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Properties of medium density fiberboards made from renewable biomass

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Abstract

The goal of this study was to determine the comparative properties of dry-formed medium density fiberboards (MDF) made from renewable biomass (wheat and soybean straw) and those from conventional soft wood fiber. The MDF properties evaluated were modulus of elasticity, modulus of rupture, internal bond strength, thickness swell, and screw holding capacity. The results show that MDF made from wheat straw fiber and soy straw fiber have weaker mechanical and water resistance properties than those made from softwood fiber. Soybean straw is comparable to wheat straw in terms of both mechanical and water resistance properties to make MDF. Water resistance of MDF decreased drastically with increasing straw fiber composition. Wheat straw fiber and soybean straw fiber should be physically or chemically treated to increase their water resistance property for MDF production.

Keywords: Ag-fiber; Wheat straw; Soybean straw; Fiberboard property; Water resistance

1. Introduction

Fiberboard—structural and decorative—is a fibrous-felted, homogeneous panel made from lignocellulosic fibers, combined with a synthetic resin or other suitable bonding system, and then bonded together under heat and pressure (ANSI Standards, 1994). Additives may be introduced during manufacturing to improve certain properties. Fiberboards are classified by density. A fiberboard with specific gravity between 0.50 and 0.80 (density between 31 and 50 lb/ft^3) is classified as medium density fiberboard (MDF) and a fiberboard with specific gravity greater than 0.80 (density greater than 50 lb/ft^3) is classified as hardboard (ASTM Standards D1554-1986). Fiberboards are manufactured primarily for use as panels, insulation, and cover materials in buildings and construction where flat sheets of moderate strength are required. The furniture industry is by far the dominant fiberboard market. They are also used to a considerable extent as components in doors, cabinets, cupboards, and millwork (FAO, 1958). Fiberboard frequently takes the place of solid wood, plywood, and particleboard for many furniture applications. Comparing to particleboard, overlaying with sheet materials and veneering, fiberboard has tight edges that need not be banded and can be routed and molded like solid wood (Seidl, 1966). The potential use of fiberboard in other interior and exterior markets such as moldings, exterior trim, and pallet decking has been explored by the industry and the market for fiberboard is fast expanding. The forest products industry in North American traditionally uses sawmill residues and small round logs as raw materials to manufacture fiberboard. However, growing concern about the environment has led to changes of forest management practices, resulting in significant reduction in wood harvest from our national forests in the midst of growing demands. Increasing import of timber and fiber supply is only a temporary solution. We must consider the prospects for developing new feedstock sources for fiberboard production. There is a clear potential for the use of agricultural fiber

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in manufacturing what have traditionally been wood-based products (Bowyer, 1995; Clancy-Hepturn, 1998). It has been estimated that 400 million dry tons of crop residues are annually produced in the United States (DOE, 2003). The literature review by Youngquist and co-workers (Youngquist et al., 1994) cited 1165 research reports worldwide on use of non-wood plant fibers for building materials and panel products from 1913 to 1993. Only two papers reported the use of soybean straw as raw material. Wheat straw particle composites have already established a niche market in the composite products (Anderson, 1995). The use of agricultural fiber for pulp and panel composite materials is commonplace in many parts of the world, but relatively rare in North America. The North American trend, however, seems to be reversing. Since 1995, there has been a proliferation of new manufacturing facilities in Canada and US to produce composite panels from agricultural residues. Most of these manufacturing plants produce particleboard from wheat straw, but soybean stover has not been considered. Because they contain cutin, a waxy substance, straw particles cannot be bonded with conventional adhesives such as urea–formaldehyde (UF) or phenol–formaldehyde (PF). Currently, isocyanate-based adhesives, such as polymeric diphenylmethane diisocyanate (MDI), are exclusively used to bind straw particleboards. MDI is much more expensive than the conventional PF or UF resin. Whether we can make fiberboard from renewable biomass using conventional UF resin is one question addressed in this study.

