Influences of Layered Structure on Physical and Mechanical Properties of Kenaf Core Particleboard

Xinwu Xu,[a] Qinglin Wu,[a,b,]* and Dingguo Zhou [a,]*

Kenaf (*Hibiscus cannabinus*), a fast-growing fiber crop, is a potential substitute for wood to make composition boards. This work investigated single- and three-layer kenaf core particleboards (KPBs) and kenaf core-cedar wood composite particleboard (KCPB) with polymeric methylene diphenyl diisocyanate (pMDI) and phenol formaldehyde (PF) resins. The physical and mechanical properties including bending modulus (MOE) and strength (MOR), internal bond (IB) strength, water absorption (WA), thickness swelling (TS), and linear expansion (LE) were tested following the ASTM D 1037 and ANSI A 208.1 standards. It was shown that kenaf core can be made into standard-satisfying particleboards with comparable performances to cedar-based wood panels. Three processing factors, *i.e*., board density, resin content, and layered construction, had significant influences on panel properties. KPBs denser than 0.70 g/cm^3 and with 6% PF met with the standard specifications. The WA, TS, and LE of single-layer KPBs decreased with increased density. Three-layer KPBs showed improved MOE, MOR, and IB strengths, and effectively avoided the unbalanced structure shown in the single-layer KPBs in thickness direction. The three-layer KPBs with a 50:50 surface-to-core ratio had the best comprehensive performances. The results can be helpful for the application of kenaf residues in the wood composites industry.

Keywords: Kenaf; Particleboard; Structure; MDI; PF

Contact information: a: College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, P.R. China 210037; b: School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA 70803, USA;
** Corresponding authors: qwusfm@gmail.com and dgzhou1111@163.com*

INTRODUCTION

Kenaf (*Hibiscus cannabinus* L.), an annual herbaceous plant originating from ancient Africa, is currently cultivated widely in the southern U.S. (Taylor 1993). This plant is characterized by pest resistance, fast growth, low input, and high output. In approximately 90 to 150 days, kenaf can reach a height of 1 to 1.2 meters, yielding 5 to 10 tons of biomass annually per acre, which is generally 3 to 5 times greater than southern yellow pine (SYP), for a 14- to 17-year growing period before harvesting (Zhang 2003; Bitzer 2009).

Kenaf consists of an outer bark and an inner solid woody core, which account for 25% to 40% and 60% to 75%, respectively, of the whole stem based on oven-dry weight. Chemically, both the bast and core fibers are comparable with wood and rice straw (Sellers *et al.* 1993). Bast fibers contain over 44.4% cellulose, 21.1% lignin, 2.7% extractives, and 4.6% ash, and the corresponding figures for pith are 37.6%, 18.7%, 1.9%, and 2.2%, respectively (Shi *et al.* 2011). On average, coniferous wood has 48% cellulose, 25.3% lignin, 11.5% extractives, and 0.2% ash, and these values for deciduous wood are 52.8%, 22.3%, 2.7%, and 0.4%, respectively. Rice straw, in comparison, only contains 36.2% cellulose and 14.05% lignin, but has 6.04% ash. Hence, in terms of chemical composition, kenaf performs between wood and rice straw and should be an ideal raw material for particleboard production.

Historically, kenaf research and utilization has had several ups and downs in the U.S. (Bowyer and Stockmann 2001). During the Second World War, kenaf was taken as an emergent alternative for jute, originally imported from Asia. The main need for kenaf was to produce cloth sacks and cordage. In the 1960s, kenaf was listed as the top candidate among 400 fibrous species for pulp and paper manufacturing by the USDA. However, the USDA terminated funding for research and development on kenaf in the early 1990s. The primary impetus was to stimulate the depressed farm economy in the U.S. Recently, some specialty organizations have been founded to undertake further investigations on kenaf utilization, *e.g.*, the International Kenaf Association (IKA) and the American Kenaf Society (AKS). Paper using 100% kenaf has been industrially produced (*e.g.*, Vision Paper, New Mexico, and Phoenix Pulp and Paper Company, Thailand). Overwhelmingly, kenaf has been accepted as a sound raw material not only for pulp and paper manufacturing, but also for use as an oil absorbent, animal bedding, poultry litter, packing material, and reinforcing filler for polymer-based composites (Lai *et al.* 2008; Akil *et al.* 2010; Xue *et al.* 2009). For example, injection-molded forty weight percent (40 wt%) kenaf fiber and polypropylene composites were found to have a tensile modulus comparable to that of glass fiber-reinforced polypropylene (8.3 GPa *vs.* 9 GPa, respectively) (Xue *et al.* 2009).

In recent years, some information on kenaf composition boards with synthetic resins has been published. One research direction is in making insulation composites. Sellers *et al.* (1993) made experimental insulation boards with kenaf core. Three kinds of resins, *i.e.*, urea formaldehyde (UF), phenol formaldehyde (PF), and polymeric methylene diphenyl diisocyanate (pMDI), were used. Tests including thermal and acoustic transmission, flame resistance, and basic mechanical and dimensional properties concluded that kenaf core was a promising material for non-load-bearing building applications. At the same time, serious water absorption was observed. In another research study (Sheikkariem 2000), low-density (0.43 g/cm^3) kenaf particleboards (KPB) were also made with UF (6%) and a combined resin system (1% pMDI and 5%UF). Compared with SYP particleboards, KPBs showed better mechanical properties but worse water-proof performances due to the lower bulk density and consequently the higher compact ratios.

Another research direction of kenaf residues is in making higher density KPBs. Charles *et al.* (1998) investigated UF-bonded kenaf core particleboards. The performances were comparable with SYP particleboards. Juliana *et al.* (2012a) made particleboards with 100% kenaf stem, bast, or core, respectively. The study examined the impacts of particle geometry on board performances. Kenaf core particles were shown to be nearly rectangular with aspect ratios nearly 3.0. Aisyah *et al.* (2013) reported a study on kenaf medium density fiberboard (MDF). The study tried to inspect the influence of the refining conditions on fiber geometry and board properties. Kenaf chips were defiberated under 3 to 7 bar for 3 and 5 min. The fiberboards achieved sound mechanical and physical properties with fibers 0.81 mm long and with an aspect ratio of 23.4.

