Manufacturing Particleboard Using Hemp Shiv and Wood Particles with Low Free Formaldehyde Emission Urea-Formaldehyde Resin

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Abstract

In order to better use the hemp shiv in manufacturing particleboard panels, tests for determining the mechanical and physical properties of this particleboard were performed according to the Chinese standard for wood-based paneling. The results showed the following. (1) The properties of the particleboard are optimal, with a 1:1 ratio of hemp shiv to wood particles; hemp shiv and wood particles actually strengthen each other when particleboard is made from a mixture of hemp shiv and wood particles. (2) The low density and the low mechanical properties of fiber cell walls were both advantages for the hemp shiv used to manufacture the particleboard panels.

Hemp (*Cannabis sativa* L.) is an ancient plant that has been cultivated for thousands of years. Hemp yields a long, strong fiber that cannot be replicated by fibers from other plants, such as cotton, flax, jute, kenaf, or ramie. Industrial hemp is potentially useful in a number of industries; for example, hemp fiber is used to make textiles (Soljacic and Cunko 1994, Zhang et al. 2009), composites of high strength (Sawpan et al. 2011), pulp and paper (Kovacs et al. 1992), fiberboard (Pecenka et al. 2009), and heat-insulating materials (Yates 2006). The hemp seed can also be used in foods such as cake, tea with milk, nuts, and oil (House et al. 2010). Hemp cultivation requires less chemical fertilizer and pesticide than does cotton, and the crop is now grown throughout the world, particularly in Europe, Canada, and China (Karus and Vogt 2004). However, the hemp shiv (the innermost layer of the hemp stalk) is a by-product of hemp fiber, and hemp seed production and is usually burnt in fields as trash after the hemp fiber (used in textile industries mainly in China now) has been harvested. The volume of the shiv is two times more than that of the hemp fiber and four times more than that of hemp seed by weight. So, finding a use for the hemp shiv will be a key factor in promoting the development of the hemp industry. China has the largest hemp acreage in the world, with 6,700 hectares in the southwestern province of Yunnan alone in 2009. By 2015 there will likely be 1.3 million hectares of industrial hemp planted in China. At that point, Chinese dry industrial hemp-stalk output may reach 10 million tons/y. Because it is possible to make 1 m^3 of wood-based panel (at a panel density of 0.75 g/cm^3) from 1 ton of hemp stalks, if 50 percent of industrial hemp stalks were used to make hemp-stalk–based panels, 5 million m^3 of industrial hemp-stalk–based panels could be produced per year—about 20 percent of the production of the annual wood-based particleboard output in China. The production of wood-based panels in China has been the largest in the world since 2005, and it was about 209.2 million m^3 in 2011. Particleboard production was 25.6 million m^3 in 2011, and the particleboard in China was used mainly to make furniture.

On the other hand, wood costs are generally rising as the demand surpasses supply (Nikvash et al. 2010); as a result, some agricultural residues, such as wheat straw, rice straw,

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sorghum stalks, kiwi prunings, castor stalks, and industrial hemp, are currently being used or are being introduced as feedstock for pulp, paper, and composite in the wood industry (Nemli et al. 2003, Thomsen et al. 2006, Barbera et al. 2011). Therefore, determining the feasibility of using various kinds of agricultural residues for the manufacture of composites based on the characteristics of the raw materials is of great importance. Studies have been performed examining the feasibility of using hemp shiv in the manufacture of lightweight construction board (Schoepper et al. 2009) and particleboard as a raw material (Theis and Grohe 2002; Nikvash et al. 2010, 2012) and examining the influence of chemical characters on the properties of particleboard (Nikvash et al. 2013). But this information is not enough to make a hemp shiv–based panel with better properties and to better use the hemp shiv in the wood-based panel industry.

The objectives of this research were to investigate the effect of using different hemp-stalk/wood mixture ratios and to study the mechanical properties of fiber cell walls and the panel density on the properties of particleboard using urea-formaldehyde (UF) resin. As a result of this research, we will provide here suggestions for making particleboard panels with better properties.

Materials and Methods

Materials

Industrial wood particles.—We used industrial wood particles (composed of 80% *Pinus kesiya* wood and 20% other wood) with a moisture content (MC) of 3 to 5 percent, provided by the Xinfeilin Wood-Based Panel Co. Ltd., Kunming, Yunnan, China, and with the particle size shown in Table 1.

