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Low density particleboard from wheat straw and corn pith

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Abstract

Agricultural residuals, such as wheat straw and corn stalks, are the renewable resources that can be utilized as raw materials for making particleboard. The objective of this research was to characterize the tensile strength (TS) and compressive strength (CS) of low-density particleboard made from wheat straw and corn stalk pith as affected by soy protein-based adhesive, press time, straw particle size, and particleboard density. A particleboard derived from 70% of wheat straw blended with 4% of methylene diphenyl diisocyanate (MDI) and 30% of corn stalk pith blended with 10% of sodium hydroxide (NaOH)-modified soy protein isolate (SPI) had the highest TS and CS. The results showed that NaOH-modified SPI increased the TS and CS of the particleboard. The TS and CS values of the particleboard with larger straw particles were greater than those of the particleboard with small and large straw particles together. The TS and CS of the particleboard increased as density increased. TS and CS increased from 2.11 MPa and 3.01 MPa to 3.24 MPa and 4.29 MPa, respectively, and the density increased from 0.30–0.34 g/cm^3. The changes in the equilibrium moisture content and dimension of particleboard were less than 9.0% and 0.25%, respectively, at conditions of the temperature from 27 to 50 °C and relative humidity from 35–90%. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Wheat straw; Corn stalk pith; Particleboard; Soy protein adhesives; Mechanical property

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1. Introduction

Agricultural fibers, such as straw and plant stalks, have been considered as renewable alternatives for making particleboard, which would ease the huge demand for wood (Kozlowski and Helwig, 1998). About 280 million metric tons of agricultural fibers are produced annually in the United States (Gallagher and Johnson, 1995). Most of these fibers are burned after harvest and may cause environmental problems. Among these fibers, 28% are corn stalks and about 35% are wheat straw (Suiter, 1993; Gallagher and Johnson, 1995).

Studies on high-density particleboard utilizing agricultural fibers include wheat straw (Dalen and Shorma, 1996; Hague et al., 1998; Han et al., 1998), sunflower stalk (Khristova et al., 1998), rice straw, cotton stalk, sugar cane bagasse, flax (Heslop, 1997), and maize husk and cob (Sam-

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pathrajan et al., 1992). These products have found applications in floor, wall and ceiling panels, office dividers, bulletin boards, furniture, cabinets, counter tops, and desk tops (Kozlowski and Helwig, 1998). Limited information is available for low-density straw particleboard, which may have potential application in insulation, packaging, or lightweight core materials.

Particleboard performance is mostly related to the properties of adhesives and their compatibility with fibers. Urea-formaldehyde (UF) has been the major adhesives for wood-based particleboard, but its adhesion to wheat straw was poor due to the wax components on the straw surface (Heslop, 1997). Wheat straw particleboard prepared with methylene diphenyl diisocyanate (MDI) resin had mechanical properties 3–10 times greater than straw particleboard with UF resin (Heslop, 1997). Soy protein or modified soy protein can be also used as adhesives in making particleboard (Kalapathy et al., 1995; Hettiarachchy et al., 1995; Clay et al., 1996; Kriebich, 1996; Mo et al., 2000). Soy protein gluing is based on the protein molecules dispersing and unfolding in solution. The unfolded molecules increase the contact area and adhesion onto other surfaces, and become entangled with each other during the curing process to retain bonding strength (Lambuth, 1994). Several methods such as heat, acid/alkali, organic solvents, detergents, and urea have been used to modify protein to promote the unfolding and bonding strength (Wu and Inglet, 1974). Alkali, such as sodium hydroxide (NaOH), has been the most common chemical used to increase the gluing strength and water resistance of soy protein-based adhesives. The objective of this research was to characterize the tensile strength (TS) and compressive strength (CS) of low-density particleboard made from wheat straw and corn stalk pith as affected by soy protein-based adhesive, press time, straw particle size, and particleboard density.