Kenaf-wood mixed raw materials were chosen as well by several researchers to make composition boards. Sheikkariem (2000) found that inclusion of kenaf into southern yellow pine optimized both mechanical and hygroscopic performances of particleboard. Other investigations, however, showed contradictory conclusions. Bajwa and Chow (2003) reported an oriented strandboard (OSB) product with kenaf and aspen. A lower percentage of kenaf flakes was found to help control thickness swelling (TS). A kenaf substitution rate of 25% was confirmed with satisfactory bending properties and TS values lower than 15%. Juliana *et al.* (2012a) made particleboards with 30% kenaf (stem, bast, and core, respectively) and 70% rubber wood. They found reduced mechanical properties and higher water absorption (WA) and TS values compared to 100% rubber wood control panels. Grigoriou *et al.* (2000) and Juliana *et al.* (2012b) investigated layered structure composites with kenaf-wood mixed raw materials. Kenaf core particles or bast fibers were paved into board middle or surface layers. The layered boards had overwhelmingly better performances than single-layer pure kenaf panels.

So far, investigations on industrial practices of kenaf composites are still limited. Little information has been reported about the distribution of kenaf particles with varied geometry in a board matrix and how this may affect board properties. The objectives of this study, therefore, were to investigate the properties of kenaf core particleboards with layered structure by particle geometry and with mixed raw materials.

EXPERIMENTAL

Experimental Design

Five types of particleboards, nominally 457 mm by 457 mm by 9.53 mm, were made (Table 1): (1) KPB1: single-layer construction, five density levels (0.25 to 0.85 g/cm^3), 3% pMDI; (2) KPB2: similar to KPB1 but with 6% PF; (3) KPB3: three-layer construction, three different surface-to-core ratios (3:7, 5:5, and 2:1, based on oven-dry weight); (4) KCPB: kenaf core–cedar wood composite boards, five kenaf substitution rates (*i.e.*, 80%, 60%, 50%, 40%, and 20%) based on oven-dry weight); and (5) CPB: cedar wood particleboard. In total, 38 boards were made, with two replications for each condition.

Table 1. Technical Information for the Manufacture of Particleboards *

Board Type	Target Density (g/cm^3)	Resin Content	Construction	Raw Materials
KPB1	0.25, 0.40, 0.55, 0.70, 0.85 (KPB1-25, 40, 55, 70, 85)	3% pMDI	1-layer	Kenaf
KPB2	0.25, 0.40, 0.55, 0.70, 0.85 (KPB2-25, 40, 55, 70, 85)	6% PF	1-layer	Kenaf
KPB3	0.85	3% pMDI	3-layer (KPB3-a,b,c)	Kenaf
KCPB	0.85	3% pMDI	1-layer	Kenaf and cedar (KCPB-80, 60, 50, 40, 20)
CPB	0.85	3% pMDI	1-layer	cedar

* Hot-pressing regulations: Temperature, 180 ^{o}C; Resination period, 30 s/mm for pMDI resin and 40 s/mm for PF resin; Pressure: 0.8 to 3.0MPa according to the target density; Wax content, 1.0% based on solid resin content.

Materials Preparation

Kenaf and cedar particles

Tainung kenaf was grown at the horticulture farm of Southern University, Baton Rouge, LA. Kenaf was planted on a silt loam soil raised bed at a seeding rate of 25 kg/ha. At planting, 70 kg/ha of NH_4NO_3 fertilizer was applied. Dead kenaf stand stalks, approximately 5 to 7 m high and 6 to 60 mm in diameter, were cropped and *in-situ* chipped with a 5-HP portable chipper without debarking. After bast fiber bundles were separated, the kenaf chips were further cut into spherically shaped particles in the Forest Products Lab of Louisiana State University (LSU) with a PHM3 Pullman hammer mill. Previously milled cedar wood particles were available in the lab. All particles were dried with a cabinet dryer to about 3% moisture content. Both particle types were sieve-analyzed (Table 2).

Table 2. Size Distribution of Kenaf and Cedar Particles by Sieve Analysis

Particle Size (mm)	Cedar Particle (%)	Kenaf Particle (%)	Average (%)
<0.6	1.02	7.68	4.35
0.6–1.18	6.75	12.36	9.55
1.18–2.00	19.35	15.76	17.55
2.00–4.76	53.63	61.84	57.74
>4.76	19.25	2.36	10.81

Resin and additives

The pMDI resin, ISOBIND-1088, supplied by Dow Chemical, had a dark brown color, viscosity of 200 to 300 cps (25 °C), specific gravity of 1.23, and flash point of about 223 °C. To compare, a commercial PF resin was used. Emulsified paraffin wax (EW-50A, Borden Chemical) was used as a water repellent. The wax had the following characteristics: specific gravity, 1.0; pH value, 8.54 (25 °C); viscosity, 27.0 (25 °C); and solids content, 51%.

Board Manufacturing

Single-layer particleboards

Kenaf and/or cedar particles were blended with pMDI or PF resin with a lab-fabricated blending system. Wax was sprayed separately using compressed air. Mats were then manually formed and were hot-pressed into solid panels using the conditions listed in Table 1.

Three-layer Kenaf particleboards

Kenaf particles were screened into fine (< 3.20 mm) and coarse particles (> 3.20 mm). According to the pre-specified surface/core ratios, *i.e.*, 3:7, 5:5, and 2:1, fine and coarse particles were glued and weighed separately and were paved into surface and core layers, respectively. Hot-pressing conditions were the same as those for single-layer boards listed above.

Kenaf and cedar composite particleboards

Kenaf and cedar particles were glued and metered separately and then mixed randomly for single-layer particleboard manufacturing.

Sample Testing

All boards were conditioned at 20±3 °C and 65±1% relative humidity (RH) for 2 weeks before sampling. The board characteristics tested included the vertical density profile (VDP), static bending modulus (MOE) and strength (MOR), internal bond (IB) strength, water absorption (WA), thickness swelling (TS), and linear expansion (LE). The VDP was tested with a QMS X-ray density profile tester. Mechanical tests were conducted with an Instron 4260 universal machine according to ASTM D 1037 (ASTM 1996).

