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Mechanical and physical properties of agro-based fiberboard

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Abstract In order to better utilize agricultural fibers as an alternative resource for composite panels, several variables were investigated to improve mechanical and physical properties of agro-based fiberboard. This study focused on the effect of fiber morphology, slenderness ratios (L/D), and fiber mixing combinations on panel properties. The panel construction types were also investigated such as hardboard (HB), medium density fiberboard (MDF), and bagasse core panel (BCP) made from bagasse/bamboo combinations with a combination of 1% pMDI/4% UF as a binder. Static bending properties and tensile strength increased as fiber L/D increased from 3 to 26. Fiber separation and morphology also influenced the mechanical property development of agro-based panels. Bagasse fiber bundles and particles smaller than L/D of 5.4 were responsible for the mechanical property loss of agro-based MDF. The BCP yielded promising results for modulus of elasticity (MOE) and modulus of rupture (MOR). However, HB appeared to be a better panel type for agro-based composites based on the property enhancement compared to wood-based panel products.

Mechanische und physikalische Eigenschaften von Faserplatten aus landwirtschaftlichen Rohstoffen

Zusammenfassung Um landwirtschaftliche Fasern als alternativen Rohstoff für Verbundplatten besser nutzen zu können, wurden verschiedene Faktoren zur Verbesserung der mechanischen und physikalischen Eigenschaften von Faserplatten aus landwirtschaftlichen Rohstoffen untersucht. Diese Studie beschäftigt sich in erster Linie mit der Wirkung von Fasermorphologie, Schlankheitsgrad (L/D) und möglichen Fasermischungen auf die Eigenschaften von Hartfaserplatten (HB), mitteldichten Faserplatten (MDF) und Verbundplatten aus Bambus mit unterschiedlich dicken Bagasse-Mittellagen (BCP) und einer Mischung aus 1% pMDI/4% UF als Bindemittel. Mit steigendem Schlankheitsgrad von 3 auf 26 nahmen statische Biegefestigkeit und E-Modul zu. Außerdem beeinflussten auch Fasertrennung und -morphologie die mechanischen Eigenschaften der Platten aus landwirtschaftlichen Rohstoffen. Bagasse-Faserbündel sowie Partikel mit einem niedrigeren Schlankheitsgrad als 5,4 führten zu schlechten mechanischen Eigenschaften von MDF aus landwirtschaftlichen Rohstoffen. BCP zeigte viel versprechende Ergebnisse in puncto Elastizitätsmodul (MOE) und Biegefestigkeit (MOR). Geht man jedoch von einer Verbesserung der Eigenschaften im Vergleich zu Holzplatten aus, so scheint sich HB als Verbundwerkstoff aus landwirtschaftlichen Rohstoffen besser zu eignen.

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1 Introduction

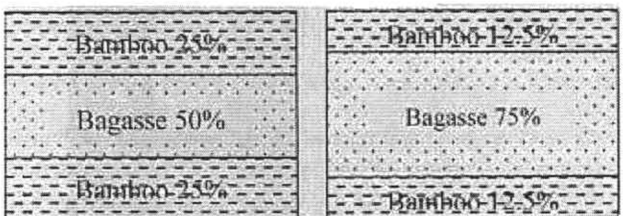
There are vast supplies of agricultural fiber residues in North America. Bagasse, jute, straws, and sisal appear to hold the most promise for continued development (Maloney 1993, Li et al. 2000). In general, lignocellulosic non-wood fibers are a relatively inexpensive alternative to higher quality wood fibers. Composite manufacturing using bagasse furnish is an option for utilization in areas where this material is abundant. Due to its large production of sugarcane and other agronomic crops, Louisiana is an ideal place in the U.S. for development of agro-based composites.

Bagasse is a fibrous by-product from sugar cane processing and has been used to produce hardboard (HB) and insulation board (Sefain et al. 1978, Atchison and Lengel 1985). Composites made from agro-fibers are typically somewhat poorer in quality than those made of wood fibers. Depithing, surface modification, and thermal/chemical treatments have provided comparable mechanical and physical properties to medium density fiberboard (MDF) made from aspen fiber (Mobarak et al. 1982, Iñiguez-Covarrubias et al. 2001). The adhesive has an important influencing on mechanical and physical properties of agro-based composites. UF (urea-formaldehyde) and PF (phenol-formaldehyde) modified with 20 to 30 percent of pMDI (4,4'-diphenylmethane diisocyanate) has provided substantially increased mechanical and physical properties of agro-based composites compared to a single UF or PF application of agro-based composites (Pizzi 1994, Hse and Choong 2000, Grigoriou 2000, Simon et al. 2002).

