Properties of Bio-Based Medium Density Fiberboard

Sangyeob Lee, Todd F. Shupe, and Chung Y. Hse

Abstract

In order to utilize agricultural waste fibers as an alternative resource for composites, a number of variables were investigated to determine whether the mechanical and physical properties of agro-based fiberboard could be improved. Fibers were classified into four different mesh sizes and used to evaluate the effect of fiber size on the mechanical and physical properties of the composite. Moisture content (MC) of the furnish and additional moisture from the resin applications were significant factors influencing the mechanical properties of the composites. Medium density fiberboard (MDF) made from bagasse fibers with 8 percent MC had a 63-percent increase in modulus of rupture (MOR) and a 30-percent increase in modulus of elasticity (MOE) compared to composites manufactured with 0 percent MC furnish. For bagasse MDF, a compounded resin system of 1 percent 4,4′-diphenylmethane diisocyanate (pMDI)/4 percent urea-formaldehyde (UF) performed as well as panels with 4.5 percent MDI in MOR and 3.5 percent MDI in MOE. Internal bond (IB) test results also showed that the modified resin system had slightly lower IB strength than with 4.5 percent MDI. Static bending and tensile strength parallel- and perpendicular-to-the surface increased as fiber aspect ratios increased from 3 to 20. Fiber bundles (11% of weight fraction, > 40 mesh) and particles smaller than 80 mesh size were responsible for the mechanical property loss of agro-based composites. Hardboard appeared to be the most promising panel type based on compatibility and property enhancement. Two mixing combinations (50/50 and 25/75) of bagasse/tallow tree fibers yielded mechanical and physical properties which statistically differed insignificantly from higher proportions of *Sapium* fibers and provided the maximum utilization of bagasse fibers into the panels.

Introduction

Fibrous materials from agricultural residues or weed trees have great potential for replacing wood in composite materials (Bowyer and Stockmann 2001). Whether used alone or in combination with wood, agricultural residues provide an attractive option to traditional composites (English et al. 1997). Because of environmental pollution and decreasing fiber resource availability, investigation and development of new products based on the utilization of agricultural residues and waste paper is gaining much attention (Lee and Lee 1994). Mobarak (1975, 1982) mentioned

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Lee:
Graduate Research Assistant
Shupe:
Associate Professor, Forest Products, School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, LA
Hse:
Principal Wood Scientist, USDA Forest Service, Southern Research Station, Pineville, LA

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the use of several agricultural residues such as the wheat straw, rice straw, cornstalk, and other grasses for paper and board production. Utilization of renewable agricultural raw materials is one key to the sustainable and environmentally acceptable production of many manufactured materials, ranging from low-cost commodity items to advanced, high-performance products (Backiel 1995).

Bio-based fiber resources such as bagasse, corn stalks, kenaf, rice husks/straws, and wheat straws are available in different locations in North America. However, agro-fibers provide unacceptable mechanical and physical properties when compared to virgin wood. The poor strength properties of agro-fiber panels are due to the lower cellulose content (Kuo et al. 1998, Hse 2000, Han et al. 2001). To avoid low strength properties, agro-fiber panels have been produced with a higher amount of resin because of the nature of the fiber and incorporated materials. The increased adhesive use resulted in a higher manufacturing cost even when renewable agricultural fibers are used as the furnish. Therefore, this study tested different resin types to establish mechanical and physical performance. The cost of using each resin was also considered. This project also attempted to find an optimal composite formulation for non-wood (bagasse and bamboo) and wood-based fibers (Chinese tallow tree [*Sapium sebiferum*]).

Bagasse is the fiber residue from processed sugar cane. Each year more than 4.5 million tons of bagasse is generated in the United States, mainly in Louisiana, Florida, and Hawaii, and it is typically burned in steam boilers to generate energy for industrial use (Choose Green Report 2001). Insulation board, hardboard, and medium density fiberboard (MDF) have been produced using bagasse fibers in both non-structural and structure panels. Hardboard, with an extremely high target density, was the only way to achieve compatible mechanical and physical properties with agrofiber-based composites. Thermal treatment of bagasse fibers reduced static bending strength but increased dimensional stability (Sefain 1978, Kuo et al. 1998). Improving mechanical properties and enhancing dimensional stability are two possible research opportunities for bagasse fiber composites. Material (surface) treatments such as acetylation, polymer grafting, cyanoethylation, and impregnation have also been applied to increase product performance (Nada 1989, Rowell et al. 1991, Hassan et al. 2000). Depithed bagasse fibers provided an increase of 40 to 60 percent in mechanical properties (Atchison 1985).