WA and TS tests were performed under the 24-h water soaking condition specified in ASTM D 1037. The TS was measured at the very edge (TS_{VE}, with half the 4.8-mm gauge tip placed on the sample edge), the edge (TS_{E}, the entire gauge tip placed exactly on the sample edge), 2.54 cm from the edge ($TS_{2.54cm}$), and at the center point (TS_{CEN}). Four measurements along the four sides of each sample were taken to obtain average values. All samples were dried to determine the oven-dry weight for actual moisture content calculation.

The measurement of LE followed the method of Suchsland (1972). Two specimens measuring 25.4 mm by 304.8 mm for every condition were sampled. Two holes (1.1 mm diameter) nominally 254 mm apart were drilled along the long dimension of each specimen. A small rivet (1.0 mm diameter) with a cross mark on the tip was plugged into every hole with epoxy glue. Actual distances between the two cross marks were measured with an optical comparator before and after 24 h of water soaking.

Data Analysis

WA, TS, and LE were calculated according to the following equations,

$$\text{WA (\%)} = (W_{24} - W_0) / W_0 \times 100 \tag{1}$$

$$\text{TS (\%)} = (T_{24} - T_0) / T_0 \times 100 \tag{2}$$

$$\text{LE (\%)} = (L_{24} - L_0) / L_0 \times 100 \tag{3}$$

where W_0 and W_{24} are the sample weight before and after water soaking (mm), T_0 and T_{24} are the measured thickness before and after water soaking (mm), and L_0 and L_{24} are the distance between two cross marks before and after water soaking (mm).

Mathematically, the TS can be taken as a function of WA, *i.e.*, TS = TS (WA). Therefore, the differential of TS against WA can reflect the variation rate of TS (TSR) along with WA and can indicate the innate hygroscopic property of composite boards. In a 24-h soaking, the TSR can be roughly deduced from the TS and WA data, *i.e.*,

$$\text{TSR} = \text{TS(\%)} / \text{WA(\%)} \tag{4}$$

RESULTS AND DISCUSSION

Single-layer Kenaf Core Particleboard

Vertical density profile

Figure 1 presents the VDP curves of single-layer KPBs. KPB1 and KPB2, especially at relatively high average density levels, *e.g.*, 0.70 and 0.85 g/cm^3, showed an asymmetrical construction with measured density decreasing from the bottom to the top surface. This is somewhat different from traditional hot-pressed wood-based composite boards, which have symmetric VDP patterns, *e.g.*, a U-shape density-thickness curve (Maloney 1977; Wong *et al.* 1999). The abnormal VDPs in KPB1 and KPB2 resulted from the size distribution of kenaf particles listed in Table 2. Kenaf fines smaller than 1.18 mm in diameter accounted for more than 20% of the total. During the mat-forming process, fines were liable to fall to the bottom of the KPB matrix and were hot-pressed into the high-density layer. Consequently, this unbalanced VDP pattern led to dimensional instability of the KPB, as discussed in the later parts of this paper.

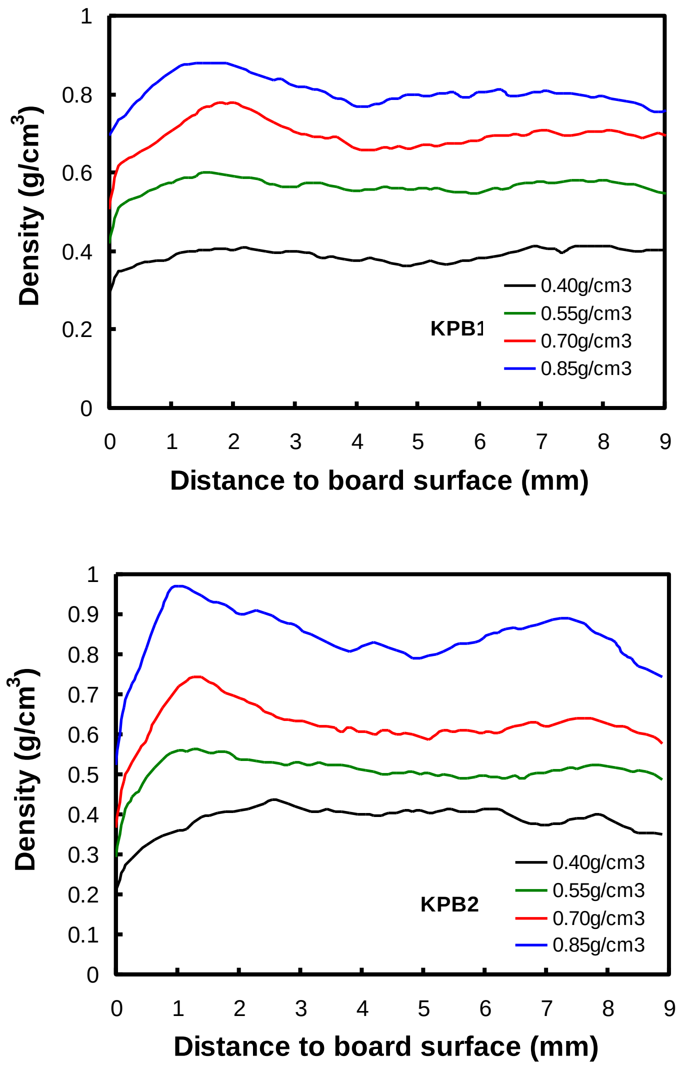


Fig. 1. Vertical density profile of single-layer KPBs

Mechanical properties

Table 3 and Figs. 2a and 2b compare the mechanical properties of KPB1 and KPB2. Both KPBs showed linearly increasing MOE, MOR, and IB values with increasing density. This is in accordance with former studies (*e.g.*, Saotome and Korai 2013; Sari *et al.* 2013). Normally, a higher board density means closer contacts between two adjacent particles and more chances of interfacial adhesion. It is then possible to design a particleboard with expected mechanical properties through density control, if other parameters, *e.g.*, particle geometry, resin content, board construction, hot-pressing parameters, *etc*., are fixed.