The objectives of this study were to produce MDF from wheat and soybean straws and investigate the comparative mechanical and water resistance properties of MDF made from soybean straw fiber, wheat straw fiber, and soft wood fiber, which were bonded with conventional urea–formaldehyde resin.

2. Methods

2.1. Experimental design and materials

The experimental design was a factorial arrangement of treatments conducted in a completely randomized block design with sampling and subsampling. The outline of the experimental design is presented in Table 1. Eighteen treatments were formulated as:

$$\text{Treatments} = 3 \text{ adhesive level} \times 2 \text{ ag-fiber type} \times 3 \text{ fiber composition}$$

Table 1
Experimental design

Factors	Factor values	Block (repetition)	Sample	Subsample
Adhesive level	6%, 9%, 12%			
Ag-fiber type	Soy straw, wheat straw	2	2	2
Wood fiber/ ag-fiber composition (%)	100/0, 50/50, 0/100			

Two batches (blocks) of MDF were produced for each treatment and two fiberboards (samples) were made for each batch. A total of 72 MDFs were produced for this research. Two subsamples were taken from each board for each property evaluated.

A conventional urea–formaldehyde adhesive (WC-10) was obtained from Borden Chemical, Inc. (Columbus, Ohio). The adhesive levels were set at 6%, 9%, and 12%, expressed as a percentage of adhesive solid weight based on the oven-dried fiber weight. The adhesive level range extended slightly higher and lower than the levels used in the industry.

A pressure-refined industrial fiberboard furnish consisting of pure Ponderosa pine softwood fiber was obtained from Pella Inc. (Pella, Iowa) and used as control fiber source. The dry-basis moisture content of the softwood furnish was 3.26%. Fibers from biomass were processed at the Center for Crop Utilization Research, Iowa State University. The raw straw was hammer-milled then soaked in tap water overnight. The soaked straw was then fiberized (pulped) by using an atmospheric Sprout-Bauer refiner with directional plates (Model 12 D.M. Sprout-Bauer Inc.). Fiberization of wheat straw and soybean straw at atmospheric pressure was carried out by passing the damp milled straw along with hot running water at 60 °C through the Sprout-Bauer refiner's rotating plates. The plates were set 0.127 mm (0.005 in.) apart. The pulps were collected, pre-dried, and preconditioned by passing through an electric vacuum blower (AirStream-II, McCulloch Corporation, Tucson, AZ) to break up fiber agglomeration. The drying process was completed in a convective oven, and then the final moisture content of the fibers was determined. The dry-basis moisture content of the ag-fibers ranged from 3.85% to 11.3%. The wood fiber was the control to compare with different compositions of wood fiber/ag-fiber, expressed as percentage of oven-dried fiber weight and formulated at compositions of 100/0, 50/50, and 0/100.

2.2. MDF production

Enough fiber furnishes to make two 250 mm × 350 mm × 12.5 mm thick (10 in. × 14 in. × 1/2 in.) MDF boards at a target specific gravity of 0.75 was weighed and placed into a drum blend. While being tumbled in the rotating drum blend, the furnish was first sprayed with 1% wax emulsion (EW 403H, Borden Chemical Inc., Columbus, Ohio) based on dry fiber weight as sizing to reduce water absorption, followed by spraying an appropriate level of urea–formaldehyde resin depending on the treatment. The atomizing air pressure and the liquid pressure for urea–formaldehyde resin were 240 kPa (35 psi) and 140 kPa (20 psi) respectively. Minor agglomeration of fibers was observed.

A pre-calculated amount of furnish was then hand-felted into a 250 mm × 350 mm (10 in. × 14 in.) forming box and pre-pressed into a mat. The mat was then hot-pressed using a Wabash Hydraulic Press (Model 50-182TMAC, Wabash Metal Products Company, Inc.) into a target thickness of 12.7 mm (1/2 in.) guided by two rectangular steel stops. The boards were first pressed at 138 °C (280 °F) to a maximum pressure of 65,500 kPa (9500 psi) for 2 min. The pressure was then gradually released resulting in a total press cycle time of 7 min. After hot pressing, all boards were cooled at room temperature followed by trimming the rough edges of the boards.

