and pressing temperatures. It is obvious from Figs. 1 and 2 that the increase in IB with increasing pressing temperature causes an increase in the MOR in dry and wet conditions, and in MOE. Table 2 shows the ratio of retention in MOR after soaking in 70°C water for 2 h and 20°C water for 1 h. The ratio of retention in the MOR increased with increasing pressing temperature. However, even the strongest binderless boards treated at 180°C lost almost three-fourths of their strength under the wet condition. The low water-resistant property of binderless boards shown in Table 2 may be attributed to the contribution of hemicellulose to self-bonding. The water-resistant property of binderless boards might be improved by the contribution of lignin to self-bonding.

Figure 3 shows the TS and WA values at different IBs and pressing temperatures, which also indicates the low water-resistant property. The TS and WA decreased with increasing IB, but even the specimens treated at 180°C could not satisfy the maximum requirements for TS (17%) and for WA (30%) set for grade 15 type medium-density fiberboard (MDF) and grade S20 type hardboard by JIS A 5905-1994. It is obvious from Figs. 1–3 that the IB correlates with the MOR under dry and wet conditions, MOE, TS, and WA (R^2 = 0.96, 0.86, 0.87, 0.72, and 0.70, respectively), which is quite different from the case of usual wood-based materials such as particleboard and hardboard.

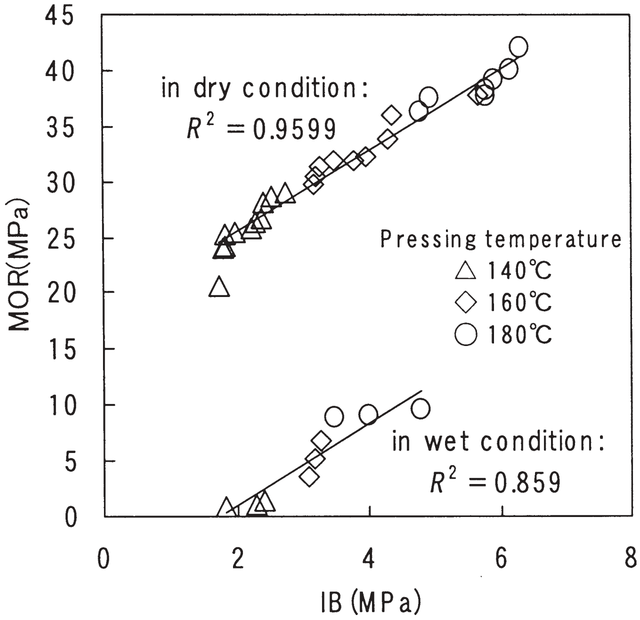

Fig. 1. Relation between internal bonding strength (*IB*) and modulus of rupture (*MOR*) under dry and wet conditions at various pressing temperatures

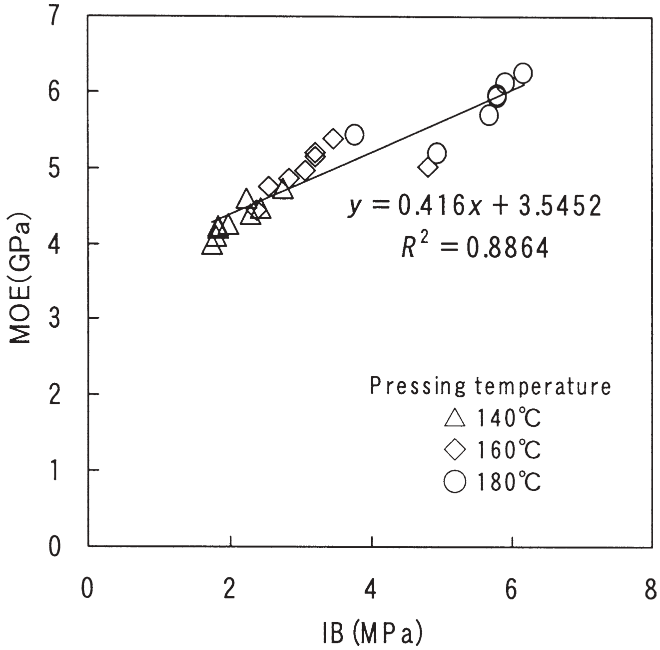

Fig. 2. Relation between IB and modulus of elasticity (*MOE*) at various pressing temperatures

We next examine the effects of the pressing temperature and time by comparing the manufacturing conditions of A–E. The board made under condition F (200°C for 5 min) exploded and broke into pieces, with no specimens obtained. Hence we could not conduct any experiments for condition F.