From Table 3 and Fig. 2, KPB1 with 3% pMDI generally had similar bending and internal bond performances with 6% PF-bonded KPB2, and both KPBs had comparable mechanical properties with traditional UF-bonded wood-based particleboards (WPBs). At 0.85 g/cm^3, KPB2 (MOE, 3045 MPa; MOR, 22 MPa; IB, 0.92 MPa) satisfied the ANSI specification for M3-grade WPBs (ANSI 1999: MOE, 2750 MPa; MOR, 16.5 MPa; IB, 0.55 MPa). KPB1-85 had excellent IB strength (0.85 MPa) but failed to meet ANSI specifications in bending. Both KPB1 and KPB2 at 0.70 g/cm^3 failed to meet ANSI requirements, even for M2-grade WPBs. A density threshold equivalent to 0.80 g/cm^3 seemed to be necessary for KPB with PF (6%) or pMDI (3%) resins.

Other single-layer KPBs fell into the low-density category defined in ANSI A 208.1 (ANSI 1999). Evidently, KPB1 and KPB2 at 0.55 g/cm^3 successfully met the requirements of grade LD-2 WPBs (MOE, 1025 MPa; MOR, 5 MPa). Boards of 0.25 g/cm^3 were too weak for mechanical tests in this study. Previous research (Sellers *et al.* 1993) can be referred to for valuable information, *e.g.*, light-weight KPB may be used for wall insulation.

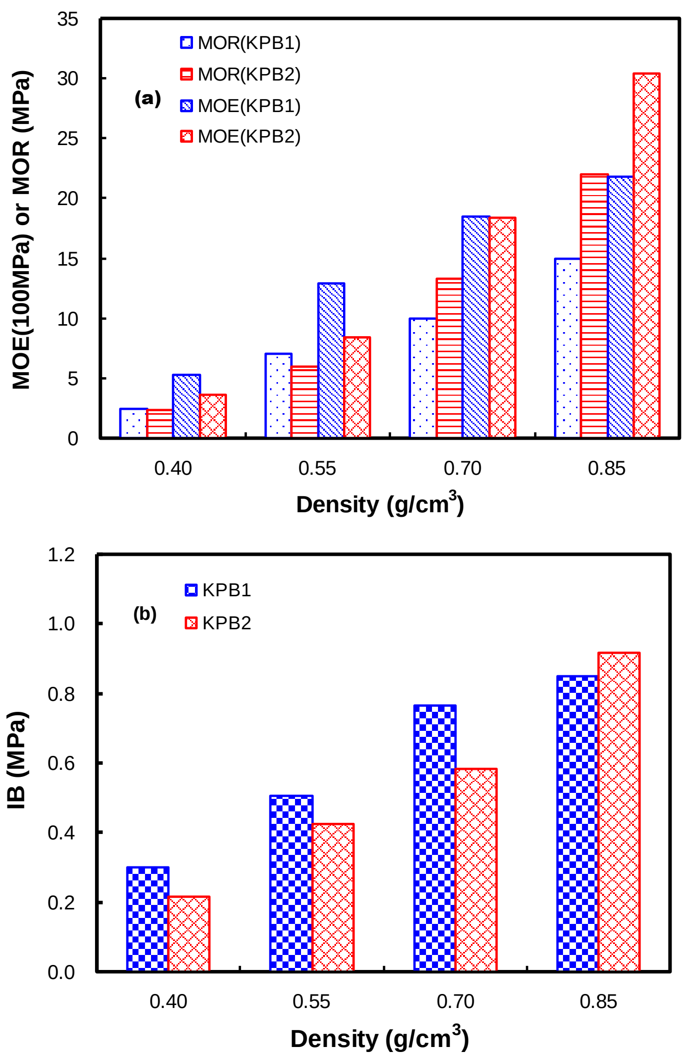


Fig. 2. Bending (a) and internal bond (b) properties of single-layer KPBs

Table 3. Mechanical Properties of Particleboards [a] [b]

Board Type	Density [c] (g/cm^3)	MOE (MPa)	MOR (MPa)	IB (MPa)
KPB1-25	-	-	-	-
KPB1-40	0.41(0.025)	528.24(87.65)	2.42(0.54)	0.30(0.06)
KPB1-55	0.58(0.025)	1290.14(186.32)	7.04(1.54)	0.51(0.08)
KPB1-70	0.69(0.035)	1846.02(242.53)	9.98(1.23)	0.76(0.16)
KPB1-85	0.79(0.055)	2182.69(505.35)	15.00(3.38)	0.85(0.05)
KPB2-25	-	-	-	-
KPB2-40	0.41(0.020)	364.48(57.94)	2.33(0.48)	0.22(0.05)
KPB2-55	0.55(0.016)	843.76(78.01)	5.97(1.06)	0.43(0.10)
KPB2-70	0.72(0.043)	1839.59(360.97)	13.32(3.41)	0.58(0.11)
KPB2-85	0.89(0.032)	3045.31(386.40)	22.00(2.93)	0.92(0.23)
KPB3a	0.77(0.046)	2559.78(375.99)	15.75(2.70)	1.02(0.20)
KPB3b	0.90(0.061)	3102.60(504.45)	19.72(4.05)	0.88(0.17)
KPB3c	0.81(0.381)	2683.76(1250.19)	16.54(7.51)	0.81(0.33)
KCPB-80	0.76(0.039)	2424.50(342.46)	15.62(2.30)	0.89(0.09)
KCPB-60	0.77(0.026)	2139.62(146.74)	15.08(1.70)	0.83(0.19)
KCPB-50	0.70(0.200)	2437.09(291.64)	16.55(2.31)	0.91(0.12)
KCPB-40	0.77(0.044)	2222.38(337.02)	14.70(2.13)	1.00(0.13)
KCPB-20	0.80(0.035)	2227.91(289.02)	15.97(2.59)	0.88(0.21)
CPB-85	0.80(0.039)	1977.78(262.65)	15.47(2.70)	1.07(0.10)

[a] Data in parentheses are standard deviations based on four samples for density, MOE, and MOR, and eight samples for IB.
[b] Boards of 0.25 g/cm^3 density (KPB1-25 and KPB2-25) were too weak to test MOR, MOE, and IB.
[c] Density was determined from samples used for MOR testing.