2.3. MDF evaluation

After being conditioned in an environment of 27 °C and 55% relative humidity for two weeks, the boards were trimmed to 250 mm × 350 mm (9 in. × 14 in.). The MDFs were tested according to the standard of ASTM D1037-96a (standard test methods for evaluating properties of wood-base fiber and particle panel materials). Modifications were made to the size of the test specimen due to the small board size. The MDF properties determined were specific gravity (SG), modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IB), thickness swell (TS), and screw-holding capacities (SH) in the face and edge. Static bending test was performed on a Sintech 2/D universal testing machine (Sintech Inc., Raleigh, NC) to calculate MOE and MOR. The internal bond strength was determined by testing tensile strength perpendicular to surface. Twenty-four-hour soaking test was employed to obtain thickness swell data. A direct screw withdrawal test was used to evaluate the screw holding capacities in the face and edge. The procedures of the tests are detailed in the ASTM Standard (D1037-96a). The specimens for each test were cut as illustrated in Fig. 1. Multifactor analysis of variance of the test data was conducted in SAS System (SAS Institute Inc., Cary, NC). Scanning electron micrographs (SEM) of the fiber furnishes and board samples were obtained using a JEOL-5800LV SEM machine (JEOL Inc., Japan) at Iowa State University, in order to gain some insight of structure–function relationship.

3. Results and discussion

The suitability of straws for fiberboard production can be explained by fiber length, cellulose content, and portion of lumen. Technologically valuable fibers are long, thick in cell wall, rich in cellulose, and low in lumen. When comparing straw stalk with either softwoods or hardwoods, the

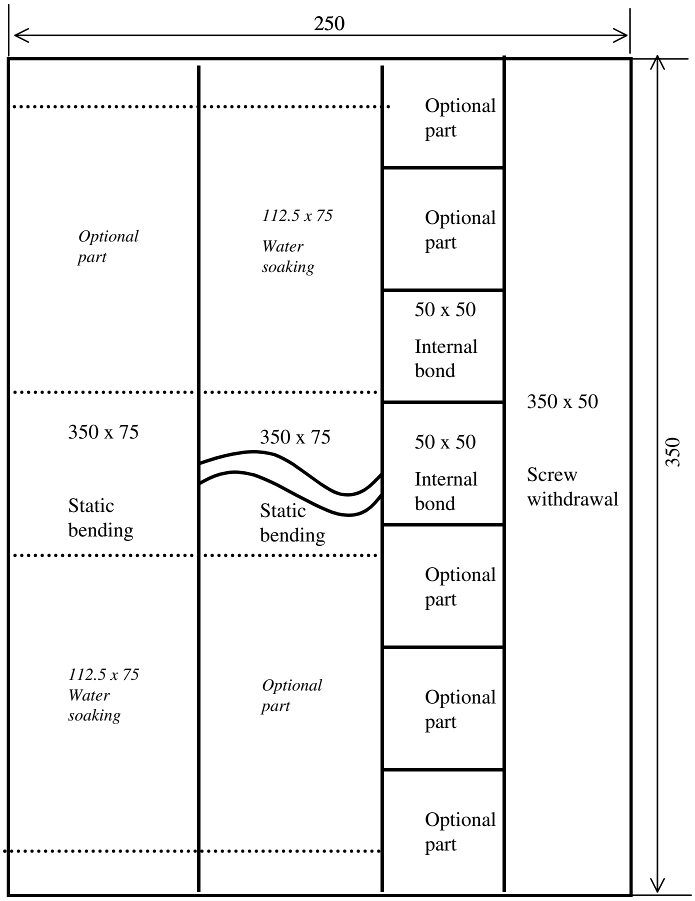


Fig. 1. Test specimen cutting pattern diagram. All dimensions are in millimeter. *Note:* Due to the limitation of board size, the broken specimen after static bending test was further trimmed for water soaking test. This is indicated by dotted lines and italic font.

former emerges technologically inferior. The morphology of the three fiber types is shown in Fig. 2. Wood fiber is observed thicker and longer than the straw fibers, consistent with the findings of another researcher (Wong, 1995). Undesirable pith materials are visible in the straw fiber furnishes. However, one must consider that a fiberboard is a composite. Its performance depends on the strength of its constituent units as well as their geometries and unit-to-unit bonding. It is in the latter two properties where straws may have advantages over wood.