2. Materials and methods

Wheat straw and corn stalk pith were used as fiber particles. Wheat straw with a particle size ranging from 1–10 mm was provided by a local company. Corn stalk pith were made from fresh corn stalks. The fresh corn stalk was harvested from a local farm and then dried in an air oven at 50 °C to reduce moisture content to about 10–15%. The peels of the corn stalks were removed by hands and the piths were ground into small particles in the range of 1.7–4.0 mm. Soy protein isolate (SPI) (PRO-Fam 970) was prepared by acid precipitation and contained more than 90% protein (dry basis) with a particle size of 90% powder passing through a US #100 mash (Archer Daniels Midland, Decatur, IL). MDI was purchased from ICI Polyurethane Group (West Deptford, NJ). NaOH, guanidine hydrochloric (GuHCl), and sodium stearoyl-2 lactylate (SSL) were obtained from Sigma Chemical Co. (St. Louis, MO).

2.1. Modification of SPI

NaOH, SSL, and GuHCI were used for SPI modification. Solutions containing 0.2% NaOH, 1% SSL, or 1M/l of GuHCI were prepared separately using distilled water at room temperature. The SPI powder was added to the solution at a ratio of 1:10 and stirred at room temperature for 2 h.

2.2. Bleaching of wheat straw

The straw particles were soaked in a solution containing 1M NaOH or 3% bleach at 50 °C for 30 min. The bleached straw was then washed thee times with 50 °C water and dried at ambient condition. Hydrophobic wax and ashes were expected to be removed partially from the straw surface by bleaching, which may enhance the bondability of the straw with SPI.

2.3. Particleboard preparation

The curing property of SPI is significantly affected by both pressure and moisture. For high-density particleboard, the curing pressure is high enough for SPI curing, and moisture content becomes less important. However, for low-density particleboard, because of low curing pressure, moisture content becomes an important factor affecting SPI curing. Preliminary test showed that raw material with initial moisture content of 40% had higher TS and CS than those with less water content. Therefore, the initial moisture content of 40% was used in this experiment. The bleached wheat straw and/or corn stalk pith was mixed with the modified SPI and/or MDI adhesives at various formulas at room temperature. The moisture content of the mixture was adjusted to 40%. This mixture was pressed into a $15.2 \times 15.2 \times 0.5$ cm^3 panel board in a hot press (Model 3890Auto "M", Carver Inc., Wabash, IN) at 140 °C and 3.0 MPa at various times. The density of the board was controlled by a mold with fixed volume. The final moisture content of the board was about 6%, which is less than equilibrium moisture content (7%) at normal temperature (27–35 °C) and low relative humidity (35%) condition.

2.4. Experimental design

2.4.1. Effect of SPI and/or MDI adhesive on TS and CS of particleboard

Preliminary test showed that particleboard with 70% of the bleached straw and 30% of the corn pith had higher TS and CS than other combinations of straw and corn pith. Therefore, a fixed ratio of straw and pith was used in this experiment. Four treatments were conducted: (A). the straw/pith mixture was blended with the unmodified SPI adhesive at a solid ratio of 1:10 (SPI:straw/pith), the mixture was dried to 40% moisture content at room temperature and then pressed; (B). the moisture content of the straw/pith mixture was adjusted to 40% and then the mixture was blended with 4% MDI adhesive; (C). the straw was blended with the unmodified SPI adhesive at a solid ratio of 1:10 (SPI:straw) and the blended straw was dried to 40% moisture content. Next the pith was adjusted to 40% moisture content and blended with 10% of MDI adhesive, and then the straw and pith were mixed at room temperature and pressed; (D). the moisture content of straw was adjusted to 40%, the straw was blended with 4% MDI adhesive, and the pith was blended with the unmodified SPI adhesive at a solid ratio of 1:10 (SPI:pith) and dried to 40% moisture content, the same procedure was followed as treatment C. Press time for all treatments was 8 min, and press temperature was 140 °C.