Dimensional properties

The poor water-proof property of KPBs can be seen in Table 4 and Fig. 3. The influence of board density on the WA and TS is evident. When PF or pMDI resin content was set, the WA of KPBs decreased as the density increased. For 3% pMDI-bonded KPB1, the WA varied from 167% to 36% with density increasing from 0.25 to 0.85 g/cm^3. The boards with 6% PF resin also varied, absorbing 168% to 57% of water after 24 h of soaking. Kenaf core mat is liable to be densified during hot-pressing at increased compression ratios with increased board density. Consequently, more voids in the board matrix are squeezed out, which prevents water entering. A wax dosage of 1.0% was evidently insufficient to control the water absorption. In comparison, boards with 3%

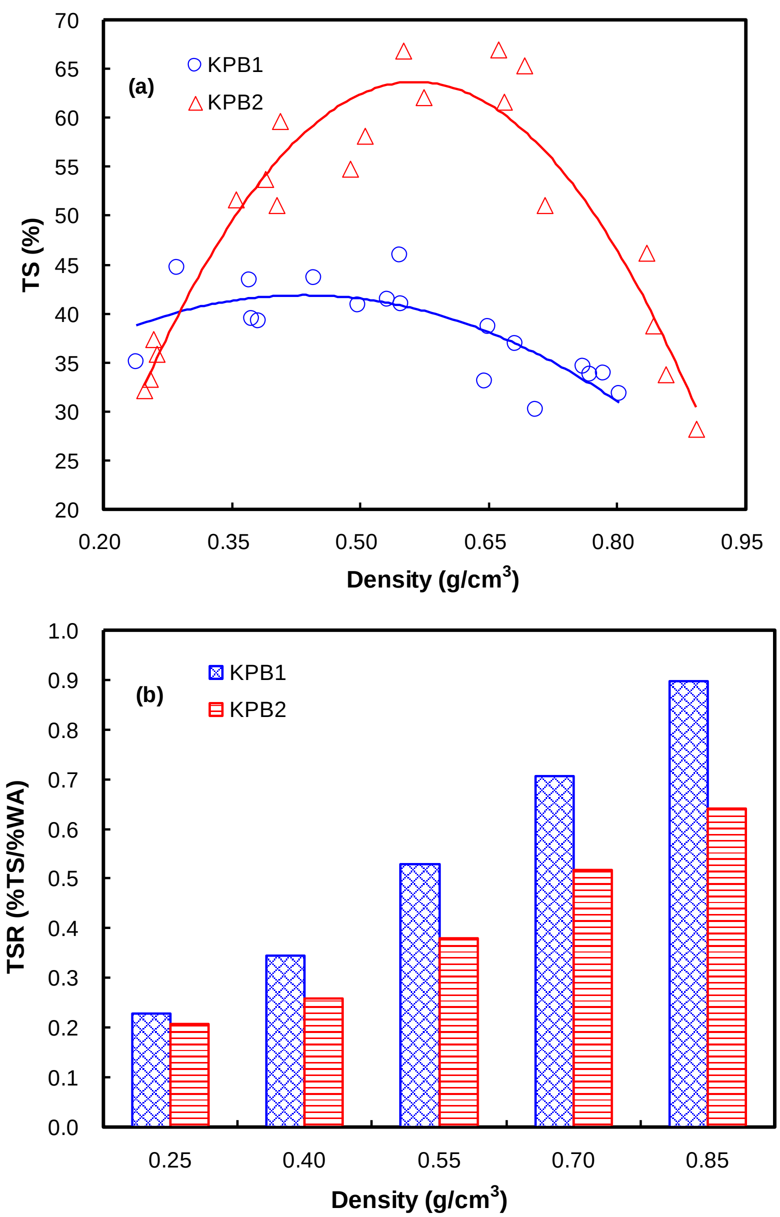
pMDI showed much lower WA and TS values than those bonded with 6% PF resin (Table 4).

