Utilization of Chinese tallow tree and bagasse for medium density fiberboard

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Abstract

The objective of this research was to investigate various adhesive systems and determine the best composite formulation for selected mechanical and physical properties of medium density fiberboard (MDF) made from wood and bagasse fibers. This study investigated opportunities of biomass utilization for natural fiber-based composites from agricultural (bagasse) and Chinese tallow tree (*Sapium sebiferum*) fibers. The mixing ratios were 100:0, 75:25, 50:50, 25:75, and 0:100 of bagasse and tallow tree fiber, and the furnish moisture content (MC) was 4 percent. The resin systems used were 8 percent urea formaldehyde (UF), 2.5 percent MDI (4,4'-diphenylmethane diisocyanate), and a mixed resin system of 1 percent MDI and 4 percent UF. Panels containing 100 percent bagasse furnish were also prepared with either 3.5 percent or 4.5 percent MDI at a furnish MC of 0 percent, 4 percent, and 8 percent. Two mixing combinations (50:50 and 25:75) of bagasse/tallow tree fibers yielded mechanical and physical properties which were not statistically different from higher proportions of *Sapium* fibers and provided the maximum utilization of bagasse fibers into the panels. The MC of the furnish and additional moisture from the resin applications were significant factors influencing the mechanical properties of the composites. MDF made from 8 percent MC bagasse fibers obtained a 63 percent increase in modulus of rupture (MOR) and a 30 percent in modulus of elasticity (MOE) compared to composites manufactured with 0 percent MC furnish. Panels at all fiber combination ratios with the mixed resin system performed superior to all furnish mixes with 4.5 percent MDI for MOR and MOE. Internal bond (IB) test results showed that the mixed resin system yielded slightly lower IB mean values than panels produced with 4.5 percent MDI.

Bio-based fibers from agricultural residues and economically low-value tree species have received increasing attention as replacements for wood in composite products (Bowyer and Stockmann 2001). Materials such as bagasse, corn stalks, kenaf, rice husks/straws, and wheat straw are available in North America. However, agrofibers generally provide poor mechanical and physical properties when compared with virgin wood materials. The poor strength properties of some agrofiber panels has been attributed to the relatively lower amounts of cellulose and lignin and large proportions of unlignified pith cells for many fiber types (Kuo et al. 1998, Hse and Choong 2000, Han et al. 2001). To avoid the weak strength properties, agrofiber composite panels have typically required a higher amount of resin. The increased amount of adhesive used in medium density fiberboard (MDF) results in higher costs even when using renewable agricultural fibers as the furnish. Therefore, this study explored different resin types to establish better mechanical and physical performance as well as cost reduction in MDF fabricated from agricultural fibers. This study also attempted to find an optimal composite formulation of the agricultural residue (bagasse) and Chinese tallow tree (*Sapium sebiferum*) fibers.

Bagasse is the matted cellulose fiber residue from processed sugar cane. Bagasse is typically burned in steam boilers to generate energy for industrial use

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(Choose Green Report 2001). More than 4.5 million tons of bagasse is generated each year in the United States, mainly in Louisiana, Florida, and Hawaii. Sugar cane that is grown with a constant hot and humid climate produces fewer and relatively weaker fibers (Hesch 1968). The smaller particles from bagasse fibers mainly consist of pith and weaker fibers. Depithed bagasse fibers provided an increase of 40 to 60 percent in mechanical properties (Hamid et al. 1983, Atchison and Lengel 1985).

Insulation board and MDF have been produced using bagasse fibers for both non-structural and structural applications. Also, hardboard, with an extremely high target density, was another way to achieve acceptable mechanical and physical properties of agrofiber-based composites. Thermal treatment of bagasse fibers has had mixed success because of reduced static bending strength but increased dimensional stability due to the glass transition temperature of lignin and its uniform distribution on fiber surfaces (Sefain et al. 1978, Kuo et al. 1998).

Improving mechanical properties and enhancing dimensional stability are two key research areas of bagasse fiber composites. Material (surface) treatments such as acetylation, polymer grafting, cyanoethylation, and impregnation have been applied to yield favorable results (Grozdits and Bibal 1983, Nada and El-Saied 1989, Rowell and Keany 1991, Hassan et al. 2000).