2.4.2. Effect of press time on TS and CS of particleboard

Four press times of 6, 8, 10, and 12 min were used. The press temperature was 140 °C, and 70% straw and 30% corn pith mixture was used. The moisture content of the straw was adjusted to 40% and then the straw was blended with 4% MDI adhesive. The pith was blended with the unmodified SPI adhesive at a solid ratio of 1:10 (SPI:pith), and then the pith was dried to 40% moisture content and mixed with the straw at room temperature and pressed.

2.4.3. Effect of straw particle size on TS and CS of particleboard

The effect of straw particle size was studied with or without small particles less than 1.7 mm in length. Press time was 8 min, press temperature was 140 °C, and 70% straw and 30% corn pith mixture was used. The straw was adjusted to 40% moisture content and then blended with 4% MDI adhesive. The pith was blended with the unmodified SPI adhesive at a solid ratio of 1:10 (SPI/pith), and then the pith was dried to 40% moisture content and mixed with the straw at room temperature and then pressed.

2.4.4. Effect of SPI modification on TS and CS of particleboard

Thee modified SPI adhesives were used in this experiment. Press time was 8 min, and press temperature was 140 °C. Particle size less than 1.7 mm was removed, and 70% straw and 30% corn pith mixture was used. The straw was adjusted to 40% moisture content and then blended with 4% MDI adhesive. The pith was blended with the modified SPI adhesives at a solid ratio of 1:10 (SPI/pith), and then the corn pith were dried to 40% moisture content and mixed with the straw at room temperature and then pressed.

2.4.5. Effect of density on TS and CS of particleboard

Five density levels of 0.30, 0.31, 0.32, 0.33, and 0.34 g/cm^3 and mixture of 70% straw and 30% corn pith were used. The same procedure described in Section 2.4.4 was used for moisture content adjustment, adhesive blending, mixing, and press. Particle size less of than 1.7 mm was removed.

2.4.6. Effect of relative humidity (RH) and temperature on equilibrium moisture content (EMC) and dimension change of particleboard

The raw material was 70% straw and 30% corn pith mixture. The same procedure described in Section 2.4.4 was used for moisture adjustment, adhesive blending, mixing, and press. Particle size less than 1.7 mm was removed. The specimens were stored in a humidity chamber (Electro-Tech Systems, Glenside, PA, model 506A) at 35, 50, 65, 80 90% RH and at 27, 35, and 50 °C temperatures. The experiment was based on a 5 × 3 factorial design.

Data were analyzed using an SAS software package (SAS, 1992 SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) and least significant difference (LSD) ($\alpha = 0.05$) were used to differentiate the treatment means. Three replicates were made for each treatment.

2.5. Measurement of TS and CS

The particleboard was cut into 3.05 × 14.73 × 0.5 cm rectangular strips for TS measurement and 2.03 × 2.54 × 0.5 cm rectangular strips for CS measurement. Before testing the specimens were preconditioned at 65% RH and 23 °C for 48 h. An Instron testing machine (model 4466, Canton, MA) was used for TS and CS determination followed by ASTM standard method (American Society for Testing and Materials, 1995). The crosshead speed was 4 mm/min for TS test and 0.5 mm/min for CS test.

2.6. Measurement of density and EMC

The density of the particleboards was calculated as the ratio of the mass of the particleboard to the volume after the particleboard were conditioned at 65% RH and 23 °C for 48 h. For EMC measurement, the specimen was removed from the humidity chamber and weighed every 24 h, then was placed back to the chamber. All specimens were monitored for weight loss every 24 h until no mass change was observed. Moisture content of specimen was determined using an oven drying method at 103 °C until an approximately constant weight was attained (American Society for Testing and Materials, 1995).