Table 4. Dimensional Properties of Particleboards

Board Type	Linear Expansion [a]			Thickness Swelling						
	Density (g/cm^3)	WA (%)	LE (%)	Density (g/cm^3)	WA (%)	TS_{VE} (%)	TS_E (%)	$TS_{2.54cm}$ (%)	TS_{CEN} (%)	TSR [b]
KPB1-25	-[c]	-	-	0.26 (0.034)	167.46 (3.82)	-	-	38.20 (6.77)	36.52 (9.10)	0.23
KPB1-40	0.41	113.4	1.56	0.39 (0.036)	120.35 (7.38)	45.51 (3.34)	46.30 (4.43)	41.49 (2.43)	42.05 (6.89)	0.35
KPB1-55	0.55	80.8	1.13	0.53 (0.023)	85.37 (5.07)	46.45 (1.49)	46.11 (1.67)	42.61 (2.45)	40.95 (0.78)	0.53
KPB1-70	0.73	55.0	0.70	0.67 (0.028)	49.19 (11.34)	43.53 (1.97)	43.48 (1.44)	34.75 (3.82)	31.69 (2.56)	0.71
KPB1-85	0.81	48.7	0.48	0.78 (0.019)	35.63 (1.88)	49.49 (3.28)	48.80 (3.58)	33.54 (1.17)	29.01 (2.66)	0.89
KPB2-25	-	-	-	0.26 (0.006)	167.56 (14.66)	-	-	34.72 (2.40)	34.28 (3.66)	0.21
KPB2-40	0.41	210.2	1.33	0.39 (0.024)	208.73 (9.64)	56.55 (3.58)	56.23 (2.80)	54.03 (3.92)	47.55 (5.83)	0.268
KPB2-55	0.53	164.9	1.08	0.53 (0.039)	168.68 (12.68)	65.78 (6.88)	65.48 (5.75)	60.51 (5.18)	58.32 (2.90)	0.38
KPB2-70	0.64	110.9	0.79	0.68 (0.025)	118.57 (10.28)	61.45 (2.70)	61.40 (2.37)	61.26 (7.14)	58.13 (4.93)	0.52
KPB2-85	0.89	46.8	0.38	0.86 (0.026)	57.37 (10.14)	43.06 (6.86)	43.77 (6.66)	36.73 (7.63)	30.28 (6.47)	0.64
KPB3a	0.83	42.5	0.48	0.81 (0.038)	37.64 (4.22)	42.00 (3.49)	41.59 (3.57)	24.93 (3.96)	21.64 (2.13)	0.66
KPB3b	0.87	38.9	0.39	0.80 (0.058)	40.67 (5.96)	44.24 (1.93)	43.62 (2.14)	26.90 (2.17)	24.06 (1.84)	0.66
KPB3c	0.86	41.3	0.59	0.84 (0.013)	39.15 (4.40)	43.12 (1.78)	42.60 (1.85)	25.91 (2.47)	22.85 (1.45)	0.61
KCPB-80	0.79	40.1	0.54	0.74 (0.017)	38.63 (1.93)	35.40 (1.28)	35.56 (1.77)	24.70 (1.15)	24.84 (4.44)	0.64
KCPB-60	0.79	41.7	0.64	0.76 (0.028)	40.58 (3.36)	38.00 (2.85)	37.69 (3.04)	26.33 (2.44)	26.26 (3.66)	0.65
KCPB-50	0.84	37.3	0.60	0.79 (0.016)	36.20 (1.78)	36.99 (2.34)	36.73 (2.59)	25.51 (3.40)	22.79 (0.77)	0.71
KCPB-40	0.83	37.6	0.77	0.74 (0.040)	40.66 (5.18)	35.20 (1.90)	34.94 (1.94)	27.52 (2.98)	27.14 (3.97)	0.67
KCPB-20	0.85	34.1	0.65	0.79 (0.018)	33.30 (1.18)	32.80 (2.28)	32.58 (2.14)	24.23 (0.35)	21.80 (1.97)	0.73
CPB-85	0.86	35.9	0.81	0.80 (0.009)	37.25 (2.68)	35.69 (2.86)	35.87 (2.57)	27.67 (1.53)	25.27 (2.58)	0.74

[a] Initial moisture content was 7.96%.
[b] TSR = $TS_{2.54cm}$ / WA.
[c] The 0.25 g/cm^3 samples were destroyed at edge during soaking, so no measurements were conducted.

The TS of KPB1 and KPB2 as a function of density is plotted in Fig. 3a. The TS first increased from 0.25 g/cm^3 and subsequently declined toward 0.85 g/cm^3, with a peak at approximately 0.55 g/cm^3. Roffael and Rauch (1972) theorized that denser particleboards were less permeable to water and hence more durable under humid conditions; *i.e.*, the TS should be negatively correlated with density. This was shown in some subsequent investigations (Wu and Piao 1999) and was also confirmed in this study (Fig. 3a, 0.55 to 0.85 g/cm^3). On the contrary, in the low-density range, *e.g.*, under 0.55 g/cm^3, the numerous voids inside the composite boards provide enough paths for water movement and the boards easily became saturated when exposed to a wet environment. In this case, low-density boards showed a better water-holding property, as is shown in Fig. 3a (0.25 to 0.55 g/cm^3).



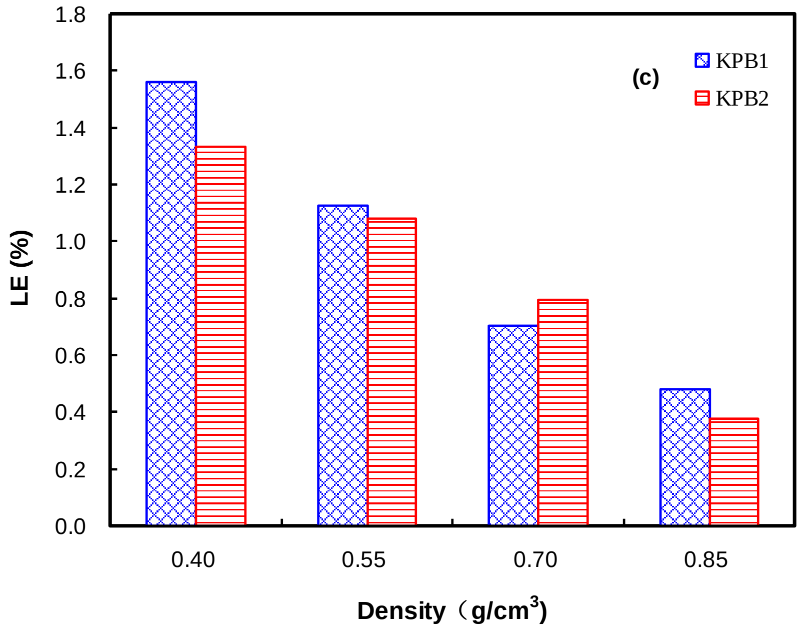


Fig. 3. Thickness swelling (a), TSR (b), and linear expansion (c) of KPBs as functions of density

The above arguments concerning the contribution of density to the water resistance of KPB rely largely on a specific exposure period. Under the conditions of short-term water soaking, *e.g.*, 24 h in this study, density did provide temporary water repellency for medium- and high-density KPBs. However, an increased density may be undependable if the boards are exposed to long-term water invasion, which can be indirectly revealed by the TSR (Fig. 3b). A study by Sari *et al.* (2012) found that high panel density negatively affected the thickness swelling after 24 h of immersion. This can be explained as the increase of water-absorbing substances, *i.e.*, woody particles. In that case, the newly defined index, TSR, can be used to indirectly reveal the trend of long-term water soaking. In Fig. 3b, TSR discloses the inherent water-absorbing ability of different kenaf-based particleboards. The TSR of KPB1 (3% pMDI) was much higher than that of KPB2 (6% PF), and high-density KPBs showed higher TSR values. The measured WA or TS, therefore, does not necessarily reflect the potential water-proof ability of particleboards.