Bamboo (*Bambusoideae*) is also a well-known agro-based fiber resource that can be turned into value-added composite products due to its bending stiffness and strength development as well as dimensional stability. Many studies have reported on the influence of bamboo fiber on the properties of composites such as oriented strandboard (OSB), particleboard, fiberboard, cement-bonded particleboard, and the impact of fiber reinforcement in the thermoplastic matrix (Jindal 1986, Shin 1989, Jain 1992, Lee et al. 1997, English 1997, Bai et al. 1999, Kawai et al. 2001). Therefore, bamboo fibers are an already accepted fiber resource of non-wood-based ligno-cellulosic fibers and can contribute as a value-added component for agro-based MDF.

Chinese tallow tree (*Sapium sebiferum*) was introduced into the United States (Bruce 1997) and is one of the fastest growing and reproducing species throughout the southeastern United States. It has been considered as a weed or noxious species by the U.S. Department of Agriculture (USDA) (Jubinsky 1996, Keay et al. 2000) because it can readily become the dominant plant in disturbed vacant lots and abandoned agricultural land. It has the ability to invade natural, wet prairies and bottomland forests. Chinese tallow is the most successful exotic invader of the native woodlands in southwestern Louisiana. It has the potential to invade surrounding marshes, changing them from herbaceous to wood plant communities and creating unbalanced ecosystems (Bruce 1997, Urbatsch 2000). *Sapium*, however, has considerable potential for composite manufacturing in combination with bagasse fibers which also grow in the same area. The reduction of the quantity of this invasive species in the ecosystem will help it to return to a more natural state and allow native plants to perform better.

Reacting polyfunctional alcohol with a diisocyanate makes prepolymers. When the prepolymer is in molar excess, the prepolymer is hydroxyl-terminated and cannot grow further until additional diisocyanate is added (Marra 1993). Urea-formaldehyde (UF) is an important wood adhesive for interior application due to its low production cost and compatible stiffness and strength of MDF made with wood-based fibers (White 1995). However, UF resin itself is less effective for binding agrofibers. Various resin systems have been developed to obtain increased strength properties and dimensional stability of agro-based composites. Adhesives included in some UF modification research include phenol-formaldehyde (PF) and pMDI (4,4'-diphenylmethane diisocyanate). Hse et al. (2000, 2001) reported that 1 percent pMDI and 6 percent UF resin system provided better mechanical and physical properties, with an increased economic gain, than using a single pMDI system for MDF manufacturing. Therefore, the goal of this research is to develop a multi-polymer resin system consisting of UF and pMDI and to optimize the physical and mechanical performance of agrofiber-based composites.

The specific objectives were to:

- evaluate the effect of pMDI concentration and fiber MC;
- determine the effect of fiber morphology and aspect ratios on mechanical properties;
- investigate fiber mixing combination with panel types (bagasse/tallow and bagasse/bamboo); and
- evaluate the effect of modified (pMDI/UF) adhesive, conclusively.

Materials and Methods

Agro- and wood-based fibers

- Bagasse fibers, Chinese tallow tree (*Sapium sebiferum*), and bamboo (*Phyllostachys pubescens*)
- MC 8 percent.
- Single disk refiner with a 0.005-inch plate clearance (Chinese tallow and bamboo).

Adhesives: Mechanically combined 1 percent pMDI/4 percent UF

- Urea-formaldehyde (UF): Dynea U.S.A. Inc. (Chembond YTT-063-02; 60% solids).
- Polymeric diphenylmethane diisocyanate (pMDI): Huntsman Polyurethane (RUBINATE® 1840; 1.2 specific gravity).

Fiber classification and critical fiber dimensional measurements

- Particle size classifier (5 min.) – USA standard 40, 60, and 80 meshes (TAPPI 1995).
- Material density using Amsler volume-meter (VM 9).
- Image analysis using Image Pro-Plus, Version 4.5 – 0.26 by 0.26-inch segments.

Experimental variables and panel fabrication

6- by 6- by 0.25-inch panels

- Screen fractions: +40, –40/+60, –60/+80, and –80.
- Panel types: single and multi-size with classified fibers.
- MC: 0 percent, 4 percent, and 8 percent
- pMDI application levels: 2.5 percent, 3.5 percent, and 4.5 percent
- Mechanical and physical properties based on ASTM D 1037-99.