The mean values of properties for the 18 treatments are presented graphically in Figs. 3–8 to allow a quick comparison of the effects of adhesive and fibers on the MDF properties. Generally, board properties improved with increasing adhesive levels and it is obvious that MDFs made from ag-fibers has much weaker water resistance than those made from wood fiber. Mixed effects can be observed when comparing the properties of the treatments with soy fiber to the corresponding treatments with wheat fiber.

The contrasts of main effects of the three factors on MDF properties are analyzed in the following two subsections. Since board density affects the board properties, the contrasts of the specific gravity of MDF by factors were first conducted and presented in Table 2. Although the actual specific gravities only deviated slightly from the target, statistical differences in specific gravity were caused by adhesive level and ag-fiber composition (Table 2). It has been shown that composite panel properties changed with density linearly (Steidl et al., 2003) or nonlinearly (Kelly, 1977). To have a fair comparison, the MDF properties were first linearly projected (normalized) based on the target specific gravity of 0.75. This linear normalization was reasonable since it was done over a very small range of

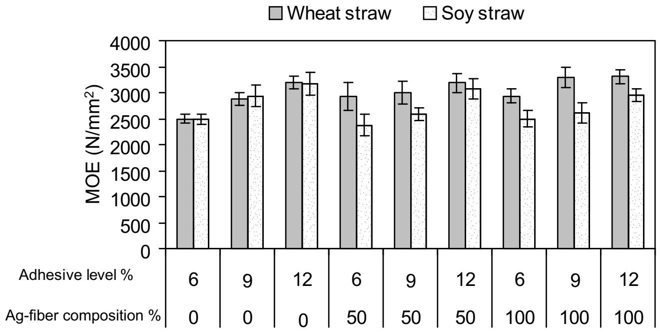


Fig. 3. Mean modulus of elasticity (MOE) of each treatment.

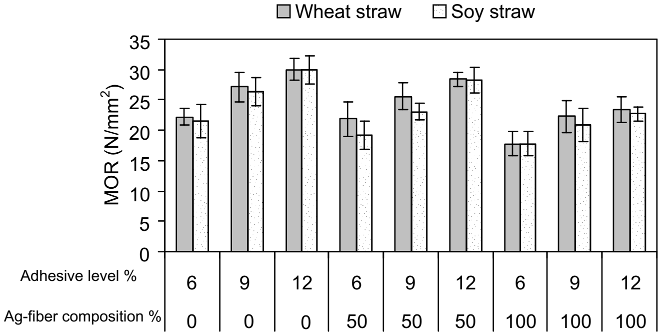
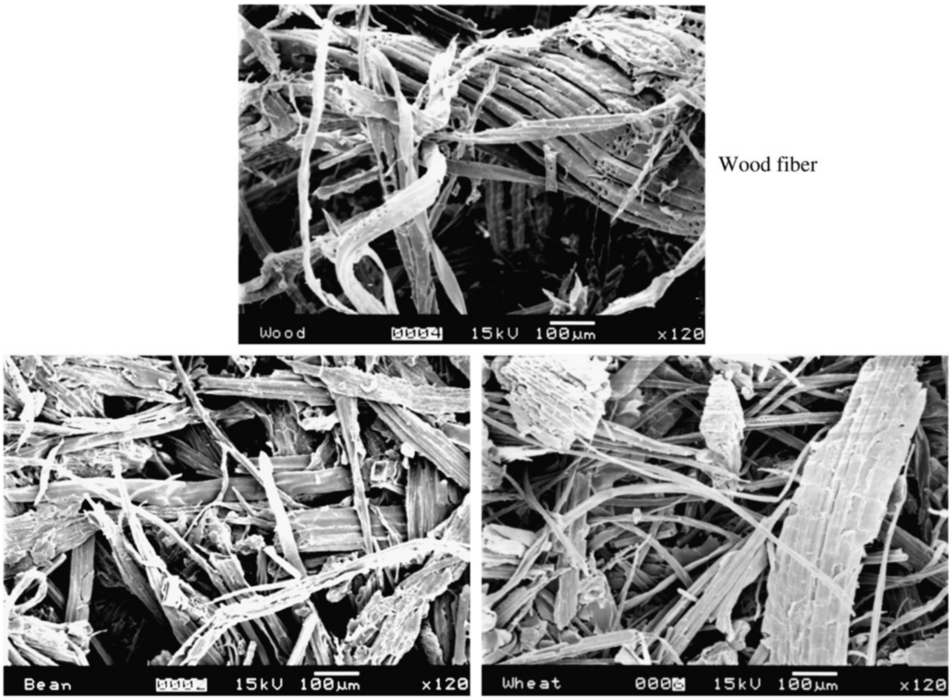