The LE of KPB1 and KPB2 decreased with increasing density (Fig. 3c). With the WA changing around 49 to 113%, KPBs with 3% pMDI expanded linearly 0.48 to 1.56%, and PF-bonded KPBs had LEs from 0.38% to 1.33%. All single-layer KPBs failed to meet the 0.35% ANSI A 208.1 requirement for M3 WPB, even though 1.0% wax was used.

Comprehensively, single-layer KPBs showed satisfactory mechanical performance, which is the main stimulus for further research and development of KPBs. Simultaneously, the inherent hygroscopic character of kenaf core brought potential dimensional instability to the KPBs. Actually, the high water uptake tendency and dimensional instability of biocomposites containing kenaf core have been universally verified in many former studies (Sellers *et al.* 1993; Sheikkariem 2000; Grigoriou *et al.* 2000; Juliana *et al.* 2012a). Sheikkariem (2000) hence took the low bulk density of kenaf core as the main reason, since this resulted in high compact ratio of a particleboard matrix. The research work of Juliana *et al.* (2012a) revealed another reason, *i.e.*, particle geometry of kenaf core particles. They prepared particles using a chipper and a ring knives flaker, which was similar to the procedure in this paper. Rectangular or nearly rectangular shape particles (length: 1.0 to 2.0 mm; aspect ratio: smaller than 3.0) were achieved. These particles have a tendency to align themselves perpendicular to board surface during mat-forming. As a result, considerable invisible internal stress was established and locked inside the board matrix during hot-pressing, which subsequently brought obvious deformation to the end panels as exposed in a humid environment. Therefore, a better method to prepare kenaf core particles, *e.g.*, disk-chipping, or an improved board construction, *e.g.*, three-layer construction, seems necessary.

Three-layer Kenaf Core Particleboard

Vertical density profile

KPB3 showed evidently optimized U-shaped VDP curves (Fig. 4) in comparison with the unbalanced construction of KPB1 and KPB2 (Fig. 1). Apparently, the distribution of particles of various sizes in a composite matrix is another important factor controlling the VDP of composite panels, in addition to the hot-pressing regulation reported in many previous investigations (Wang *et al.* 2001). Among the three constructions, KPB3a (70% core) had the narrowest wings, KPB3b (50% core) had a median value, and KPB3c (1/3 core) owned the widest wings. Hence, through adjustments of the surface/core ratios, the structure of KPB can also be effectively manipulated.

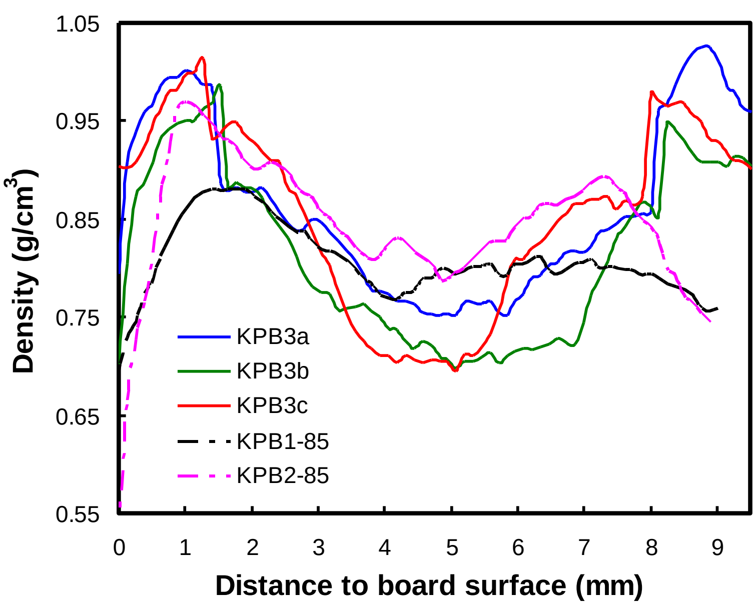


Fig. 4. Density profiles of three-layer KPBs

Mechanical properties

The mechanical properties of KPB3 can be seen in Table 3 and Fig. 5. The MOE, MOR, and IB values of KPB3 all were higher than those of KPB1 or KPB2 at the same average density level (nominally 0.85 g/cm^3). Among the three kinds of three-layer KPBs, KPB3b showed the highest MOE and MOR values, while KPB3a had the maximum IB value. Only KPB3b and KPB3c successfully met the M3-grade specifications of ANSI A 208.1 (ANSI 1999) for both bending and internal bond properties.