12- by 12- by 0.25-inch panels

- Fiber mixing combinations in weight fractions.
  - Bagasse and tallow: 100/0, 75/25, 50/50, 25/75, and 0/100 with 8 percent UF, 2.5 percent pMDI, and 1 percent pMDI/4 percent UF (45 panels total)
  - Bagasse and bamboo: 75/25, 50/50, and 0/100 with 1 percent pMDI/4 percent UF and three panel types (24 panels total)
- Panel types: hardboard, MDF, and BCP (bagasse core panel: 50% and 75%).
- Mechanical and physical properties based on ASTM D 1037-99.

Results and Discussion

Effect of MC and pMDI concentration levels on bagasse fibers

Figure 1 and 2 show the effect of MC and pMDI concentration levels on the mechanical properties. Increased furnish MC from 0 to 8 percent increased mechanical performances of bagasse-based MDF without a significant difference in internal bond (IB) strength properties. Furnish and additional moisture from resin (60% solid content) acted as significant factors on panel property development. This result indicates that eliminating material drying expenses can be a contribution in panel products. Eight percent MC provided a 63-percent increase in MOR and a 30-percent increase in MOE compared with 0 percent MC. Increased resin content also contributed to MOR and MOE development. Property performance (MOE, MOR, and IB) of mechanically modified resin (1% pMDI/4 % UF) provided an equal or better to 4.5 percent pMDI and 3.5 percent pMDI. Statistically insignificant difference between 2.5 percent and 3.5 percent pMDI usage on IB strength was also observed. One hundred percent bagasse fibers and 2.5 percent pMDI yielded poor mechanical properties due to the insufficient surface coverage.

Aspect ratios (L/W) and fiber morphology

Table 1 shows aspect ratios of two fibers from a particle classifier and generated from image analysis. It should be noted that the screen fractions from 40 to 60 mesh had more than 50 percent (ovendried weight basis) of both fiber types. L/W decreased with increased screen fraction.

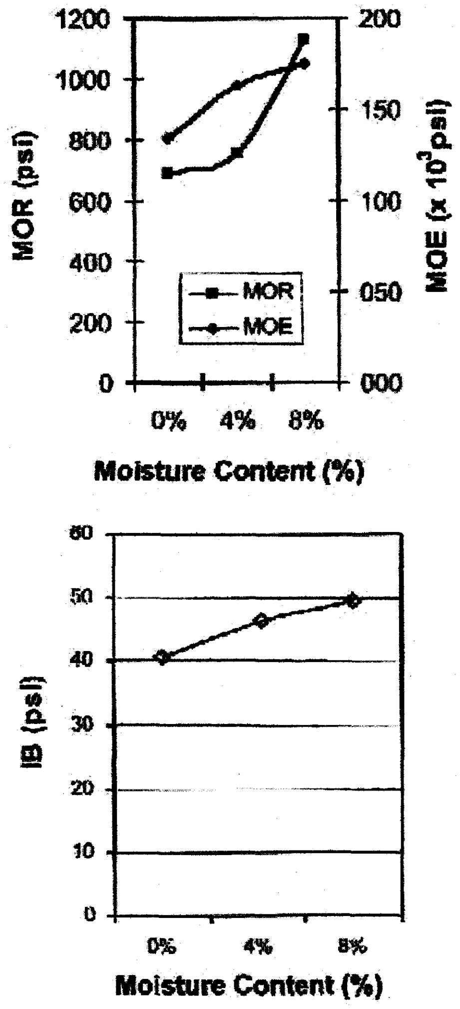

Figure 1. — *Influence of MC on the mechanical properties of MDF made from bagasse fibers and 2.5 percent pMDI.*