Industrial hemp shiv particles.—The industrial hemp shiv (*Cannabis sativa* L.) is called ''Yun-ma No. 1'' in China (kindly provided by Yunnan Industry Hemp Co., Ltd., Kunming, Yunnan, China) and grows to a height of about 3 to 4 m; it is 10 to 30 mm in diameter with a hollow core, and the time to maturation is 180 to 200 days. Hemp of this variety can be stored for 1 year without any decay, because the hemp stalk has excellent antibacterial properties, low density, and some special chemical composites (Zhang et al. 2009). The hemp shiv that is harvested in the summer can be stored in a dry or ventilated place for several years, so it can be used as an insulating material (Yates 2006).

UF resin.—We used UF resin adhesive at a pH of 9.0, a solid content of 60 to 61 percent, and a low free formaldehyde content of 0.12 percent (UF resin provided by Xinfeilin Wood-Based Panel Co. Ltd.). The UF is a new low-formaldehyde-emission–type resin; the emission of free formaldehyde from particleboard panels made with this type of UF is about 5.0 mg/100 g, and it can satisfy the request of E_1 grade (emission of free formaldehyde is lower than 9 mg/100 g).

Hemp shiv particle preparation

We cut the whole hemp shiv or hemp shiv from different stem parts (0 to 20, 100 to 120, 200 to 220 cm above the base of the hemp stem) to 3 to 5 cm in length, 0.5 to 1.0 cm in width, and 3 to 12 mm in thickness using a chipping machine at the Wood-Based Panel Laboratory. We then rechipped at the same location with a hogging machine to create smaller sized particles of 5 to 8 mm in length, 3 to 5 mm in width, and 2 to 3 mm in thickness, and then oven-dried the particles until they had a MC of 3 to 5 percent at a constant 100°C ± 2°C temperature; the particle sizes are shown in Table 1.

Particleboard manufacturing

We followed the project details of particleboard manufacturing methods shown in Table 2.

The mixture of hemp shiv particle/wood particle–based particleboard panels.—The hemp shiv particles and wood particles were mixed together in different ratios (hemp stalk:wood particle ratios were 0:5, 1:4, 2:3, 1:1, 3:2, 4:1, 5:0). The mixtures of particles were then blended with 12 percent liquid UF resin (because the glue mixing equipment in the laboratory is very simple and the UF resin dispersion to the particles depends mainly on the friction force between particles, some resin conglutinated on the equipment, while in the factory, the industrial wood-based particleboard with good properties can be obtained with the same UF resin, 8 percent in the middle layer and 10 percent in the surface layer), 1 percent catalyst (NH_4Cl, A. R., bought in

Table 1.—The particle size.

Raw material	Mesh size (no./24.5 mm)						
	≥10	≥20	≥30	≥40	≥60	≥80	<80
Hemp shiv (%)	45.14	32.90	11.14	4.80	3.08	1.70	1.24
Industrial wood particles (%)	50.12	25.09	10.05	8.27	2.96	2.01	1.50

Table 2.—The project of particleboard manufacturing.

Raw material	Hemp shiv–to–wood ratio	Height above the base (cm)	Target density (g/cm^3)	UF resin (%)[a]	NH_4Cl (%)	Wax (%)
Mixture of hemp shiv and wood particles	0:5, 1:4, 2:3, 1:1, 3:2, 4:1, 5:0	—	0.75	12	1	No
Castor stalk	—	Whole	0.70	10	1	No
Hemp shiv	—	10–20, 100–120, 200–220	0.70	10	1	1.5
Hemp shiv	—	Whole	0.55, 0.65, 0.70, 0.75	10	1	1.5

[a] UF = urea-formaldehyde.

Kunming, Yunnan, China), and with no wax used as a hydrophobing agent. The mixture of hemp shiv/wood particles with resin was formed into mats (42 by 32 by 1 cm) and pressed into particleboard at 150°C for 5 minutes. (In the laboratory, all of the operations were done by hand. If the press temperature is too high, 200°C for example, it is easy to burn one's hand, so we used a low temperature over a long time period.) The target density was 0.75 g/cm^3. If the density was low, the properties of wood-based particleboard panels were poor. Three samples of each series of particleboard were produced in a laboratory press (XLB-500X500X2, made in Qingdao, Shandong, China). The amount of resin added was based on the ovendry weight of the particle, while the amount of catalyst added was based on the ovendry weight of the UF resin.