We see from Table 1 that the highest board performances were obtained at condition C, which indicates that

Table 1. Manufacturing conditions and mechanical properties of all binderless boards

Material	Manufacturing conditions					Mechanical properties					
	Temperature (°C)	Pressure (MPa)	Time (min)	Density (g/cm^3)	Thickness (mm)	MOR (MPa)		MOE (GPa)	IB (MPa)	TS (%)	WA (%)
						Dry condition	Wet condition				
Powder											
condition A	140	5.3	10	1.0	5	25.4	1.1	4.3	2.2	81.0	133.6
B	160	5.3	10	1.0	5	33.2	5.2	5.1	3.3	34.5	57.2
C	180	5.3	10	1.0	5	36.1	9.3	5.5	5.7	19.6	40.9*
D	180	5.3	5	1.0	5	34.4	–	4.7	4.4	25.8	49.2
E	200	5.3	2	1.0	5	29.0	–	4.3	3.1	26.7	54.8
F	200	5.3	5	1.0	5	–	–	–	–	–	–
Powder	180	5.3	10	1.0	5	36.1	9.3	5.5	5.7	19.6	40.9*
Powder	180	5.3	10	1.0	10	20.3	–	3.0	1.7	51.8	104.8
Powder	180	5.3	10	0.5	5	2.7	0.0	0.75	0.20	63.2	262.5
Powder	180	5.3	10	0.8	5	15.9	2.6	2.8	2.2	27.2	75.5
Powder	180	5.3	10	1.0	5	36.1	9.3	5.5	5.7	19.6	40.9*
Chip content of board mix											
0%	180	5.3	10	1.0	5	36.1	9.3	5.5	5.7	19.6	40.9*
50%	180	5.3	10	1.0	5	23.5	4.8	5.1	2.3	23.5	56.6
100%	180	5.3	10	1.0	5	22.1	3.7	4.6	2.0	21.6	50.0
Furfural content of powder											
0%	140	10, 8, 6	4, 3, 3	0.8	5	–	–	–	0.25	–	–
5%	140	10, 8, 6	4, 3, 3	0.8	5	–	–	–	0.50	–	–
10%	140	10, 8, 6	4, 3, 3	0.8	5	–	–	–	0.39	–	–
15%	140	10, 8, 6	4, 3, 3	0.8	5	–	–	–	0.40	–	–
Requirement by JIS A 5905-1994											
15 Type MDF						>15	>7.5	>1.3	>0.3	<17	–
25 Type MDF						>25	>12.5	>2	>0.4	<17	–
S20 Hardboard						>20	–	–	–	–	<30

*same data; –, no data; MOR, modulus of rupture; MOE, modulus of elasticity; IB, internal bonding strength; TS, thickness swelling; WA, water absorption; MDF, medium-density fiberboard

Table 2. Retention ratio for MOR under wet and dry conditions

Pressing temperature (°C)	MOR in dry condition (MPa)	MOR in wet condition (MPa)	Retention ratio for MOR (%)
140	25.4	1.1	4.4
160	33.2	5.2	15.6
180	36.1	9.3	25.7