Bamboo (*Bambusoideae* sp.) was introduced in the agro-based composite field in the early 19th century. Due to its rapid growth, high bending stiffness, and dimensional stability, bamboo has potential as a raw material for composite panel production. Many studies have evaluated the properties of bamboo-based composites such as oriented strandboard (Lee et al. 1997), medium density fiberboard (Yusoff et al. 1994, Zhang et al. 1997), bamboo fiber reinforced cement boards (Sulastiningsih et al. 2002) and bamboo fiber/thermoplastic composites (Jindal 1986, Jain et al. 1992).

It is generally accepted that longer fibers obtain an increased network system by themselves and result in increased bending properties of composites (Mobarak et al. 1982, Li et al. 2000). Processing variables (i.e., plate clearance, plate size, and material moisture) influence fiber sizes. Fiber sizes correlate to total surface area, which affects resin efficiency. In particles, a smaller percentage of fine fractions lowered the strength properties of composites (Hill and Wilson 1978). The strength loss was due to the relatively larger surface area (up to 88% increased surface area) of the fine materials. However, most studies have not focused on the property enhancement of a multi-fiber layer system for agro-based MDF.

The objective of this study was to determine the effect of fiber morphology and slenderness ratios on MDF properties (Phase I). This study also investigated fiber mixing combinations (Phase II) with three panel types (HB, MDF, and bagasse core panel (BCP)) made from agro-based fibers with a modified resin system (Fig. 1).



a b

Fig. 1a,b Layout for manufacturing of bagasse core panels (BCP). a 50% Bagasse Core and b 75% Bagasse Core
Abb. 1a,b Aufbau der Bambus-/Bagasseverbundplatten BCP. a 50% Bagasse-Mittellage und b 75% Bagasse-Mittellage

2 Experimental

2.1 Materials

Bagasse fibers were provided by a local sugarcane mill near Baton Rouge, LA. USA. The bamboo (*Phyllostachys pubescens*) was harvested from sites near Pineville, LA. USA. Bamboo fibers were generated using a single disk refiner at the USDA Forest Service, Southern Research Station at Pineville, LA. USA. The internode region of the bamboo was cross cut with a hand saw into 25.4 mm long disks. The disks were radially split with a knife to produce chips of 12.7 mm in width. The culm wall thickness of the chips was approximately 6.35 mm, which was the thickness of the bamboo shells. The bamboo chips were soaked under steam pressure for 2 hours and then transferred to a single disk refiner with a 0.13 mm plate clearance. The chips were processed under atmospheric pressure with hot tap water flowing through the refiner. The refined fibers were placed under a vacuum to remove excessive water and dried at 80 °C for 48 hours. The moisture content of both fiber types was 8% for composite formulation.

The following adhesives were physically combined and used as the binder; 1% polymeric diphenylmethane diisocyanate (pMDI; Huntsman Polyurethane RUBINATE® 1840, 1.2 specific gravity) and 4% liquid urea-formaldehyde (UF; Dynea U.S.A. Inc. Chembond® YTT-063-02, and 60% solids).

2.2 Fiber classification and image analysis

Both bagasse and bamboo fibers were classified with a particle size classifier for five minutes. The US standard series used to classify the fibers were 40, 60, and 80 mesh (TAPPI 1995). For the density calculation for each fiber type, fiber volumes were measured using an Amsler volume-meter (VM 9). A scanner with 1200 dpi (dots per inch) resolution generated three to four macro-images for each mesh size and fiber type. The actual size of the macrographs was 101.6×152.4 mm^2. The generated macrographs were moved to image analysis software for

Table 1 Experimental design for each phase
Tabelle 1 Versuchsdesign für jede Phase

	Phase I	Phase II
Panel Type (s)	MDF	HD, MDF, and BCP
Number of Panels	24 (2 Fiber types × 4 Size classification × 3 Replicates)	24 (3 mixing combination × 3 Panel types × 3 Replicates)
Panel Dimension	$152 \times 152 \times 6.4$ mm^3	$305 \times 305 \times 6.4$ mm^3
Furnish Fibers	Single Classified Fibers	Mixing Combinations (bagasse/bamboo = 75/25, 50/50, and 0/100)
Adhesive	1% MDI/4% UF	

quantitative measurement. The image analysis software, "Image Pro-Plus, Version 4.5", was used for fiber length and width measurements of the two fiber types of agro-based fibers. Macro-images were successfully imaged to show clear boundaries of fibers. A perspective two-dimension view (6.6 × 6.6 mm^2) is given in Table 3. Dark and bright backgrounds were applied to visualize the fibers effectively under the light reflection depending on the color of the agro-based fibers. After fiber length and width were collected, slenderness ratios (L/D) were calculated.