Fig. 4. Mean modulus of rupture (MOR) of each treatment.



Wood fiber

Soy straw fiber

Wheat straw fiber

Fig. 2. Scanning electron micrographs of fiber furnishes.

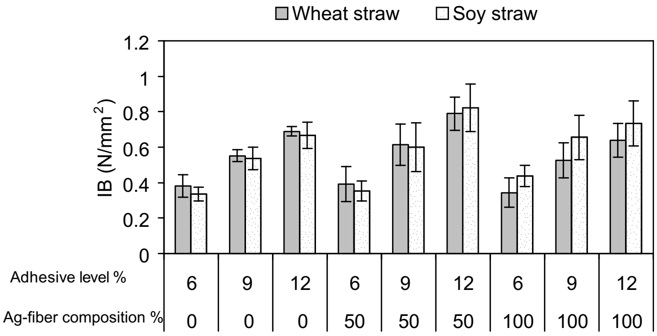


Fig. 5. Mean internal bond strength (IB) of each treatment.

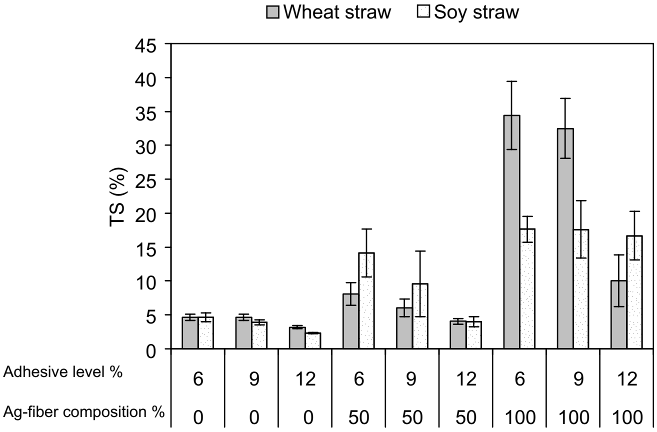


Fig. 6. Mean thickness swell (TS) of each treatment.

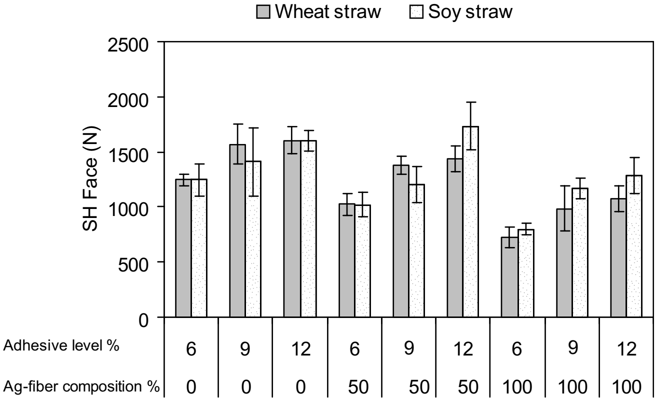


Fig. 7. Mean screw-holding capacity in face (SH face) of each treatment.