The Chinese tallow tree (*Sapium sebiferum*) was introduced into the United States from China (Bruce et al. 1997). It is one of the fastest reproducing species throughout the southeastern United States and is classified as a weed or noxious species (Jubinsky and Anderson 1996, Keay et al. 2000). The species can readily become the dominant plant in disturbed vacant lots and abandoned agricultural land. Chinese tallow is the most successful exotic invader of the native woodlands in southwestern Louisiana. It has had a major impact on plant community structure and species composition by becoming the most abundant woody species. It has the potential to invade surrounding marshes, changing them from herbaceous to woody plant communities and creating unbalanced ecosystems (Bruce et al. 1997, Urbatsch 2000). This species has considerable potential for composite manufacturing in combination with bagasse fibers.

Although most of the board properties made from agricultural and wood-based fibers are lower than fiberboard made from virgin wood fiber, strength properties of composites can be improved by controlling resin types and the amount used in the composite formulation. Urea-formaldehyde (UF) is an important wood adhesive for interior application due to its low cost and ability to yield satisfactory stiffness and strength properties of wood-based MDF (White 1995). However, UF resin itself is less effective for binding agrofibers than other resins. 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 4,4'-diphenylmethane diisocyanate (PMDI). Hse and Choong (2000) and Hse and Wang (2001) reported that a 1 percent MDI and 6 percent UF resin system provided better mechanical and physical properties at a lower cost than using a single resin system for MDF manufacturing. Therefore, the primary objectives of this research were to increase physical and mechanical properties and increase the effectiveness of various resin combinations for agrofiber-based composites. Another objective of this study was to investigate the influence of moisture content (MC) and three different levels of MDI on the mechanical property performance of MDF made from bagasse fibers.

Materials and methods

Bagasse fibers were collected from a local sugar cane plant near Baton Rouge, Louisiana. A representative tallow tree was also felled near Baton Rouge, LA. Both fibers were generated using a disk refiner at the USDA Southern Research Station at Pineville, LA. Mechanically processed particles were soaked under steam pressure for five minutes and transferred to a disk refiner with 0.005-inch plate clearance. The particles 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 then dried at 80°C for two days. Further break down was achieved by processing with a single disk refiner. Fiber size analyses were conducted to determine the different contribution of material geometries.

A liquid urea-formaldehyde (UF) resin (Chembond® YTT-063-02, 60% solids and 0.1 ~ 0.25% formaldehyde by weight) was obtained from Dynea USA, Inc. Huntsman Polyurethane provided a liquid 4,4'-diphenylmethane diisocyanate (4,4'-MDI; RUBINATE® 1840) with a 1.2 specific gravity (SG). An additional mixed adhesive type of 4 percent UF and 1 percent MDI was combined in the laboratory.

A total of 45 air-laid MDF panels were produced based on the combinations of five fiber mixing combinations, three resin combinations, and three panel replications. The five fiber mixing combinations of bagasse and tallow tree fibers were 100:0, 75:25, 50:50, 25:75, and 0:100 in weight fractions. Three resin applications of 8 percent UF, 2.5 percent MDI, and 4 percent UF/1 percent MDI were also applied. The target density was 40.6 pcf and nominal panel dimension were 12 by 12 by 0.25 inches. The furnishes were dried to 4 percent MC at 105°C (221°F) in an air circulation oven. Composite furnishes were transferred to a drum mixer for resin application using air-atomizing nozzles. Panels were pressed at 180°C (355°F) with a 10-second closing time and 1 minute at maximum pressure (500 psi, 3,447 kPa) before gradually releasing the pressure for 3 minutes until zero psi. All of the boards were immediately cooled and post cured under room temperatures overnight. Additional subsets of 18 MDF boards were manufactured with 100 percent bagasse fibers under 0 percent, 4 percent, and 8 percent MC with 2.5 percent, 3.5 percent, and 4.5 percent MDI, respectively.

After conditioning for 24 hours at room temperature, MDF boards were trimmed into 11 in.^2 (27.9 cm^2) specimens. Three static bending specimens measuring 2 by 11 inches (5 by 28 cm) were cut from each panel and tested using a 6-inch (15 cm) span (0.12 in./min. [3.05 mm/min.] crosshead speed) with an Instron model 4465. Modulus of rupture (MOR) and modulus of elasticity (MOE) were determined. Nine specimens for each furnish formulation were tested and the results averaged. Samples for internal bond (IB) tests were cut from failed bending samples. Nine specimens measuring 2 by 2 inches (5 by 5 cm) for each board were tested and the results averaged. Weighed and measured specimens were placed in a 5-inch- (12.7 cm) deep container for the water-soaking test. Dimensional measurements and weight of the test specimens were taken before and after 24-hour water soak at room temperature. Two 2- by 11-inch (5 by 28 cm) specimens for each board were tested. All mechanical and physical property tests were performed according to ASTM Standard D 1037 (ASTM 1999).