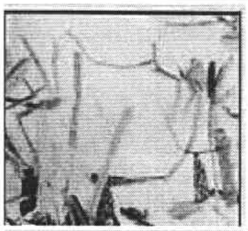
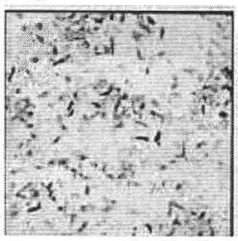
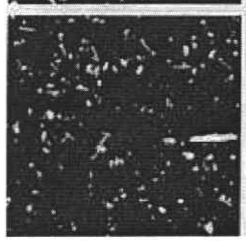
2.3 Fiberboard fabrication

Table 2 shows the experimental variables of both of the experimental phases. Phase I was designed to evaluate the effect of fiber morphology and L/D on panel properties. Phase II was designed to determine the influence of fiber mixing combinations and panel types on the mechanical and physical properties of agro-based fiberboards. The target density was 673 kgcm^{-3} for MDF and BCP and 1010 kgcm^{-3} for hardboard. The furnishes were transferred to a laboratory-scale blade separator/blender (Liang et al. 1994) for resin application using an air-atomizing nozzle. Panels were pressed at 179 °C with a 10-second closing time and one minute at maximum pressure (3.4 MPa) before gradually releasing the pressure for 3 minutes until 0 Pa. After panels were removed from the hot press, they were cooled and equilibrated at room ambient conditions to moisture content of approximately 6%.

2.4 Property evaluation and data analyses

The mechanical properties evaluated for phase I included modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB), and tensile strength (TS) of 152.4 × 152.4 × 6.4 mm^3 panels. Due to the panel size, bending and tensile test speci-

Table 2 Fiber size distribution from a particle classifier and fiber morphology of 6.6 × 6.6 mm^2 segments (Phase I)
Tabelle 2 Fasergrößenverteilung und Fasermorphologie von 6, 6 × 6,6 mm^2 großen Proben (Phase I)

Bagasse Fibers		Screen Fraction		Bamboo Fibers
	51%	-40	48%	
	22%	−40/ + 60	20%	
	11%	−60/+80	15%	
	16%	−80	17%	

mens were slightly modified from ASTM D 1037 (ASTM 1999). The dimensions of the bending test specimens were 12.7 × 139.7 × 6.4 mm^3. The test span was 76.2 mm. Two IB test samples (50.8 × 50.8 mm^2) from each panel were tested according to ASTM D 1037 (ASTM 1999). Mechanical and physical properties of 305 × 305 × 6.4 mm^3 panels from phase II were determined according to ASTM D 1037 (ASTM 1999). The experimental design was a CRBD (completely randomized block design) with a factorial treatment.

3 Results and discussion

3.1 Morphological characteristics and size distribution of classified fibers

The size distribution of the agro-based fibers and their morphologies are shown in Table 2. More than 50% of both fiber types were from > 40-mesh screen fractions. Both fiber types showed a similar size distribution through the screen fractions. It is noted that the bagasse fibers were not depithed and contain considerable amount of fiber bundles (> 40-mesh). Table 3 shows average fiber length, width, and slenderness ratios for the bagasse and bamboo fibers on the three different boundaries of US standard mesh sizes. As expected, L/D decreased consistently with a decrease in screen sizes. Bamboo had a high percentage of fibers separated into single fibers during the mechanical pulping process. Bagasse fibers had a longer mean fiber length and width than bamboo fibers. However, the median values for L/D of bamboo fibers were slightly higher than bagasse fibers. Bagasse fibers (< 60-mesh) had a relatively lower L/D than bamboo fibers. The bamboo fibers had shown slender fiber shapes with a lower mean width than bagasse fibers. Bamboo fibers, therefore, can build a fiber network system because of their inherent slender morphology.