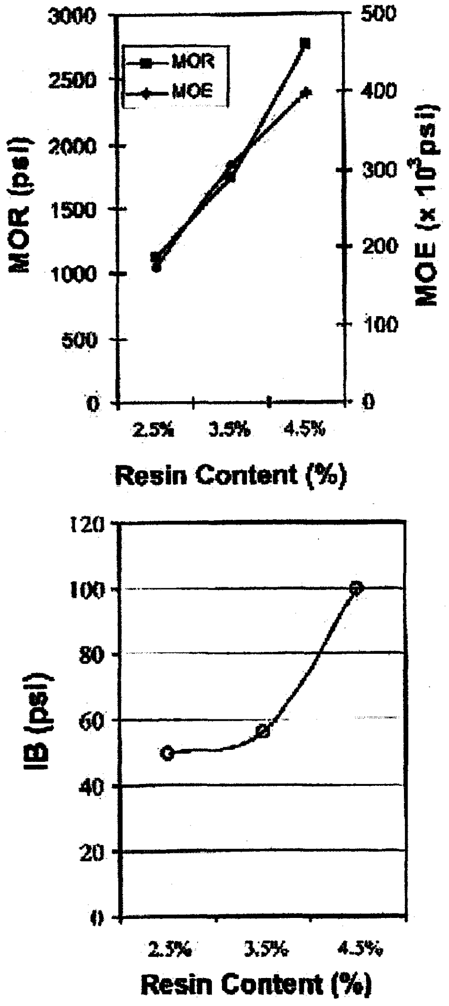

Figure 2. — *Mechanical property changes with increased resin content of MDF manufactured from bagasse fibers with 8 percent MC.*

Table 1. — *Aspect ratios of two fibers from particle classifier and generated from image analysis of 0.26- by 0.26-inch segments.*

Screen fraction	Bagasse	Bamboo
+40	26.5 (1.04 ~ 226)	26.4 (1.1 ~ 207)
-40/+60	9.7 (1.1 ~ 64.4)	11.1 (1.2 ~ 48.3)
-60/+80	6.6 (1.1 ~ 38.3)	6.63 (1.0 ~ 36.5)
-80	5.4 (1.0 ~ 32.2)	3.5 (1.0 ~ 21.7)

Larger particles showed a relatively clean surface observed from the bagasse fibers. Average L/W insignificantly differs from each other. Bagasse fibers consisted of longer and thicker fibers than bamboo fibers. Even though the bagasse fiber had a higher average fiber length and diameter, inherent slender morphology of bamboo fibers were enhanced as well as < 60 mesh size. This may contribute to the fiber network system during panel fabrication. Material density was 29.28 pcf for bagasse and 46.73 pcf for bamboo. To achieve the target density (42 pcf) for MDF, bagasse fiber required more fibers for panel manufacture which can contribute to a resin shortage when producing acceptable panel properties.

Influence of aspect ratios (L/W) on mechanical properties

The influence of the fiber's dimensional characteristics on the mechanical properties of agro-based composites was also evaluated. Figure 3 and 4 show the influence of fiber fraction of two fibers on MOR and MOE, respectively. Fiber size influenced MOR and MOE of MDF except fibers classified as > 40 mesh. MOR and MOE increased with increased aspect ratios. Fiber fraction > 40 (L/W = 26.5) of bamboo fibers pro-