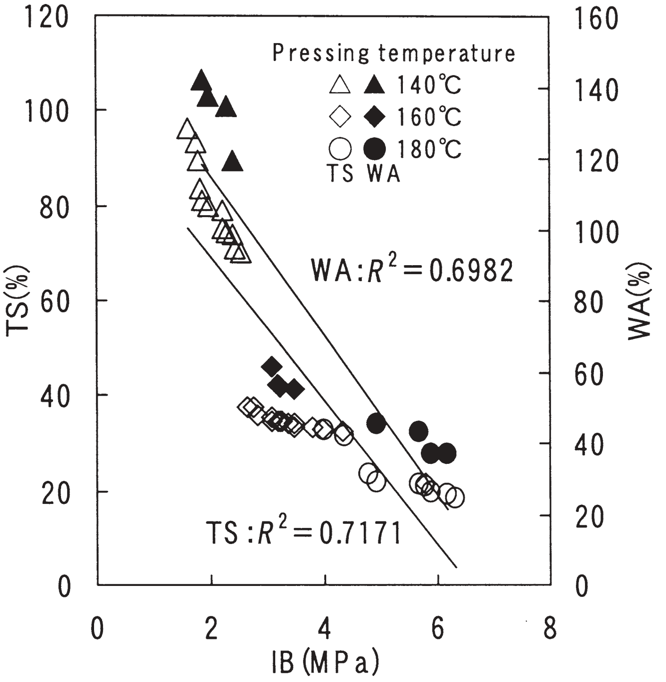

Fig. 3. Relations between IB and tensile strength (*TS*) and between IB and water absorption (*WA*) at various pressing temperatures

pressing at 180°C for 10 min was the best of the five (A–E) conditions. The values for MOR in the dry condition, MOE, and IB for all specimens under conditions D and E also exceeded the respective minimum requirements of 15 MPa, 1.3 GPa, and 0.3 MPa for grade 15 type MDF by JIS A 5905-1994.

In contrast, TS and WA under conditions D and E exceeded the respective maximum permitted values of 17% and 30% for grade 15 type MDF and grade S20 type hardboard by JIS A 5905-1994. Although the specimens for the TS and WA test from the boards made under conditions B–E still had stiffness and tight edges after 24 h of a water soak, small cracks were observed at their core layers. It was found through this experiment that binderless boards with high performances exceeding the minimum requirement by JIS A 5905-1994 under dry conditions were obtained in 2 min by using high temperature conditions (around 200°C).

Effects of board thickness

Figure 4 shows the relation between IB and MOR in the dry condition, MOE, TS, and WA at various board thicknesses.

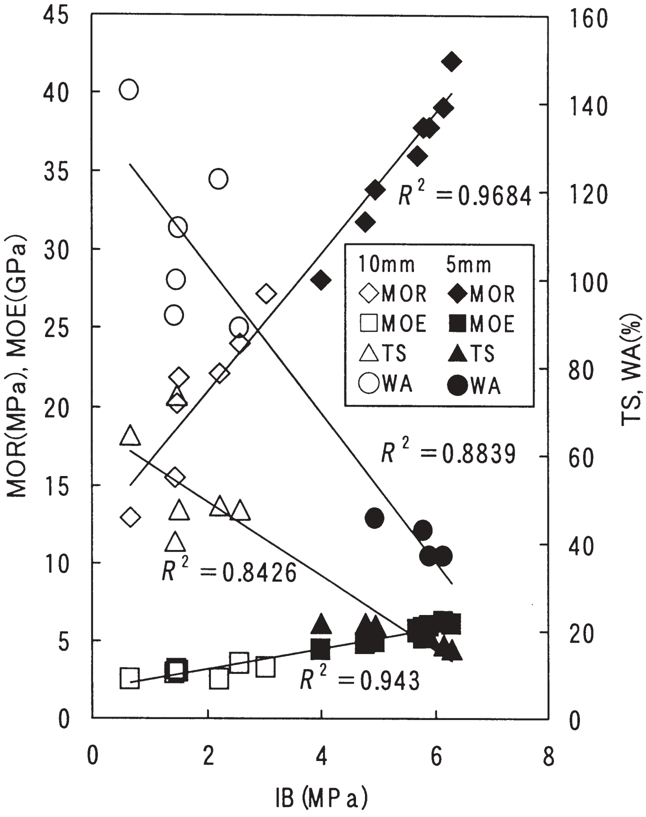

Fig. 4. Relations between IB and MOR, MOE, TS, and WA at various board thicknesses

IB showed significant correlations with MOR in the dry condition, MOE, TS, and WA (R^2 = 0.97, 0.94, 0.84, and 0.88, respectively) and decreased with increasing board thickness, which lowered the other board properties. The reduction in IB in this case was due to the following: The core layer of the 10-mm boards had lower bonding strength than the surface because the heat added to boards was used at the surface at first, especially in the case of 10-mm boards. It follows from this experiment that a thickness of 5 mm was better than that of 10 mm for making binderless boards. In the next section we develop 10-mm-thick binderless boards by changing the heating conditions to obtain various uses of boards.