3.2 Effect of slenderness ratio on the mechanical properties

Figure 2 shows the influence of slenderness ratios on the mechanical properties of MDF manufactured from classified fibers. The mechanical properties rapidly increased with increased L/D of fibers from 3 to 10 regardless of fiber type. At L/D higher than 10, the mechanical properties remained constant for both agro-fibers with the exception of bending stiffness and strength of MDF made from bamboo fibers. Bamboo fibers showed almost two fold higher mechanical properties at L/D = 26 compared to

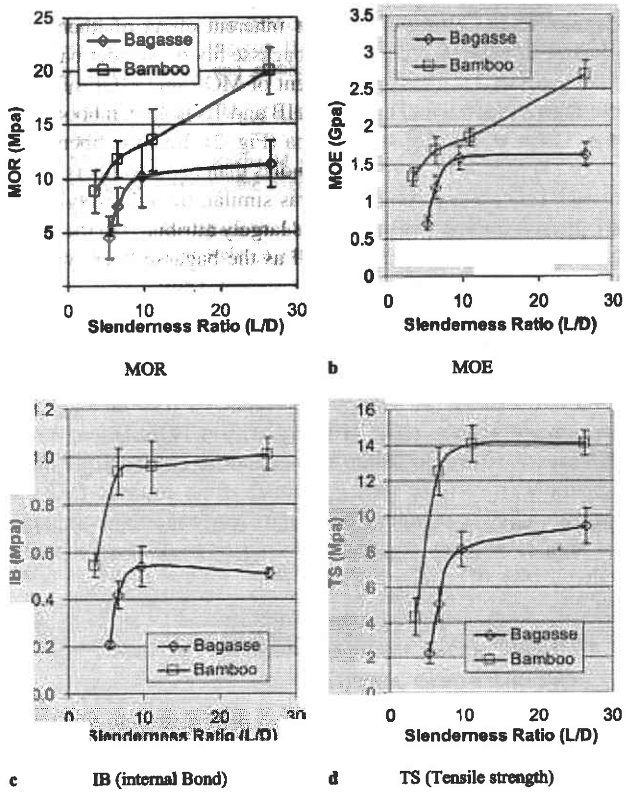


Fig. 2 Influence of fiber slenderness ratios on the mechanical properties of agro-based MDF made from different fiber classifications (Phase I)
Abb. 2 Einfluss des Faserschlankheitsgrads auf die mechanischen Eigenschaften von MDF aus landwirtschaftlichen Rohstoffen aus unterschiedlichen Fasern (Phase I)

Table 3 Fiber length, width, and slenderness ratios (L/D) of the bamboo and bagasse fibers from measurements of twenty five 6.6 × 6.6 mm^2 segments (Phase I)
Tabelle 3 Faserlänge, -breite und Schlankheitsgrad (L/D) von Bambus- und Bagassefasern von fünfundzwanzig 6,6 × 6,6 mm^2 großen Proben (Phase I)

Screen Fraction	Bagasse Fibers				Bamboo Fibers			
	Length (mm)	Width (mm)	Slenderness ratios (L/D)	L/D Median	Length (mm)	Width (mm)	Slenderness ratios (L/D)	L/D Median
+40	5.9 (0.8–25.2)	0.38 (0.05–2.4)	26.5 (1.04–226)	16	2.76 (0.06–10.7)	0.12 (0.02–0.98)	26.4 (1.1–207)	20
−40/+60	1.59 (0.36–8.3)	0.22 (0.03–0.5)	9.7 (1.07–64.4)	6	0.71 (0.04–2.8)	0.08 (0.02–0.45)	11.1 (1.2–48.3)	9
−60/+80	0.77 (0.21–6.5)	0.15 (0.02–0.4)	6.6 (1.12–38.3)	5	0.51 (0.08–2.1)	0.09 (0.02–0.32)	6.6 (1.01–36.5)	6
−80	0.6 (0.04–3.9)	0.14 (0.03–0.3)	5.4 (1.01–32.2)	4	0.23 (0.04–1.3)	0.07 (0.02–0.23)	3.5 (1–21.7)	3

(): Range of each measurement

bagasse fibers. This indicates the inherent effect of fiber morphology of bamboo compared to bagasse fibers. Slender bamboo fibers provided further development of MOR and MOE of bamboo fiber based MDF. The highest IB and TS from bamboo fibers was 1 Mpa at L/D 26, and 14 Mpa (Fig. 2). Bagasse fibers also mainly consisted of more fiber bundles than bamboo fibers. Even though L/D for each fiber type was similar, the relatively lower IB strength for bagasse panels was largely attributed to the smaller mesh size (<80-mesh) as well as the bagasse fibers yielded lower MOE and MOR.