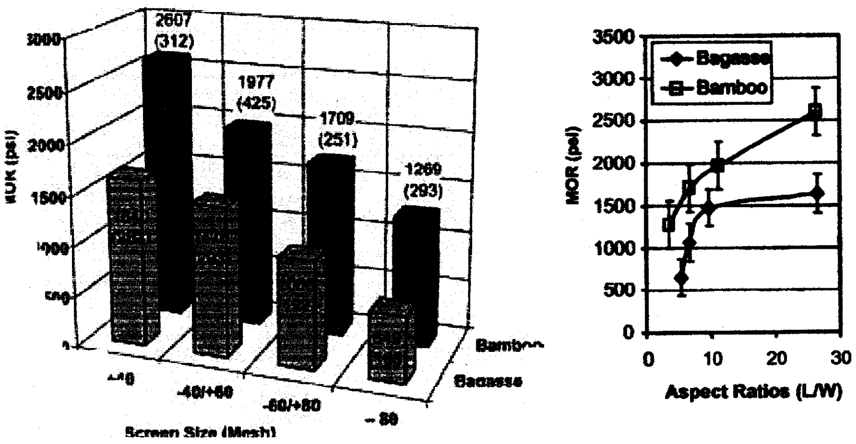

Figure 3. — *MOR of 6- by 6- by 0.25-inch MDF made from classified fibers.*

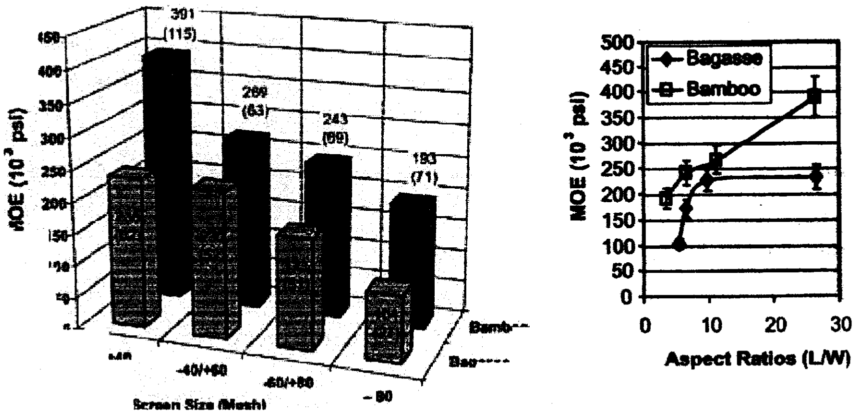

Figure 4. — *MOE of 6- by 6- by 0.25-inch MDF made from classified fibers.*

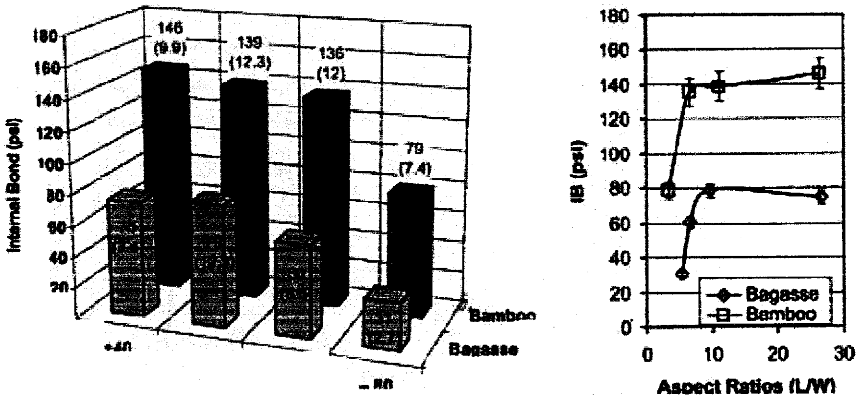

Figure 5. — *IB of 6- by 6- by 0.25-inch MDF made from classified fibers.*

vided the highest MOR and MOE. L/W (< 3.5) may provide a negative contribution to the MOE and MOR of MDF made with unclassified fibers. The fine geometry produced discontinues fibers in panels and may provide less effective stress transfer.

Figure 5 shows the influence of aspect ratios and size fraction on internal bond (IB) strength of MDF made from both classified fibers. The highest IB was 146 psi for bamboo fibers and 79 psi for bagasse. Dimensional characteristics (length and diameter) influenced IB strength of ag-based panels and showed different behavior with bamboo fibers. The IB strength changes rapidly with aspect ratios from 3.5 to 10. Less than 80 mesh (L/W = 3.5) showed the low-

Table 2. — *Effect of fiber mixing ratios and resin types on the mechanical/physical properties of agrofiber-based composites.*

Adhesive types[a] and properties		Fiber mixing ratios (bagasse fibers/tallow tree fibers)				
		100/0	75/25	50/50	25/75	0/100
8% UF	MOR (psi)	1,918	2,139	2,737	2,490	1,251
	MOE (× 10^3 psi)	232	273	260	216	199
	IB (psi)	56	54	56	52	40
	TS (%)	17	22	26	31	36
	WA (%)	38	97	101	107	137
2.5% pMDI	MOR (psi)	757	2,235	2,673	2,895	4,153
	MOE (× 10^3 psi)	163	279	269	265	343
	IB (psi)	46	71	108	154	189
	TS (%)	21	19	18	17	16
	WA (%)	48	31	30	31	25
1% pMDI/4% UF	MOR (psi)	2,232	2,987	3,656	3,676	4,898
	MOE (× 10^3 psi)	313	354	351	322	389
	IB (psi)	83	98	112	118	122
	TS (%)	17	17	17	19	18
	WA (%)	27	26	24	27	28

[a] UF = urea formaldehyde; pMDI = polymeric diphenylmethane diisocyanate.

est IB from this study. Particle morphology appeared to be a major strength property reduction due to the role of surface area. The improvement in bending properties of MDF was attributed to particle geometries of the classified fiber sizes as well as the interaction between surface area and amount of applied adhesive.