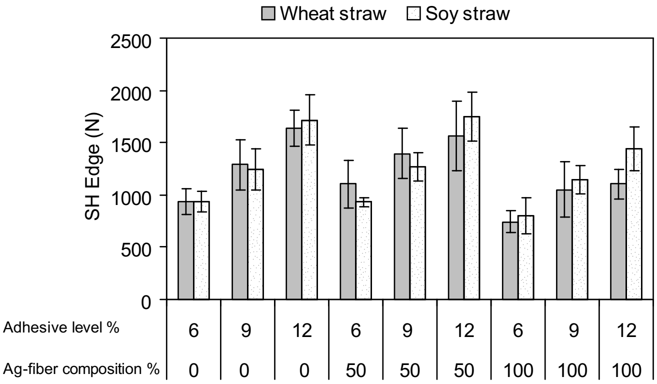


Fig. 8. Mean screw-holding capacity in edge (SH edge) of each treatment.

specific gravity. The normalized main effect values are pooled means cross all other factors. All the mean contrasts were conducted using the Tukey multiple comparison procedure at the significance level $\alpha = 0.1$.

3.1. *Effect of adhesive level*

The main effect of adhesive level was summarized in Table 3. The adhesive level was significant for every tested property except for thickness swell between 6% and 9%. All the properties improved with the increase of adhesive level.

3.2. *Effect of fibers*

The main effect of the ag-fiber type on the properties of MDF is presented in Table 4. With an exception for MOE, soy straw fiber and wheat straw fiber make MDF with comparable properties. Wheat straw fiber resulted in significantly higher MOE, consistent with our observation during the test. This information is useful when a high modulus of elasticity is required in application.

The ag-fiber composition (Table 5) had significant effects on modulus of rupture, thickness swell, and screw holding capacities. All the aforementioned properties became worse with the increase of ag-fiber content. Especially, thickness swell increased drastically with the increasing ag-fiber content. Wood fiber provided much better water resistance. On the other hand, modulus of elasticity and internal bond strength are insensitive to the change of ag-fiber composition.

Fibers from agricultural residues such as wheat straw and soy straw are shorter than soft wood fiber. Paper made from ag-fibers has lower tear strength (Schellenberger, 1995). This might explain why screw-holding capacities decreased as the ag-fiber content increased since the failure

Table 2
Contrasts of the specific gravity of MDF by factors

Adhesive level (%)	Specific gravity	Ag-fiber type	Specific gravity	Ag-fiber composition (%)	Specific gravity
6	0.78333 a	Soy straw	0.79014 a	0	0.77750 a
9	0.78271 a	Wheat straw	0.78486 a	50	0.78208 a
12	0.79646 b			100	0.80292 b

Means with different letter groupings in the same column are significantly different at 90% confidence level.

Table 3
Contrasts of the effects of adhesive level on the properties of MDF

Adhesive level (%)	MOE (N/mm^2)	MOR (N/mm^2)	IB (N/mm^2)	TS (%)	SH face (N)	SH edge (N)
6	2504.6 a	19.235 a	0.35740 a	13.287 a	969.8 a	869.1 a
9	2763.3 b	23.208 b	0.55608 b	11.766 a	1230.7 b	1182.8 b
12	2969.5 c	25.618 c	0.68179 c	6.249 b	1373.8 c	1446.5 c

Means with different letter groupings are significantly different at 90% confidence level.