Effects of board density

Figures 5, 6, and 7 show the IB, MOR in dry and wet conditions, and MOE of binderless boards, respectively, at different board densities. Similar to the usual particleboards or hardboards, IB, MOR in dry and wet conditions, and MOE increased with increasing board density. In other words, the increase in the heat conductivity of boards with increasing board density caused the increase in IB, which results in an increase in MOR and MOE.

Figure 8 shows the TS and WA at various densities. In general,[14] for particleboards or hardboards the TS and WA after long-duration water soaking have a tendency to in-

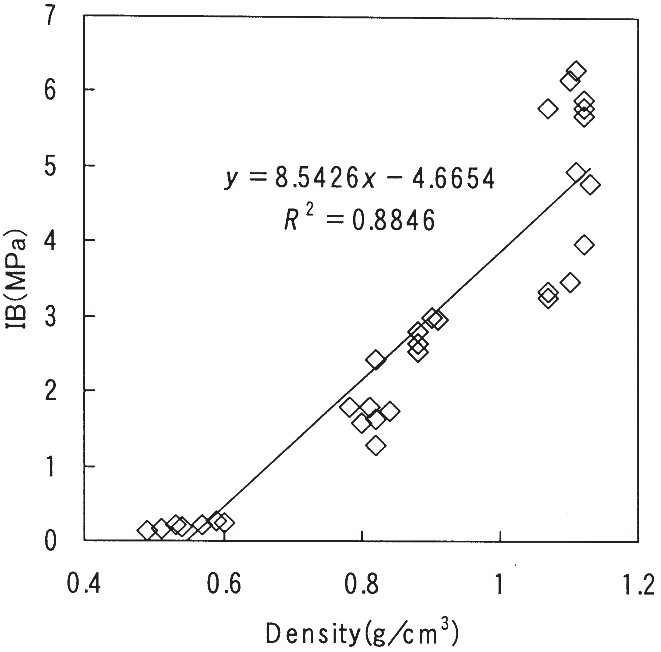

Fig. 5. Relation between board density and IB

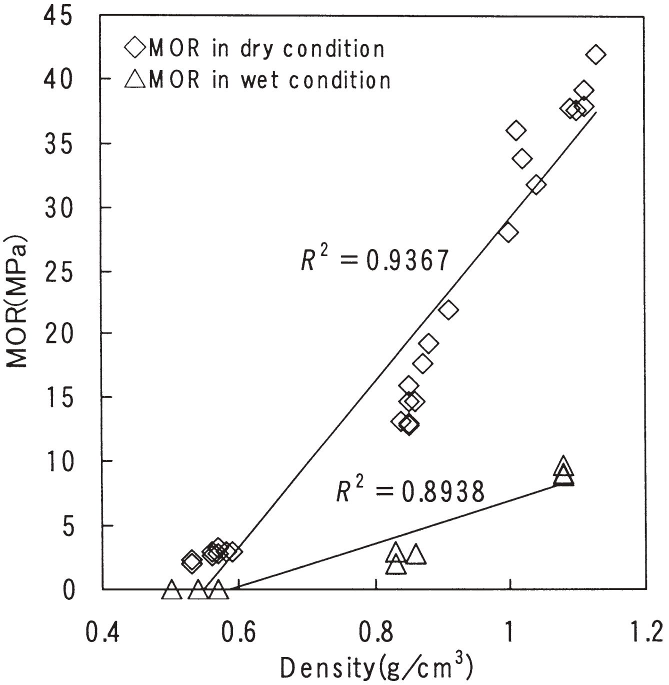

Fig. 6. Relation between board density and MOR under dry and wet conditions

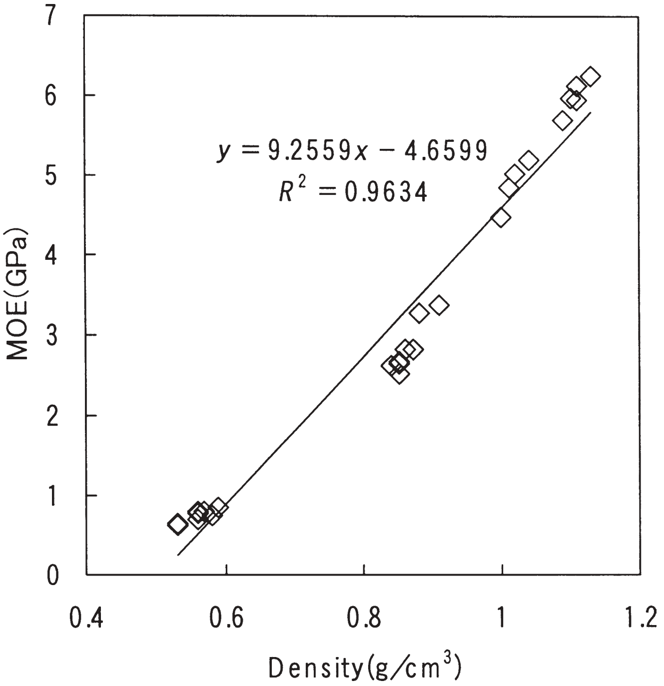