Fiber mixing ratios (bagasse/tallow tree) and resin types

Table 2 shows the effect of bagasse/tallow fiber mixing ratios and different adhesive application on panel properties. Resin type influenced MOE more than fiber volume fraction. A modified resin (pMDI/UF) provided better or equal performance of the mechanical and physical properties. From this result we may conclude that the pMDI/UF system and furnish moisture provide close to optimum MC for pMDI functionality. The quantity of UF provided an extended volume to cover the exposed fiber surface. The 1 percent pMDI/4 percent UF system has great potential for increased dimensional stability as well as mechanical values. MDF made with UF showed poor dimensional stability when compared to that of any other adhesive application. Modified pMDI/UF system provided better dimensional stability regardless of fiber mixing combinations. Mechanical and physical properties of bagasse volume fractions (50% to 75%) insignificantly differed from *Sapium* sp. fibers with UF resin. However, tallow tree fibers (100%) with 2.5 percent pMDI and 1 percent pMDI/4 percent UF showed statistically significant difference compared to the other fiber mixing ratios. MDF made from bagasse and *Sapium* fiber combinations of 50 percent/50 percent and 25 percent/75 percent provided a better or equal mechanical and physical performance than other fiber combinations with maximum bagasse fiber utilization.

Fiber mixing ratios (bagasse/bamboo) and panel types

Table 3 shows the influence of bagasse/bamboo fiber mixing ratios and panel types on mechanical and physical properties of fiberboards. In general, the addition of bagasse fibers into the furnish results in decreased strength properties but not a significant difference in bending stiffness and physical properties. Regardless of the fiber mixing ratio, hardboard showed better mechanical and physical properties than MDF and bagasse core panel. It should be noted that 75 percent and 50 percent weight fractions of bagasse showed an insignificant difference on the mechanical and physical properties regardless of panel type. Therefore, bagasse fiber utilization combined with other fiber resources can govern panel properties to optimize biomass utilization. Bamboo fibers

Table 3. — *Mechanical and physical properties of fiberboards (12- by 12- by 0.25-in.) made from combinations of bamboo and bagasse fibers with 1 percent pMDI/4 percent UF.*

	Fiber mixing ratios (bagasse/bamboo)		
	75/25	50/50	0/100
High-density fiberboard			
Density (pcf)[a]	72 (1.15)	68 (1.09)	63 (1.01)
MOR (psi)	4,659	4,770	5,734
MOE (× 10^3 psi)	520	516	548
IB (psi)	198	174	198
TS (%)	17	14	13
WA (%)	29	31	36
Medium density fiberboard			
Density (pcf)[a]	46 (0.74)	45 (0.73)	46 (0.74)
MOR (psi)	1,691	1,948	2,613
MOE (× 10^3 psi)	257	285	367
IB (psi)	64	81	103
TS (%)	15	14	13
WA (%)	48	46	46
Bagasse core panel			
Density (pcf)[a]	46 (0.74)	46 (0.74)	n/a
MOR (psi)	2,204	2,324	
MOE (× 10^3 psi)	329	325	
IB (psi)	38	50	
TS (%)	17	15	
WA (%)	50	48	

[a] Value is parentheses is specific gravity.

also provided better mechanical and physical properties compared to the other fiber combination. The bagasse core panel added some degree of mechanical and physical property development compared to the MDF.

Conclusions

This research investigated mechanical and physical properties of ag-based panels in terms of material condition, modified adhesive, and furnish formulation for biomass utilization. Mechanical properties of MDF made from bamboo and *Sapium* sp. fibers and modified adhesive were statistically superior to the bagasse fibers from this study. The mixed resin formulation (1% pMDI and 4% UF) resulted in equal or better property values and possibly 66 percent less resin cost compared to the 4.5 percent pMDI system. Panel mechanical and physical property values are strongly related to the furnish MC, moisture addition from the adhesive, and resin content. Increased L/W from 3 to 20 and compaction ratios positively influenced panel property development of agro-based fiberboards. Fiber bundles in the screen fraction > 40 mesh may also lead to some mechanical property loss. This result was supported by image analysis of the agro-based fibers. Bamboo fibers had a better mechanical performance and more slender fibers than the bagasse fibers. Therefore, material geometry and fiber separation influence the mechanical properties of agro-based MDF. Twenty-five to 50 percent of bagasse fibers in the mixing combinations were beneficial to manufacture ag-based panel. The high-density fiberboard provided the best mechanical properties from our study. It was found that hardboard made from bagasse/bamboo combinations is compatible with wood-based composites for mechanical and physical properties.

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Recent Developments in Wood Composites

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Edited by
Todd F. Shupe
Associate Professor,
Louisiana Forest Products Development Center,
School of Renewable Natural Resources,
Louisiana State University Agricultural Center,
Baton Rouge, Louisiana, USA

Forest Products Society
2801 Marshall Court
Madison, WI 53705-2295
phone: 608-231-1361
fax: 608-231-2152
www.forestprod.org

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