Fiber size distributions (**Table 1**) were conducted with two different classifiers because of the different material natures. Bagasse fibers were classified with a low tap particle classifier, and *Sapium* fibers with a McNett wet fiber classifier. All fiber classification followed TAPPI standard T 233 cm-95 (TAPPI 1995).

The effect of fiber and resin types on the mechanical and physical properties of MDF made from bagasse and wood fibers were analyzed as a two-factor factorial experiment with different levels of fiber combinations and adhesive applications. Further differences within each variable were analyzed with Tukey's standard range test.

Results and discussion

Material classification

The test results indicate different volume fractions of fiber length and particle size between the two materials. **Table 1** shows that bagasse fibers consist of relatively higher volume fraction (74%) of particle sizes bigger than 60-mesh size, while *Sapium* fibers have 43 percent short fibers of fiber lengths shorter than 50-mesh size. The higher short fiber contents of *Sapium* fibers also explains the relatively slower drainage of these fibers that was observed during the processing stage.

Table 1. — Fiber size distribution of bagasse and Chinese tallow tree fibers.

Low tap (bagasse)		McNett (Chinese tallow tree)	
Mesh size	Volume fraction (%)	Mesh size	Volume fraction (%)
> 20	20 ± 2	> 16	7.2 ± 1.3
20 to 40	32 ± 0.9	16 to 30	22.9 ± 1.1
40 to 60	22 ± 1	30 to 50	27 ± 1.6
60 to 100	15 ± 0.6	50 to 100	15.7 ± 2.5
< 100	12 ± 0.5	< 100	27.4 ± 3.4

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

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

[a] UF = urea-formaldehyde resin; MDI = 4,4'-diphenylmethane diisocyanate.

[b] MOR = modulus of rupture; MOE = modulus of elasticity; IB = internal bond strength; TS = thickness swelling; WA = water absorption.

Effect of fiber and resin types on MDF properties

Table 2 shows mechanical and physical properties of agrofiber-based MDF. In general, as expected most mechanical and physical properties decreased as the percentage of wood fibers in the furnish decreased. The exception to this trend was the mechanical properties for panels bonded with 8 percent UF. Regardless of the resin types, panels with mixed fibers show better or equal mechanical performance compared with 100 percent bagasse fibers. It is interesting to note that binding bagasse fibers with MDI results in significantly lower mechanical properties (MOR, MOE, and IB) and poorer dimensional stability compared to that of either UF or MDI/UF. This result might be attributable to a number of different factors such as poor compatibility of the furnish and adhesive, insufficient moisture in the furnish, inadequate resin distribution, and insufficient resin content.

MDF made with 8 percent UF resin showed no significant difference in IB strength among the fiber mixing ratios except 100 percent bagasse fibers were marginally better than 100 percent tallow tree fibers. The panels made with 2.5 percent MDI showed the highest IB strength, as expected, even though a greater amount of relatively short fibers increased surface areas. However, panels made with 100 percent bagasse fibers and 2.5 percent MDI yielded poor mechanical properties. This indicates the incompatibility of the MDI and the bagasse fibers in this study can largely be attributed to the high bagasse pith content rather than resin distribution. Bagasse fibers also show a better compatibility with the modified resin system of 1 percent MDI and 4 percent UF with increased resin coverage on the fiber surface and increased functionality of the MC (around 6% total MC – 4% from fibers and 2% from the UF resin, respectively). Sufficient mat moisture contents for MDI are 8 to 10 percent (Palardy et al. 1994; Johns et al. 1981, 1984). Therefore, the MDI and UF mixed system when combined with any furnish provided close to the optimum MC for

MDI functionality of the hydroxyl groups.

The mechanical properties of the 2.5 percent MDI and 100 percent bagasse samples were unusually low. This is likely due to insufficient furnish MC. The mechanical properties of bagasse panels were greatly improved with the addition of 25 percent wood fiber. The improvement was approximately three times in MOR, 71 percent in MOE, and 54 percent in IB of MDF produced with 25 percent *Sapium* fiber and 2.5 percent MDI. Therefore, the 25 percent wood fiber addition had a significant effect on the mechanical and physical properties of MDF made with 2.5 percent MDI.