Hemp shiv particles of different parts along stem-based particleboard panels.—The hemp shiv particles were mixed with 10 percent liquid UF resin, 1 percent catalyst, and 1.5 percent wax used as the hydrophobing agent (based on the ovendry weight of hemp particles). The mixture of hemp shiv particles from different parts with resin was formed into mats (42 by 32 by 1 cm) and pressed into particleboard at 150°C for 5 minutes; the target density was 0.70 g/cm^3. Three samples of each series of particleboard were produced in a laboratory press.

Hemp shiv particle–based particleboard panels with different densities.—The hemp shiv particles were mixed with 10 percent liquid UF resin, 1 percent catalyst, and 1.5 percent wax. The mixture of hemp shiv particles with resin was formed into mats (42 by 32 by 1 cm) and pressed into particleboard at 150°C for 5 minutes; the target densities were 0.55, 0.65, 0.70, and 0.75 g/cm^3. Three samples of each series of particleboard were produced in a laboratory press.

Particleboard testing

The panels were tested for their physical and mechanical properties according to the Chinese local standard (GB/T 17657-1999; Chinese National Standardization Technical Committee for Wood-Based Panel 1999) for wood-based panels. Target properties included modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), and thickness swelling (TS). After the panels were stored at 20°C and 65 percent relative humidity for 48 hours, they were cut into samples. Four samples with dimensions of 250 by 250 by 10 mm were used for the MOR and MOE tests, and six samples with dimensions of 50 by 50 by 10 mm were used for the IB test and were tested with a Universal Testing Machine (AG-50KNI, made in Japan). In addition, six samples of every panel for the TS test, with dimensions of 50 by 50 by 10 mm, were placed in conditioned water (with temperatures at 20°C ± 2°C and pH at about 7.0) for 2 and 24 hours.

Results and Discussion

Mixture of hemp shiv/wood–based particleboard panels

The IB of the panels, from 1.48 to 1.88 MPa, is shown in Table 3. The addition of hemp-stalk particles resulted in an increase of IB under all conditions, especially for the 3:2 ratio of hemp stalk to wood; the IB values were significantly higher than those of other particleboard, and all the IB values met the IB requirements (0.4 MPa) of the Chinese local standard for interior decoration and furniture using particleboard (GB/T 4897.3-2003; Chinese National Standardization Technical Committee for Wood-Based Panel 2003). The bending properties of the panels (MOR and MOE) also improved after the hemp stalk was added into the particleboard (see Table 3) and were higher than those required by the Chinese standard for interior decoration and furniture using particleboard. The MOR and MOE reached the highest values when the ratio of industrial hemp stalk to wood particles was 1:1. In addition, the mechanical properties of the particleboard panels made with industrial hemp shiv particles were better than those of the panels made with castor stalks under the same manufacturing parameters (Table 4). Also, the TS of the particleboard panel could not satisfy the requirements of the Chinese standards for particleboard panels, since there was no hydrophobing agent added to the panels.

First, the chemical composition of raw materials can greatly influence the properties of panels; changes in the chemical composition of wood or nonwood materials can alter the distribution of the resin on the wood surface (Hosseinaei et al. 2011, Nikvash et al. 2013). There were some differences between the chemical composites of hemp stalk, wood particles, and castor stalk. In addition, there was a definite difference between the physical and mechanical properties of the hemp stalks, wood particles, and castor stalks.

The hemp shiv is a light nonwood material with lower mechanical properties (including elastic modulus and

Table 3.—Properties of industrial hemp shiv/wood particle–based particleboard panels.[a]

Hemp shiv–to–wood ratio	Panel target density (g/cm^3)	Panel density (g/cm^3)	IB (MPa)	MOR (MPa)	MOE (MPa)	TS_{2h} (%)
0:5	0.75	0.76 (0.07)	1.48 (0.11)	14.7 (1.31)	2,080 (20.9)	16.4 (1.23)
1:4	0.75	0.74 (0.13)	1.64 (0.13)	17.9 (1.23)	2,245 (21.8)	16.2 (1.24)
2:3	0.75	0.75 (0.08)	1.80 (0.16)	19.6 (1.12)	2,362 (22.6)	16.0 (1.21)
1:1	0.75	0.76 (0.07)	1.82 (0.15)	19.9 (1.56)	2,680 (23.6)	15.9 (1.09)
3:2	0.75	0.75 (0.06)	1.88 (0.16)	18.8 (1.71)	2,603 (22.6)	16.1 (1.19)
4:1	0.75	0.75 (0.09)	1.84 (0.14)	18.1 (1.62)	2,552 (24.1)	16.2 (1.28)
5:0	0.75	0.76 (0.10)	1.83 (0.12)	18.0 (1.49)	2,531 (23.4)	16.4 (1.20)
Chinese standard for using particleboard for interior decoration and furniture			>0.40	>14	>1,800	<8
Chinese standard for using particleboard for common uses			>0.28	>12.5	—	<8

[a] The standard deviations (in parentheses) represent the variability of the panel density, internal bond (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling of panels with no wax after soaking in water for 2 hours (TS_{2h}).