3. Results and discussions

3.1. Effect of SPI and/or MDI adhesive on TS and CS of particleboard

The TS and CS of particleboard with four resin formulas and application procedures are presented in Table 1. At constant density, the particleboard made from straw blended with MDI and

Table 1
Effect of SPI, MDI, and blending methods on tensile strength (TS) and compression strength (CS) of the particleboard made from 70% of straw and 30% of corn stalk pith at a press condition of 140 °C and 3.0 MPa for 8 min

Adhesive/blending	Density (g/cm^3)	TS (MPa)	CS (MPa)
SPI [a]	0.34	2.04 a [e]	2.25 a
MDI [b]	0.34	2.75 b	2.78 b
Straw/SPI and Pith/MDI [c]	0.34	2.15 a	2.58 b
Straw/MDI and Pith/SPI [d]	0.34	2.64 b	3.26 c

[a] SPI = the mixture of wheat straw and corn stalk pith were blended with 10% unmodified SPI.

[b] MDI = the mixture of wheat straw and corn stalk pith were blended with 4% MDI.

[c] Straw/SPI and Pith/MDI = wheat straw was blended with 10% unmodified SPI and corn stalk pith was blended with 10% MDI, respectively.

[d] Straw/MDI and Pith/SPI = wheat straw was blended with 4% MDI and corn stalk pith was blended with 10% unmodified SPI, respectively.

[e] Values within the same column followed by different letters are significantly different at $P < 0.05$.

Table 2
Effect of press time and straw particle size on tensile strength (TS) and compression strength (CS) of the particleboard

Press time (min)	Density (g/cm^3)	TS (MPa)	CS (MPa)
6	0.35 a [a]	2.46 a	2.51 a
8	0.34 b	2.64 b	3.26 c
10	0.34 b	2.69 b	2.91 b
12	0.33 c	2.64 b	3.04 b
Particle size			
With particle <1.7 mm	0.34 a	2.64 a	3.26 a
Without particle <1.7 mm	0.34 a	2.81 b	3.69 b

The particleboards were made from 70% of straw blended with 4% MDI and 30% of corn stalk pith blended with 10% unmodified SPI at press condition of 140 °C and 3.0 MPa.

[a] Values within the same column followed by different letters are significantly different at $P<0.05$.

corn stalk pith blended with SPI (treatment D) had the highest TS and CS. The particleboard with MDI only (treatment B) had the second highest CS, but the same TS as treatment D. The corn stalk pith absorbed MDI readily. At low MDI concentration, less MDI was available for the straw because of the absorption by corn stalk pith, and consequently, resulting in low cohesion during curing. Such absorption also was observed when the MDI was applied to corn stalk pith in treatment C, causing the particleboard to have lower TS and CS than those of the particleboard made in treatment D. In treatment D, MDI was not only used as adhesive, but also as a reagent reacting with SPI during hot press. The isocyanato group (–N=C=O) of MDI may react with the hydroxyl group from soybean protein to form urethane bonds, resulting in structures like straw-MDI-SPI-corn stalk pith, increasing the TS and CS of the particleboard.

3.2. Effect of press time on TS and CS of particleboard

The particleboard pressed at longer time period had lower density than the short period because the moisture content of the particleboard decreased as press time increased (Table 2). The TS of the board pressed with 6 min was low and then leveled off at about 2.6 MPa after 8 min. The particleboard pressed with 8 min had the highest CS. Mo et al. (2000) found that there was an optimum curing condition, such as temperature, pressure, and time, for SPI to cure. Soy protein would unfold at its denaturation temperature (Wold, 1970; Sun et al., 1999) and would entangle upon curing. SPI cured at optimum conditions would have strong mechanical properties. SPI over-cured, such as cured at higher temperature or for a longer time, had lower strength because SPI was thermally degraded. In this study, 8 min was needed for the SPI to cure, resulting in higher TS and CS. As press time increased, the reductions in TS and CS were not significant. The temperature used in this experiment was 140 °C, lower than the SPI's denaturation temperature at lower moisture content, so the thermal degradation of SPI was slow.