Dimensional stability of composites made with 8 percent UF was poor (**Table 2**). Increased proportions of bagasse fibers corresponded to increased dimensional stability of MDFs. While MDI is less compatible with bagasse fibers, the modified resin system provided further increased dimensional stability and mechanical values than both single resin systems. This result indicates that the 1 percent MDI and 4 percent UF mixed system has great potential because of its high compatibility. Panels made from 100 percent bagasse fibers in combination with 2.5 percent MDI also showed lower dimensional stabilities than the bagasse panels with 8 percent UF resin system. This result indicates that bagasse fibers are either not compatible with the MDI resin system used in this study or the 2.5 percent resin application is insufficient to cover surfaces of bagasse fibers.

Table 3 shows the effect of fiber and resin types appraised by Tukey's studentized range test at $\alpha = 0.05$. Regardless of the fiber mixing combination, the mixed resin provided better or equal performances for the mechanical and physical properties. **Table 3** also shows that resin types influenced MOE more than fiber volume fractions in the composites. Bagasse fibers show a significantly different behavior compared to the other fiber mixing types. Bagasse volume fractions from 50 to 75 percent in the furnish also obtained mechanical and physical properties which insignificantly differed from higher proportions of *Sapium* fibers and provide a maximum utilization of bagasse fibers. The mixed resin also had a significant effect on MOR and MOE.

Significant influences with resin and fiber mixing types as well as their interaction on the mechanical and physical properties are shown in **Table 4**. Panels with UF resin and all fiber mixing types did not show significant differences among the fiber types for the mechanical properties. Higher bagasse fiber contents yielded significantly lower IB strength when the fibers were combined with 2.5 percent MDI. Increased bagasse fiber proportion with the 1 percent MDI and 4 percent UF mixed system also showed a gradual decrease in IB strength. However, IB strength from 100 percent bagasse with the 1 percent MDI and 4 percent UF resin system was greater than the other resins. It should be noted that the panels manufactured with 1 percent MDI and 4 percent UF had a higher IB strength at higher bagasse fiber contents (> 50% by weight) than boards with the single MDI system. This trend is also evident with other property values. This observation clearly indicates that the bagasse fibers are either not compatible with the single MDI system used in this study or the 2.5 percent resin content is insufficient to obtain satisfactory mechanical and physical properties.

Table 3. — Multiple comparisons of the effects of fiber and resin types on mechanical/physical properties of agrofiber-based composites at $\alpha = 0.05$ (95% confidence interval). Separate comparisons were made for the resin types and fiber combinations.[a]

	Modulus of rupture	Modulus of elasticity	Internal bond	Thickness swelling	Water absorption
	(psi)	($\times 10^3$ psi)	(psi)	- - - - - (%) - - - - -	
Resin types[b]					
8% UF	(2,187) B	(233) B	(51) B	(27) A	(98) A
2.5% MDI	(2,542) B A	(263) B A	(113) A	(18) B	(33) B
1% MDI/4% UF	(3,458) A	(346) A	(106) A	(17) B	(26) B
Fiber combinations[c]					
100% Tallow	(3,430) A	(298) A	(109) A	(25) A	(71) A
75% T:25% B	(3,020) A	(268) A	(108) A	(22) A	(55) A
50% T:50% B	(3,022) A	(294) A	(92) A	(20) A	(52) A
25% T:75% B	(2,506) A B	(307) A	(77) A	(19) A	(49) A
100% Bagasse	(1,635) B	(236) A	(62) A	(18) A	(38) A

[a] In comparisons of experimental means within different resin and fiber types applied, means followed by the same letter are not significantly different.

[b] UF = urea formaldehyde resin; MDI = 4,4'-diphenylmethane diisocyanate.

[c] T = Chinese tallow tree fibers; B = bagasse fibers.