Table 4.—Properties of particleboards made with different raw materials.[a]

Raw material	Material density (g/cm^3)	Elastic modulus of fiber cell wall (GPa)	Hardness of fiber cell wall (GPa)	Target density (g/cm^3)	Panel density (g/cm^3)	IB (MPa)	MOR (MPa)	MOE (MPa)
Hemp shiv	0.25 (0.03)	12.3 (4.02)	0.41 (0.10)	0.70	0.69 (0.05)	0.97 (0.13)	18.3 (1.23)	2,231 (24.13)
Castor stalk	0.39 (0.07)	15.9 (2.16)	0.49 (0.06)	0.70	0.71 (0.08)	0.89 (0.14)	17.8 (1.28)	1,927 (21.79)

[a] The standard deviations (in parentheses) represent the variability of the elastic modulus, hardness, panel density, internal bond (IB), modulus of rupture (MOR), and modulus of elasticity (MOE).

hardness) in fiber cell walls, as tested by nanoindentation, compared with those of fiber cell walls in castor stalks (Li et al. 2013, 2014; see Table 4) and possess a density of only 0.25 g/cm^3, which is 64 percent of that of castor stalk (see Table 4). Therefore, the fiber cell wall is easy to compress due to its low mechanical properties (Hosseinaei et al. 2011), just as when the wood-based panel was made, the mat needed some moisture content (Cai et al. 2006). Moisture content can improve the plasticity properties and can also reduce the mechanical properties of fiber cell walls (Yu et al. 2010). In addition, the mechanical properties of the hemp shiv–based particleboard panels with different parts of the stem were negatively correlated with the mechanical properties of the hemp shiv fiber cell walls (Table 5) when different hemp stem parts with similar chemical characters were used in making the particleboard panel.

Thus the low mechanical properties of fiber cell walls and the low density of hemp shiv both allowed the hemp shiv pieces to form a good interface in the particleboard panels. The microstructures of the panels and stalk fibers in the castor stalk–based particleboard, tested by scanning electron microscope, are shown in Figures 1A and 1B (Li et al. 2011), and the microstructure and hemp shiv fibers in the hemp shiv–based particleboard are shown in Figures 1C and 1D. Based on the Figure 1 images, the interface was poor, and the fiber cell wall was broken in the castor stalk–based particleboard panels, reducing the mechanical properties of the fiber itself. In contrast, in the particleboard with hemp shiv particles, the interface was good, and the fiber cell wall was whole, preventing damage to the mechanical properties of the hemp fiber itself. These results confirmed that the hemp shiv was easy to compress and was capable of forming a good glue interface with the resin, keeping the mechanical properties of hemp shiv fiber intact because of the lower mechanical properties of the fiber cell wall. The fiber cells with lower mechanical properties are soft and were therefore easy to compress, whereas fiber cells with higher mechanical properties are hard and when compressed at high pressure, some cells were broken and could not retain their strength.

Hemp shiv–based particleboard panels of different density

The chemical, mechanical, and physical properties of hemp shiv in fiber cell walls were all advantages in forming a good interface between the fibers in the particleboard panels discussed above. The mechanical properties of hemp shiv–based particleboard panels with different densities are shown in Table 6. As the density of the panels increased from 0.54 to 0.75 g/cm^3, the properties of hemp shiv–based particleboard panels also increased. When the density of the