Fig. 7. Relation between board density and MOE

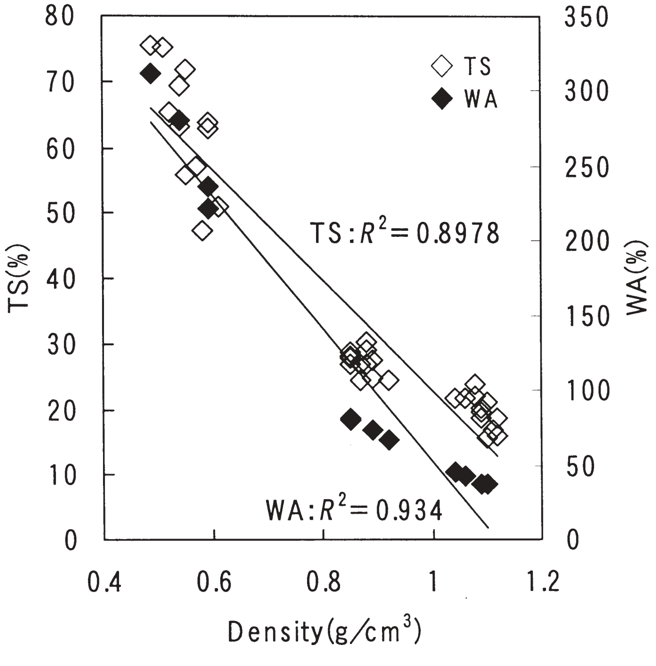

Fig. 8. Relations between board density and TS and between board density and WA

crease with increasing board density because of the greater springback of pressed particles in boards of higher density. However, in this experiment, the TS and WA values of binderless boards decreased with increasing board density. Hence we can say that, in the case of binderless boards, the higher bonding strength at high density shown in Fig. 5 played a more dominant role than the pressed ratio of particles. Thus, we have found through this experiment that a board density of $1.0\,g/cm^3$ is the best condition for making binderless boards.

Effects of grain size of raw materials

Figure 9 shows the relation between chip mixing ratio and IB. The IB of the binderless boards decreased with increas-