Effect of MC and MDI application levels on bending strength and stiffness development

Table 2 shows that 100 percent bagasse fibers with 2.5 percent MDI yielded extremely low mechanical and physical properties compared with the other fiber combinations and 2.5 percent MDI or 1 percent MDI and 4 percent UF. This finding indicates that the bagasse furnish MC of the 2.5 percent MDI panels was too low. The performance of the different adhesive systems can be partly attributed to the different solid contents of each adhesive and the moisture addition to the furnish that comes from the adhesive. The amino-based adhesive (UF resin) has a 60 percent solids content. When 8 percent UF was applied, 6 percent of additional MC was consequently involved in the composite formulation and similarly 3 percent MC with 4 percent UF. The 3 percent addition of MC into the composite system influenced mechanical properties due to increased functionality of the MDI. Also, the amount of resin applied may be insufficient. Therefore, a small experiment was designed as a result of these findings to more thoroughly evaluate the influence of bagasse furnish MC when using a MDI resin on panel properties.

Increased furnish MC from 0 to 8 percent provided increased mechanical performances of bagasse-based MDF (**Fig. 1**). MC of the furnish and additional moisture from the different resin applications was one of the significant factors for the mechanical property development of the panels. A 63 percent increase in MOR and 30 percent in MOE was achieved with 8 percent furnish MC as compared to 0 percent MC (**Fig. 1a**). Eight percent MC in the bagasse fibers provided better mechanical and physical properties than fibers with

Table 4. — ANOVA table of the effects of fiber and resin types on mechanical/physical properties of agrofiber-based composites at α = 0.05 (95% confidence interval).[a]

	Source		n	DF	F-value	Pr > F
MOR	Model		47	14	18.14	< 0.0001
		Resin		2	38.12	< 0.0001
		Fcom		4	26.28	< 0.0001
		Resin*Fcom		8	9.08	< 0.0001
	Error			32		
	Total			46		
MOE	Model		47	14	11.06	< 0.0001
		Resin		2	46.10	< 0.0001
		Fcom		4	6.41	0.0007
		Resin*Fcom		8	4.63	0.0008
	Error			32		
	Total			46		
IB	Model		47	14	31.55	< 0.0001
		Resin		2	100.09	< 0.0001
		Fcom		4	23.62	< 0.0001
		Resin*Fcom		8	18.38	< 0.0001
	Error			32		
	Total			46		
TS	Model		47	14	31.44	< 0.0001
		Resin		2	116.72	< 0.0001
		Fcom		4	12.60	< 0.0001
		Resin*Fcom		8	19.54	< 0.0001
	Error			32		
	Total			46		
WA	Model		47	14	57.44	< 0.0001
		Resin		2	295.44	< 0.0001
		Fcom		4	11.360	< 0.0001
		Resin*Fcom		8	20.66	< 0.0001
	Error			32		
	Total			46		

[a] n = population size; MOR = modulus of rupture; MOE = modulus of elasticity; IB = internal bond strength; TS = thickness swelling; WA = water absorption; Fcom = fiber combinations.

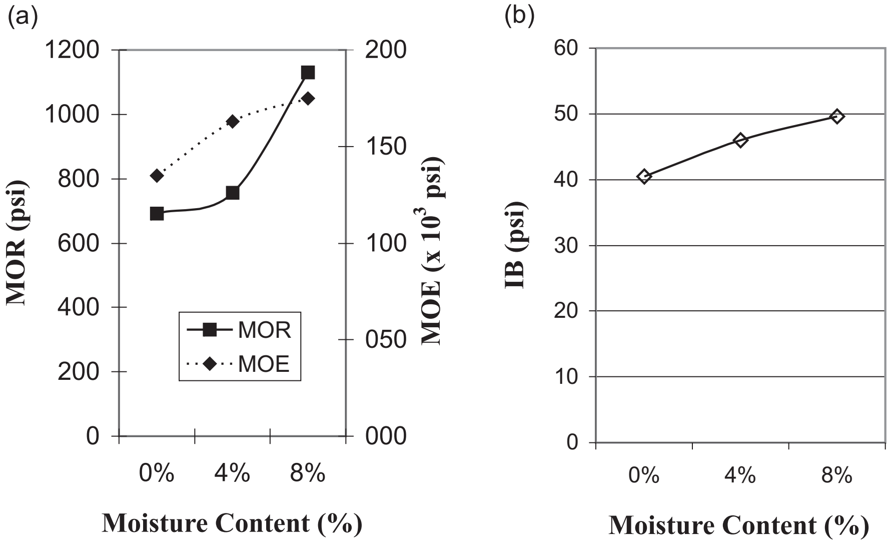

Figure 1. — Influence of MC on the mechanical properties of MDF made from bagasse fibers and 2.5 percent MDI.