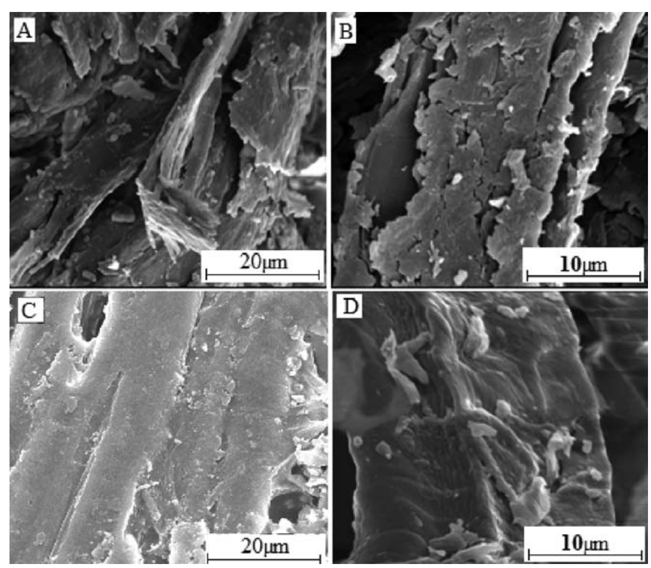

Figure 1.—The microstructure and fiber cell wall structure of particleboard. (A) Microstructure of castor stalk–based particleboard (Li et al. 2011); (B) fiber in castor stalk–based particleboard (Li et al. 2011); (C) microstructure of hemp sheaf–based particleboard; (D) fiber in hemp sheaf–based particleboard.

Table 5.—Properties of hemp shiv particleboards made with different stem parts.[a]

Height above the base (cm)	Elastic modulus of fiber cell wall (GPa)	Hardness of fiber cell wall (GPa)	Target density (g/cm^3)	Panel density (g/cm^3)	IB (MPa)	MOR (MPa)	MOE (MPa)	TS_{2h} (%)	TS_{24h} (%)
0–20	14.0 (3.02)	0.45 (0.09)	0.70	0.70 (0.60)	0.92 (0.13)	19.2 (1.25)	2413 (25.09)	6.68 (0.25)	8.03 (0.47)
100–120	16.9 (2.60)	0.52 (0.05)	0.70	0.71 (0.12)	0.76 (0.12)	13.5 (1.06)	2162 (24.86)	5.73 (0.27)	7.25 (0.43)
200–220	8.10 (2.27)	0.37 (0.08)	0.70	0.69 (0.08)	1.03 (0.15)	21.4 (1.31)	2569 (23.63)	4.56 (0.31)	6.11 (0.38)

[a] The standard deviations (in parentheses) represent the variability of the elastic modulus, hardness, raw materials density, panel density, internal bond (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling of panels with 1.5 percent wax after soaking in water for 2 and 24 hours (TS_{2h} and TS_{24h}).

Table 6.—Mechanical properties of hemp shiv–based particleboards with different densities.[a]

Target density (g/cm^3)	Panel density (g/cm^3)	IB (MPa)	MOR (MPa)	MOE (MPa)	TS_{2h} (%)	TS_{24h} (%)
0.55	0.54 (0.05)	0.75 (0.08)	12.8 (0.18)	1655 (20.51)	5.63 (0.15)	6.38 (0.16)
0.65	0.65 (0.07)	0.86 (0.06)	13.6 (0.21)	1728 (21.36)	5.98 (0.16)	6.50 (0.18)
0.70	0.69 (0.03)	0.97 (0.05)	18.3 (0.35)	2231 (22.49)	6.43 (0.17)	7.91 (0.23)
0.75	0.75 (0.07)	1.09 (0.06)	19.5 (0.41)	2358 (21.98)	7.01 (0.21)	8.97 (0.29)

[a] The standard deviations (in parentheses) represent the variation of panel density, internal bond (IB), modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling of panels with 1.5 percent wax after soaking in water for 2 and 24 hours (TS_{2h} and TS_{24h}).

panels is 0.54 g/cm^3, the properties of particleboard panels can satisfy the local Chinese standards for common particleboard panels, and when the density is 0.65 g/cm^3, the properties of panels, including IB, MOR, and MOE, can satisfy all of the requirements of the local Chinese standards for particleboard used for interior decoration and furniture. In a word, the hemp shiv is an excellent nonwood material, and it can be used to make the low-density particleboard panels of 0.54 g/cm^3.

Conclusions

The low mechanical properties of hemp shiv fiber cell walls and the low density of hemp stalk both are advantageous to compressing hemp shiv fibers and forming a good interface between the fibers; thus one kind of low-density (0.55 g/cm^3) particleboard with good properties can be manufactured with hemp shiv and UF resin. When hemp stalk is used to make particleboard, the fiber should be taken off for its high strength, which is hard to cut with the chipping machine. In addition, the hemp shiv should be stored in a dry or ventilated place to prevent decay, although it does not decay easily because of its special physical and chemical characteristics.

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