Table 4
Contrasts of the effects of ag-fiber type on the properties of MDF

Ag-fiber type	MOE (N/mm^2)	MOR (N/mm^2)	IB (N/mm^2)	TS (%)	SH face (N)	SH edge (N)
Soy straw	2603.0 a	22.148 a	0.54068 a	9.489 a	1209.0 a	1184.8 a
Wheat straw	2888.6 b	23.226 a	0.52283 a	11.379 a	1173.9 a	1147.5 a

Means with different letter groupings are significantly different at 90% confidence level.

in those tests is mainly due to tear force. The MOR test involves both tear and shear forces. The fact that shorter fibers have more surface area requiring more adhesive further explains the weakening of MOR with increasing content of short ag-fibers.

A correlation analysis was also performed among the properties, fiber composition and adhesive level. The correlation relationship is expressed in Pearson linear correlation coefficients and is shown in Table 6. The upper number in a cell of Table 6 is Pearson linear correlation coefficient and the lower number in a cell is the significance level for testing the null hypothesis that the corresponding correlation coefficient is zero. It is evident from Table 6 that correlation does exist between structure/composition and properties. The comparatively high correlation coefficients (>0.5) are underlined. Ag-fiber composition is most highly correlated with thickness swell. On the other hand, the adhesive level is highly correlated with every tested property except for thickness swell. This indicates that ag-fiber composition instead of adhesive level is the main cause of increased thickness swell. Other high correlation coefficients, such as those between screw-holding capacities and MOR or IB, also support the results of the statistical contrasts.

The cut surface SEM micrographs of MDFs made from pure wood fiber, pure wheat straw fiber, and pure soy straw

Table 5
Contrasts of the effects of fiber composition on the properties of MDF

Ag-fiber composition (%)	MOE (N/mm^2)	MOR (N/mm^2)	IB (N/mm^2)	TS (%)	SH face (N)	SH edge (N)
0	2755.3 a	25.233 a	0.50791 a	3.761 a	1392.9 a	1245.3 a
50	2737.8 a	23.401 b	0.56937 a	7.357 b	1243.3 b	1276.3 a
100	2744.4 a	19.427 c	0.51799 a	20.184 c	938.1 c	976.9 b

Means with different letter groupings are significantly different at 90% confidence level.

Table 6
Matrix of correlation coefficients

	MOE	MOR	IB	TS	SH face	SH edge	Adhesive level	Ag-fiber composition
MOE	1.000 0.0	–	–	–	–	–	–	–
MOR	$\underline{0.658}$ 0.0001	1.000 0.0	–	–	–	–	–	–
IB	0.423 0.0001	$\underline{0.512}$ 0.0001	1.000 0.0	–	–	–	–	–
TS	−0.105 0.004	$\underline{-0.514}$ 0.0001	−0.239 0.0009	1.000 0.0	–	–	–	–
SH face	0.312 0.0001	$\underline{0.719}$ 0.0001	$\underline{0.574}$ 0.0001	$\underline{-0.639}$ 0.0001	1.000 0.0	–	–	–
SH edge	0.472 0.0001	$\underline{0.716}$ 0.0001	$\underline{0.705}$ 0.0001	−0.474 0.0001	$\underline{0.731}$ 0.0001	1.000 0.0	–	–
Adhesive level	$\underline{0.583}$ 0.0001	$\underline{0.636}$ 0.0001	$\underline{0.769}$ 0.0001	−0.261 0.0001	$\underline{0.597}$ 0.0001	$\underline{0.719}$ 0.0001	1.000 0.0	–
Ag-fiber composition	0.084 0.337	−0.496 0.0256	0.065 0.1101	$\underline{0.618}$ 0.0001	$\underline{-0.581}$ 0.0001	−0.290 0.4421	0.000 1.0	1.000 0.0