0 percent and 4 percent MC. This result indicates that some drying costs could be saved in commercial production. The increased MC provided an enhanced functionality to the MDI. Increased functionality was also achieved with greater reactive groups with NCO/OH ratios and had a greater elastic modulus value, which is attributed to the higher crosslink densities in those samples (Chiou and Schoen 2002). However, IB test results indicate that there is not a statistically significant difference with MC changes (**Fig. 1b**).

Figure 2a shows that increased resin content substantially influenced the development of MOR and MOE. **Figure 2a** also shows that less than 3.5 percent MDI application is insufficient to achieve satisfactory mechanical performance with bagasse-based fibers. Additionally, the 1 percent MDI and 4 percent UF resin system with bagasse fibers performed as well as 4.5 percent MDI for bending strength and as well as 3.5 percent MDI for bending stiffness. IB strength from bagasse fibers and 1 percent MDI and 4 percent UF mixed resin combination was better than 3.5 percent MDI and slightly less than 4.5 percent MDI (**Fig. 2b**). There was also no statistically significant difference between 2.5 percent and 3.5 percent MDI usage on IB strength of bagasse-based composites. Therefore, MC and resin amount play an important role in the mechanical performances of bagasse-based MDF.

Since the MDF made from 4.5 percent MDI and 8 percent MC of bagasse fibers met the ANSI property requirements for nominal thickness of 13/16 inch (ANSI 1993), these findings have economic implications for the panel industry. As of April 2003, isocyanate and UF were selling for approximately $US 0.85/lb. and $US 0.12/lb., respectively. Therefore, the mixed resin system could be used to produce acceptable panels at 34 percent of the expense of panels made with 4.5 percent MDI.

Conclusions

The objectives of this study were to evaluate the influence of fiber mixing types and various resin combinations on the physical and mechanical properties of MDF. The influence of furnish MC and three different levels of MDI on the mechanical property development of panels made from bagasse fibers were

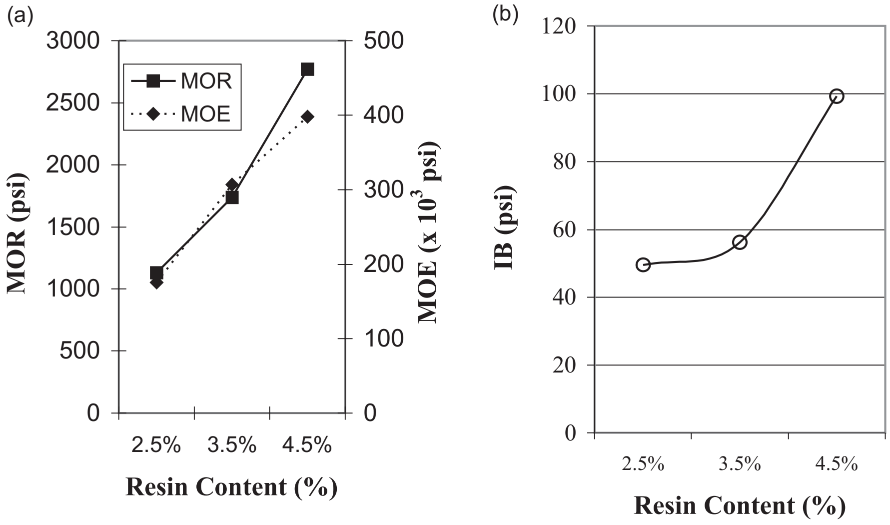

Figure 2. — Mechanical property changes with the increased resin contents of MDF manufactured from bagasse fibers with 8 percent MC.

also evaluated. Based on this research, the following conclusions can be drawn:

1. Mechanical properties of MDF made from *Sapium* fibers and 2.5 percent MDI were statistically superior to the bagasse fibers. However, this finding was not true for the measured physical properties.
2. MDF made from *Sapium* and bagasse fiber combinations of 50%:50% and 25%:75% provided better or equal mechanical and physical performance than other fiber combinations with maximum bagasse fiber utilization.
3. The mixed resin formulation (1% MDI and 4% UF) resulted in equal or better property values and possibly up to 66 percent lower resin cost compared to the 4.5 percent MDI system.
4. Panel mechanical and physical property values are strongly related to the furnish MC, moisture addition from the adhesive, and resin content.

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