3.3. Effect of straw particle size on TS and CS of particleboard

The board prepared with straw particle size excluding the fine particles had higher TS and CS than that including the fine particles (Table 2). At a fixed mass ratio of adhesive and straw, the total surface area of straw containing fine particles was larger than that without the fine particles. In this case, the adhesive was not enough to cover the straw surface, resulting in lower TS and CS. The composite made from corn stalk pith alone is much weaker in TS and CS than that from straw alone. In the mixture of straw and corn stalk pith, the straw acted as a matrix and the corn pith acted as a filler. The large particle size straw increased the TS and CS of the particleboards.

3.4. Effect of SPI modification on TS and CS of particleboard

At constant density, the board made with the SPI modified by NaOH had the highest TS and CS (Table 3). Straw and corn stalk pith are mainly composed of cellulose, hemicellulose, lignin, and pentosan, which are rich in polar hydroxyl groups. Soy proteins also have strong polar groups, such as hydroxyl, amide, and carboxyl groups. The major molecular forces between the fibers and SPI are the interactions of polar groups. The NaOH treatment is used to break the internal hydrogen bonds of the coiled protein molecules, extensively unfold them and expose abundant available polar groups for adhesion. The protein molecules were hydrolyzed in the NaOH solution, producing peptide chain with suitable molecule weight distribution that contributed to the good bondability.

The TS and CS of the particleboards made with the SPI modified by SSL and GuHCI were even lower than that of the particleboard with the unmodified SPI. As a surfactant, the SSL was expected to enhance SPI curing strength (Mo et al., 2000). However, the board with SSL modified SPI had a larger thickness swell, which is called 'spring back' effect as described by Youngquist et al. (1986). Such spring back resulted in the formatting many small voids and reduced the TS and CS. Curing time would affect the curing strength of the SSL modified SPI, which need to be further studied. The GuHCI-modified SPI was reported to have higher adhesion strength for plywood (Sun and Bian, 1999). The result from this work was not encouraging, and not well understood. Many factors could cause such result, such as press temperature, pressure, time, difference in adherent structure, etc. Further studies need to be conducted.

Table 3
Effect of SPI modification on tensile strength (TS) and compression strength (CS) of the particleboard

Modification	Density (g/cm^3)	TS (MPa)	CS (MPa)
NaOH	0.34	3.24 a[a]	4.29 a
GuHCI	0.34	2.46 c	3.06 c
SSL	0.33	2.24 c	2.45 d
Control	0.34	2.81 b	3.69 b

The particleboards were made from 70% of straw blended with 4% MDI and 30% of corn stalk pith blended with 10% modified SPI at press condition of 140 °C and 3.0 MPa for 8 min.

[a] Values within the same column followed by different letters are significantly different at $P < 0.05$.

Table 4
Effect of density on tensile strength (TS) and compression strength (CS) of the particleboard

Density (g/cm^3)	TS (MPa)	CS (MPa)
0.34	3.24 a[a]	4.29 a
0.33	3.05 b	4.05 b
0.32	2.75 c	3.63 c
0.31	2.65 c	3.30 d
0.30	2.11 d	3.01 e

The particleboards were made from 70% of straw blended with 4% MDI and 30% of corn stalk pith blended with 10% NaOH modified SPI at press condition of 140 °C and 3.0 MPa for 8 min.

[a] Values within the same column followed by different letters are significantly different at $P < 0.05$.

3.5. Effect of density on TS and CS of particleboard

TS and CS of the particleboards increased as the density increased (Table 4). The TS and CS were significantly reduced from 3.24 and 4.29 to 2.11 and 3.01 MPa, respectively, when the density was from 0.34 to 0.30 g/cm^3. SPI was a pressure sensitive polymer, and curing strength was very low at pressure lower than 10 MPa and at low moisture content ($< 20\%$) regardless of curing temperature or time (Mo et al., 2000). The density of the particleboard was controlled using a fixed mold volume, meaning that the dimension of the particleboard was constant. To produce a lower density board, the mass of the fiber and resin mixture was lower, causing lower pressure within the composite, and consequently poor curing of SPI, resulting in lower TS and CS.