The small particles for bagasse were possibly generated from sugar cane pith and fiber surface fractures. The fines increased surface area exposed to glue. Therefore, fines led to insufficient resin coverage on the surface and resulted a poor strength performance (Maloney 1970, Hill and Wilson 1978, Dunky 1998, Bekhta and Hiziroglu 2002). Discontinuous fibers, additionally, generated from fines also prevented stress transfer in MDF (Maloney 1993). Amount of adhesive applied on the composites became more an important factor on the mechanical property enhancement of panels.

3.3 Influence of fiber mixing combinations and construction types on the panel properties

Table 4 shows phase II results of mechanical and physical properties of panels made from combinations of bamboo/bagasse fibers for three panel types (HB, MDF, and BCP). As expected most mechanical and physical properties increased with the increased percentage of bamboo fibers in the furnish. The exception to this trend was the panel properties of BCP with bagasse fibers as core materials. It is interesting to note that bamboo fibers with hardboard (HB) and MDF obtained significantly higher mechanical properties (MOR, MOE, and IB) with equal dimensional stability compared to panels combined with bagasse fibers. The partial replacement of bagasse fiber by bamboo in fiber mixing ratios influenced the mechanical properties of panel types. The MDF and BCP panels, however, showed insignificant difference in mechanical and physical properties regardless of fiber mixing ratios except for MDF made from 100% bamboo fibers. The bagasse core panels showed slightly better mechanical and physical property performance than the MDF made with fiber mixing combinations, but the differences were not statistically significant. It was also found that hardboard made from fiber combinations of bagasse/bamboo is compatible to wood-based composite properties of standard grade hardboard (ANSI/AHA 1995). Regardless of the fiber mixing combinations, HB showed a better mechanical and physical enhancement. Panel compaction ratios (ratio of panel density to the material density) of HB were also significantly higher than the ratios from the other panel types. Increased weight fraction of bamboo fibers into the furnish resulted decreased compaction ratios due to the inherent fiber properties.

Table 4 Mechanical and physical properties of MDF ($305 \times 305 \times 6.4$ mm^3) made from combinations of bamboo and bagasse fibers and panel construction types with 1% pMDI/4% UF (Phase II)

Tabelle 4 Mechanische und physikalische Eigenschaften von MDF ($305 \times 305 \times 6{,}4$ mm^3) aus Bambus- und Bagassefasern und Plattenarten mit 1% pMDI/4% UF (Phase II)

Board Types	Properties	Fiber Mixing Ratios (Bagasse/Bamboo fibers) 75/25	50/50	0/100
HB	Density (kgcm^{-3})	1150	1090	1010
	Compaction Ratio*	2.13	1.79	1.35
	MOR (Mpa)	32	33	40
	MOE (Gpa)	3.6	3.6	3.8
	IB (Mpa)	1.4	1.2	1.4
	TS (%)	17	14	13
MDF	Density (kgcm^{-3})	737	721	737
	Compaction Ratio*	1.37	1.19	0.99
	MOR (Mpa)	12	13	18
	MOE (Gpa)	1.8	2.0	2.5
	IB (Mpa)	0.44	0.56	0.71
	TS (%)	15	14	13
BCP	Density (kgcm^{-3})	737	737	
	Compaction Ratio*	1.37	1.21	
	MOR (Mpa)	15	16	
	MOE (Gpa)	2.3	2.2	N/A
	IB (Mpa)	0.26	0.34	
	TS (%)	17	15	

Note: HB=Hardboard, MDF=Medium density fiberboard, BCP=Bagasse Core Panel, MOR=Modulus of rupture, MOE=Modulus of elasticity, IB=Internal bond strength, TS=Thickness swelling, WA=Water absorption, *=dividing panel density by material density

4 Conclusions

The objectives of this study were to evaluate the influence of fiber morphology, slenderness ratios, and fiber mixing combinations on the mechanical and physical properties of agro-based MDF. Increased slenderness ratios from 3 to 26 positively influenced panel properties of agro-based fiberboards. The fiber geometries contributed to 1) improved bending properties, 2) tension parallel and perpendicular to the surface of MDF, and 3) an interaction between surface area and the amount of applied adhesive. Bamboo fibers had better mechanical performance and were more slender fibers than the bagasse fibers. The later of which contained a considerable amount of fiber bundles. Therefore, material geometry and fiber refinement influenced the mechanical properties of agro-based MDF. The hardboard provided the best mechanical properties with the highest compaction ratio.

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