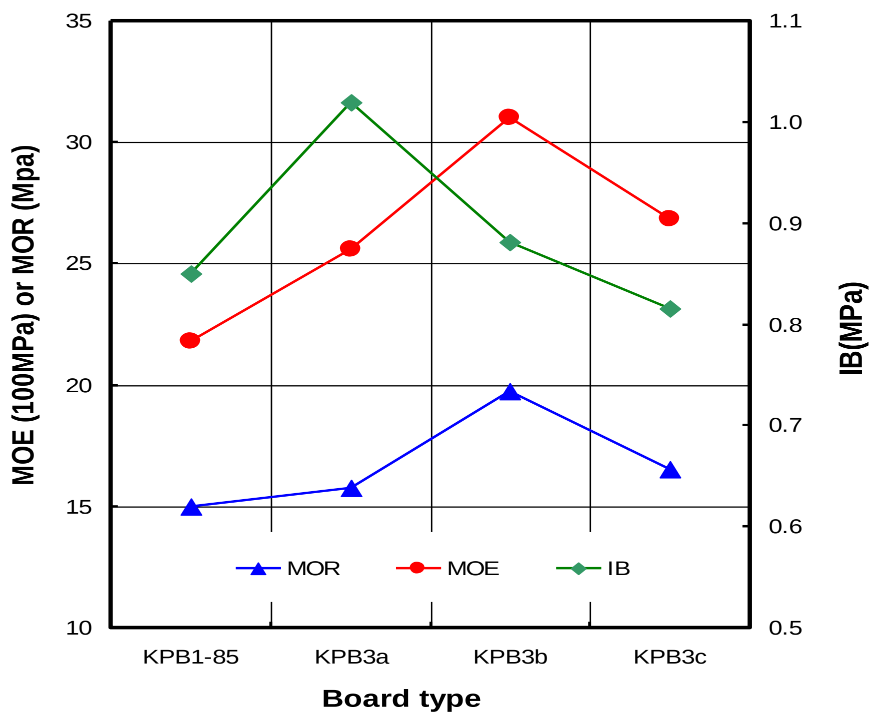


Fig. 5. Influences of construction on MOE, MOR, and IB strength

Dimensional properties

Table 4 shows that KPB3 had a higher dimensional stability than either KPB1 or KPB2. Although three-layer boards absorbed more water than single-layer KPBs, they had much less thickness swelling. Accordingly, the TSR of KPB1-85 (*i.e.*, 0.898) was much larger than those of KPB3 (a, 0.662; b, 0.661; and c, 0.612). Likewise, the layered construction also helped improve the linear dimensional stability of KPB3. Figure 4 can be used to illustrate the above phenomena. The three-layer particleboards had two high-density surface layers and a low-density core, which is different from KPB1 and KPB2. The voids in the core layer provided paths for water penetration, leading to high WA values, while the consolidated surface layers effectively prevented board swelling.

Figure 5 shows that all the KPB3 panels had higher MOR, MOE, and IB values than KPB1-85. This further demonstrated the advantage of layered construction of kenaf -based composite boards. Similar results can also be found in Juliana's study (2012b). Three-layer particleboards with mixed raw materials (core layer: kenaf core-KC; surface layers: rubber wood-RW) with changed surface to core ratios were fabricated. The boards with RW particles exhibited higher MOR, MOE, and IB values while lower TS and WA values than 100% KC control panels. The authors attributed the phenomenon to the higher density of rubber wood than kenaf core. Figure 5 further shows that 100% KC particles may also be made into particleboards with improved properties if the boards are made with a layered pattern.

Among the three-layer KPBs, KPB3b had the best comprehensive performances. With more fines (KPB3c), the water-proof property was worse, and with fewer fines (KPB3a), the bending property was worse. Layered construction also helped ensure KPBs with symmetric structures, which made them sturdier and more promising in competition with other kinds of composite panels.

Kenaf and Cedar Composite Particleboard

Figure 6 graphically compares the mechanical and dimensional properties of KCPBs. Compared with pure cedar wood particleboard, the substitution of kenaf core for wood showed different influences on the physical and mechanical properties. With the addition of kenaf core particles from 0 (*i.e.*, CPB) to 100% (*i.e.*, KPB1-85), the MOE slightly varied between 1.98 GPa and 2.5 GPa, the MOR showed no evident change, the LE decreased sharply from 0.81% to 0.48%, and the TS also became lower. From the tested results, the only disadvantage caused by kenaf seems to have been the weaker internal bond strength. However, the tested values (*i.e.*, 1.07 MPa to 0.65 MPa) all met the ANSI standard specifications. Similar ideas were also found in limited publications. Bajwa and Chow (2003) made kenaf-aspen composite oriented strandboards (kenaf substitution rate: 25%), and the boards achieved the specifications of commercial OSB. Juliana (2012b) also successfully made three-layer kenaf-rubber wood particleboard. All these practices demonstrated the acceptability of kenaf core as a potential substitute for wood in the manufacture of composite panels. Quantitatively, a substitution rate of 20% to 50% is suggested, which achieved sound comprehensive performances in this study.

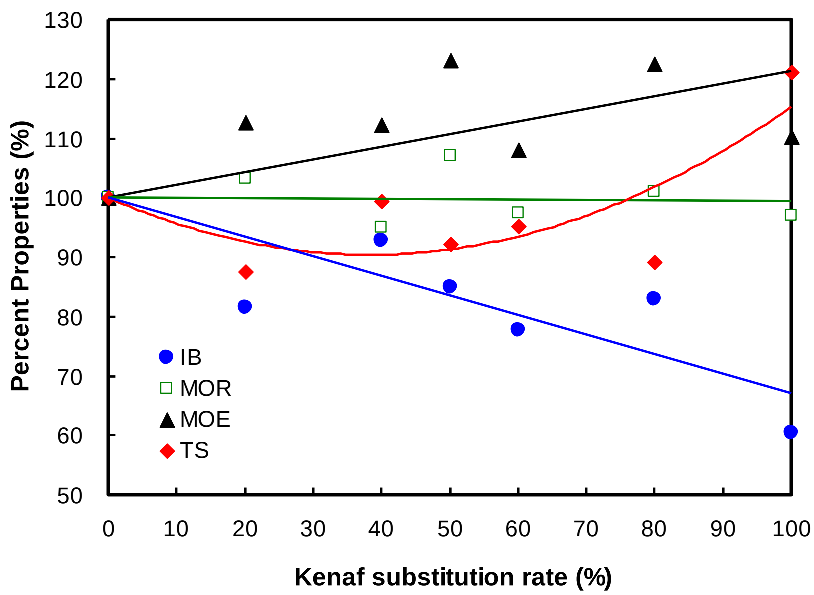


Fig. 6. Board performance variations with kenaf substitution rates

CONCLUSIONS

1. Kenaf core, as a residue of fiber cropping, is a potential substitute for wood in producing composite boards. It is demonstrated in this study that kenaf core can be made into ANSI-satisfactory particleboards with both MDI and PF resins. Density and resin content were two primary factors affecting KPB performance. KPB denser than 0.70 g/cm^3 and with 6% PF met or exceeded the mechanical specifications of ANSI A 208.1. Boards with only 3% pMDI failed to meet the standard value, and slightly higher resin content and density were necessary to acquire dependable board performance. The poor water-proof character of KPBs was demonstrated, and WA, LE, and TS varied as functions of board density with pre-regulated resin content.

2. The layered construction of KPB helped optimize board structure, improve mechanical properties, and stabilize board dimensions. KPBs with 50% fines equally paved in two surface layers showed the best comprehensive performances.
3. The addition of kenaf core to cedar composites did not show significant performance optimization or deterioration. To industrialize, a substitution rate of 20% to 50% is suggested.

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