3.6. EMC and dimensional stability of particleboard

The EMC of the particleboard was affected significantly by temperature and RH (Table 5). The EMC increased as RH increased. At a constant RH, the EMC increased as temperature decreased. The EMC increased faster at higher RH from 65 to 90% than those at lower RH from 35 to 65%. The largest EMC change was about 9.0% as RH was from 35 to 90%. Temperature and RH had a significant effect on dimension

Table 5
Equilibrium moisture content (EMC) (%) of the particleboard affected as relative humidity (RH) and temperature (T)

Temperature (°C)	RH (%)				
	35	50	65	80	90
27	7.25 bc [a]	8.98 d	10.45 ef	13.89 I	16.25 j
35	7.02 b	8.25 cd	9.75 e	11.13 h	15.75 j
50	5.24 a	6.85 b	7.75 c	10.35 f	11.95 h

The particleboards were made from 70% of straw blended with 4% MDI and 30% of corn stalk pith blended with 10% NaOH-modified SPI at press condition of 140 °C and 3.0 MPa for 8 min.

[a] Values in both columns and rows followed by different letters are significantly different at $P<0.05$.

Table 6
Effect of relative humidity (RH) and temperature (T) on the dimension change of the particleboard (%)

RH (%)	27 °C			35 °C			50 °C		
	Length	Width	Thickness	Length	Width	Thickness	Length	Width	Thickness
35	−0.03 a [a]	−0.06 a	−0.07 a	−0.07 a	−0.09 a	−0.12 a	−0.16 a	−0.15 a	−0.17 a
50	−0.01 a	−0.02 b	−0.02 b	−0.04 b	−0.05 b	−0.07 b	−0.12 b	−0.11 b	−0.11 b
65	0.06 b	0.05 c	0.07 c	0.02 c	−0.01 c	0.03 c	−0.03 c	−0.05 c	−0.06 c
80	0.11 c	0.11 d	0.11 cd	0.07 d	0.05 d	0.09 d	0.01 d	0.02 d	0.02 d
90	0.17 d	0.14 d	0.16 d	0.11 e	0.08 d	0.12 d	0.06 e	0.06 e	0.08 e

The particleboards were made from 70% of straw blended with 4% MDI and 30% of corn stalk pith blended with 10% NaOH-modified SPI at press condition of 140 °C and 3.0 MPa for 8 min.

[a] Values within the same column followed by different letters are significantly different at $P<0.05$.

stability of the particleboard (Table 6). In general, the particleboard has negative linear expansion at low RH, and positive linear expansion at high RH. Dimensional changes ranged from −0.07–0.16% at 27 °C, from −0.12–0.12% at 35 °C, and from −0.17–0.08% at 50 °C in the RH range tested. The thickness swell was larger than the linear expansion of the length and width. In the thickness direction, the bonding force was the adhesion force from SPI and MDI. SPI was hydrophilic and could absorb water at higher RH, reducing bonding strength. While in the length or width direction, the large particle size straw, acting as matrix holding the composite together and resulting in a low linear expansion.

4. Conclusion

A low-density particleboard was developed from a combination of wheat straw, corn stalk pith, a modified soy protein adhesive, and a small amount of MDI. Formula and processing condition had a significant effect on TS and CS of the particleboard. The particleboard made from the corn stalk pith blended with the NaOH-modified SPI and the straw blended with MDI had the highest TS and CS. Curing pressure and initial moisture content of raw material had a significant effect on the TS and CS of the particleboards. For low-density particleboard, maximum mechanical strength was obtained from the raw material with 40% moisture content. The particleboard developed from this work may have potential application for ceiling panels, core materials, and bulletin boards.

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