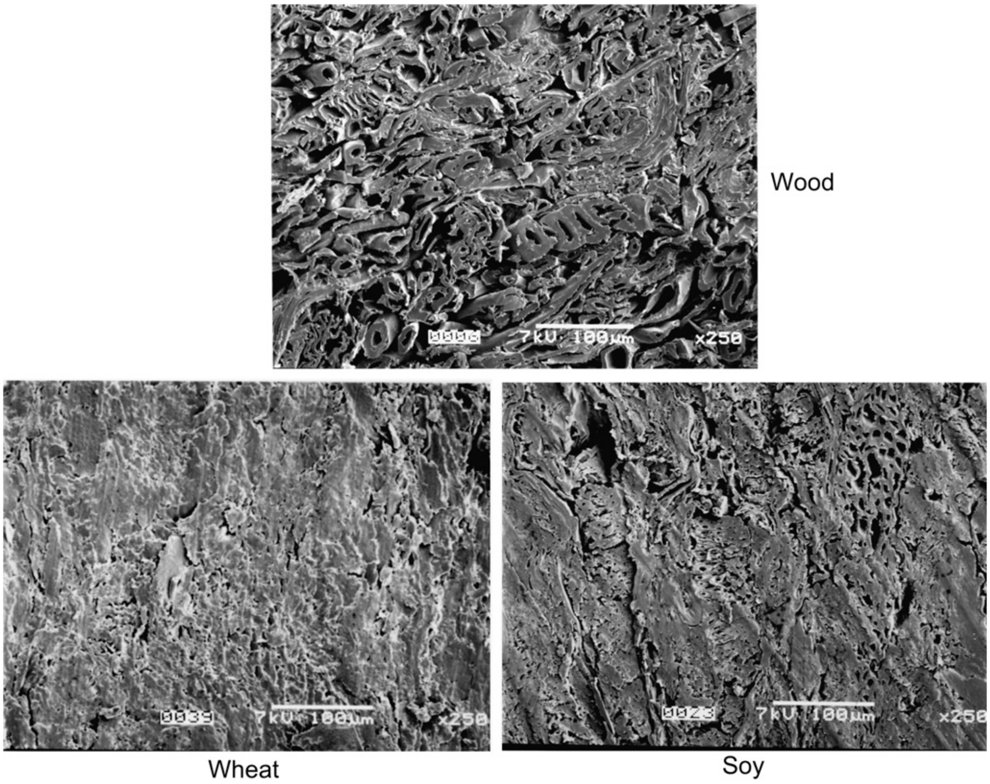


Fig. 9. Scanning electron micrographs of cut surfaces of MDF made from the three fiber types.

fiber are shown in Fig. 9. It can be observed from the micrographs that the hollow structure of all wheat straw fibers and most of soy straw fibers collapsed under heat and pressure during the hot pressing. Wood fiber collapsed to a much smaller degree. These observations indicated that the cell wall of wood fiber is thicker than that of wheat straw fiber and soy straw fiber and soy straw fiber has a thicker cell wall than wheat straw. The collapsed thin-walled fiber could lead to more intimate contacts and therefore better interfiber bonding and compacting. This was also reflected in greater specific gravity of boards made from ag-fibers (Table 2). On the other hand, the collapse of the cell walls caused more mechanical damage that reduced MOR and increased thickness swell.

4. Conclusions

Dry process was employed to produce medium density fiberboards from renewable sources. The variations of board properties due to fiber composition and adhesive level were studied. The following conclusions can be drawn. All the tested MDF properties improved with the increase of adhesive level with only one exception for thickness swell between the adhesive levels of 6% and 9%; wheat straw and soybean straw are comparable to each other in making MDF in terms of mechanical and water resistance properties; wheat straw fiber resulted in higher modulus of elasticity than soy straw fiber; wheat straw fiber and soy straw fiber are inferior to soft wood fiber in making MDF, but these renewable and environmentally friendly feedstocks are promising alternatives to the declining wood supply; the thickness swell of MDF increases drastically with increasing percentages of wheat straw fiber and soy straw fiber; fibers rather than adhesives were the major contributors to thickness swell; wheat straw fiber and soy straw fiber should be physically or chemically treated to increase their water resistance property.

It is an unanswered question if the fiberization process employed in this study successfully washed out most of the cuticle substances in the wheat straw and soy straw so that they could be bonded with UF. Further research is needed to investigate how much the chemical and morphological characteristics or their interactions of wheat straw and soy straw fibers would influence fiberboard properties.

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