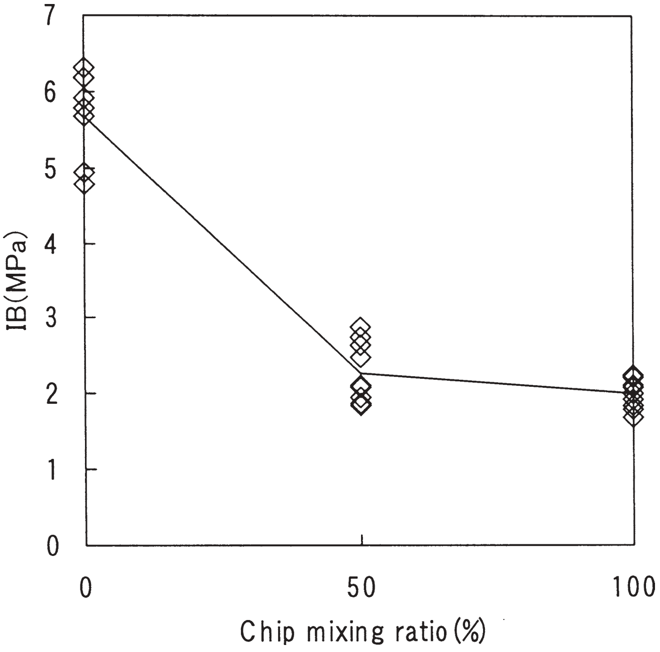

Fig. 9. Relation between the chip mixing ratio and IB

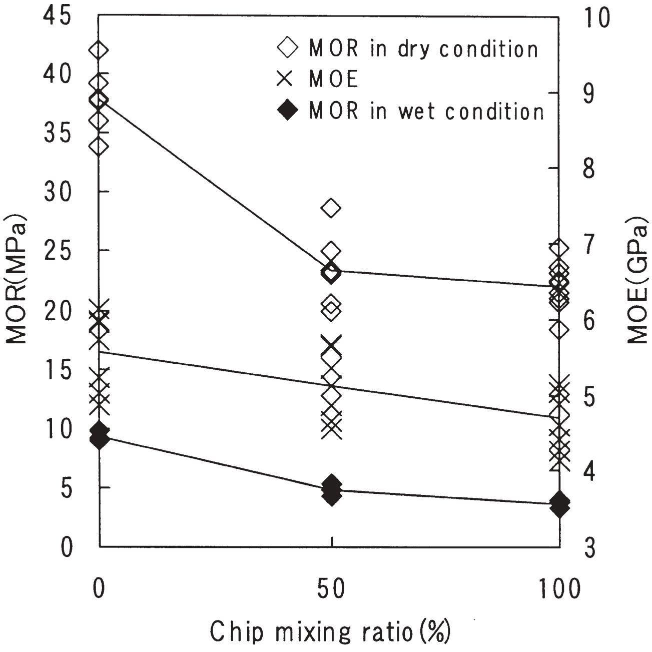

Fig. 10. MOR under dry and wet conditions and MOE at various chip mixing ratios

ing chip mixing ratio, which indicates the contribution of powders to the improvement of bonding strength. It seems reasonable to suppose that the large surface area of finely ground raw materials enhanced the self-bonding strength. Because finely ground materials such as powders require energy to manufacture and are difficult to handle during the board fabrication process, using coarsely ground materials for making binderless boards is the subject for a future study.

The results of the bending tests, MOR and MOE, are shown in Fig. 10, which demonstrate the same tendencies as the IB. Significant correlations of IB with the MOR in dry and wet conditions and the MOE ($R^2 = 0.96$, 0.91, and 0.65, respectively) were observed. It is obvious from Figs. 9 and 10 and Table 1 that binderless boards with good performances exceeding the minimum requirement by JIS A 5905-1994 under dry conditions were obtained even at a chip mixing ratio of 100%.

The TS and WA values at various chip mixing ratios are shown in Fig. 11. The TS and WA showed no correlation with the chip mixing ratio ($R^2 = 0.05$ and 0.25, respectively), with tendencies different from those of the IB. Although the boards at a chip mixing ratio of 100% had lower IB strength and greater springback of particles than those at 0%, the TS and WA values for the boards with a 100% chip mixing ratio were unexpectedly low. Although we cannot say so definitely, it may be due to the high temperature. We see from Table 1 that binderless boards at the conditions of C–E, despite the shortened manufacturing time, also have relatively low TS and WA values (around 20%–25% and 50%, respectively). We need to analyze the chemical composition of binderless boards treated at high temperatures.

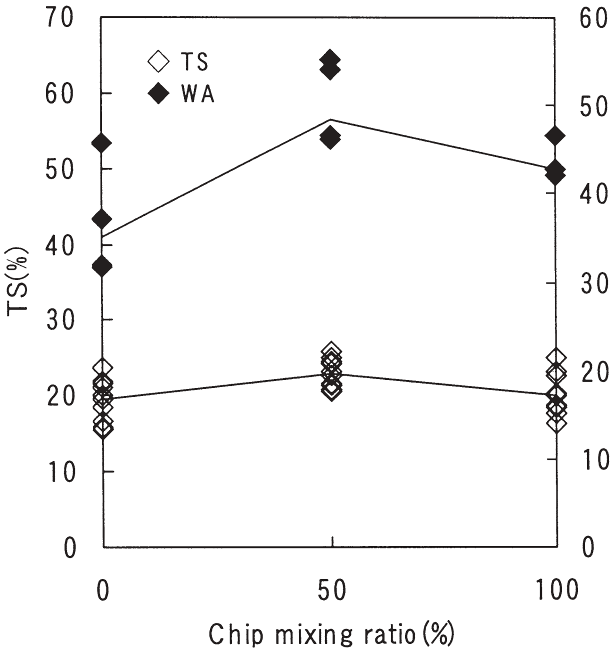

Fig. 11. TS and WA at various chip mixing ratios

Effects of additional substances

Figure 12 shows the IB at various furfural contents. Although no correlation of IB with furfural contents was observed ($R^2 = 0.17$), IB values observed at furfural contents of 5%, 10%, and 15% were higher than those at 0%. Furfural proved to be effective in increasing IB, which would upgrade the other board performances, such as the MOR.

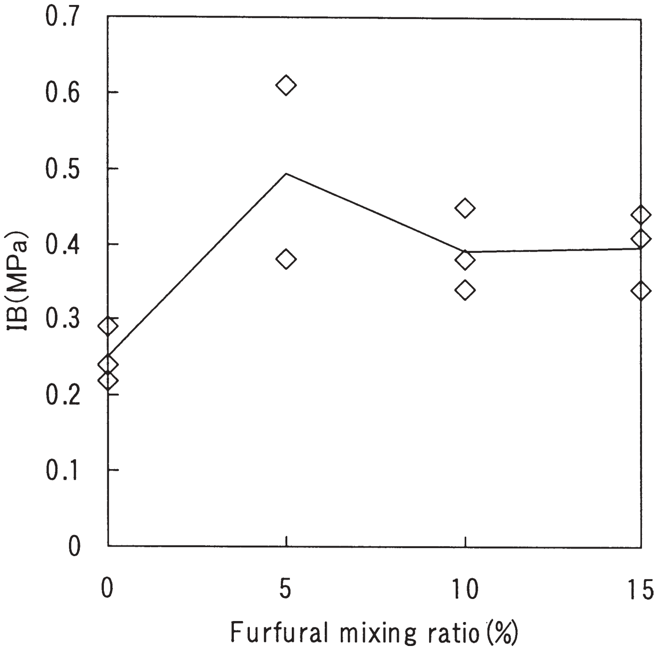

Fig. 12. Relation between the furfural mixing ratio and IB

However, the effect of furfural might be partly reduced because adding furfural would restrain the pressing temperature at the boiling point of furfural (around 162°C). Furthermore, the addition of furfural requires special equipment, such as the rotating drum we used in this experiment. Taking into consideration the industrial manufacture of binderless boards, therefore, it seems that it is not necessary to add furfural to the raw materials of binderless boards.

Conclusions

Binderless boards were prepared from kenaf core under varying manufacturing conditions, and their mechanical properties were investigated. The manufacturing conditions of the pressing temperature and time, board thickness, board density, the grain size of the raw materials, and addition of furfural were then individually evaluated. Based on the results, the conclusions can be summarized as follows.

1. The MOR in dry and wet conditions, the MOE, and the IB of the binderless boards increased linearly with increasing board density. Almost all the specimens showed values for MORs in the dry condition, MOEs, and IBs high enough to exceed the minimum requirement for grade 15 type MDF by JIS A 5905-1994. As for TS and WA, the values decreased with increasing board density but still exceeded the maximum permitted levels for grade 15 type MDF and S20 type hardboard by JIS A 5905-1994. Briefly stated, binderless boards show high performance under dry conditions but have low water resistance. It followed from this that binderless boards are especially suitable for use in the dry condition or a temporary wet condition such as for interior use or disposable trays.
2. Except for the case of TS and WA of chip-mixed boards, the IB showed significant correlations with the MOR in dry and wet conditions, MOE, TS, and WA, which is different from the usual particleboards.
3. The results of each experiment revealed that the best manufacturing conditions proved to be as follows: pressing temperature 180°C and time 10 min; pressing pressure 5.3 MPa; board thickness 5 mm; board density 1.0 g/cm^3; powder with chip mixing ratio 0%; and powder with furfural content 0%. Binderless boards employing all these manufacturing conditions (condition C, as shown in Table 1) showed the highest performances in this study: MOR in dry and wet conditions 36.1 MPa and 9.3 MPa, respectively; MOE 5.5 Gpa; IB 5.7 Mpa; TS 19.6%; WA 40.9%. The IB values at around 5–6 MPa that we obtained in this study were especially high in contrast to those of usual wood-based materials.

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