Flax Shive and Hemp Hurd Residues as Alternative Raw Material for Particleboard Production

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Flax shive and hemp hurd residues were characterized, and the feasibility of manufacturing three-layered particleboards was evaluated using 2.5% and 5% polymeric diphenyl methane diisocyanate resin loadings. The flax shive and hemp hurd residues had lower bulk densities and higher aspect ratios compared with the wood residues. Their higher aspect ratios offered greater overlap in bonding, which led to consistently higher bending properties that exceeded the American National Standards Institute (ANSI) requirements for low-density (LD2) particleboard and, in some cases, medium-density (M2) particleboard. Because of their particle geometry, the flax shive and hemp hurd particleboards also showed minimal linear expansion with changes in the moisture content at 20 ± 3 °C and between 50% and 90% relative humidity. The high absorption capacity of the flax shive and hemp hurd residues resulted in higher thickness swell and water absorption properties than the wood residues. The results indicated that low-density flax shive and hemp hurd particleboards (500 to 620 kg/m^3) can be manufactured using isocyanate resin quantities as low as 2.5% to produce panels that conform to ANSI specifications with a greater mechanical performance than that of wood residue particleboards.

Keywords: Flax shive; Hemp hurd; Wood; Particleboard; pMDI; Differential scanning calorimetry (DSC)

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INTRODUCTION

The major costs in particleboard production are the wood residue and resin. The costs incurred from resins are primarily due to the overall increase in crude oil and natural gas prices. In contrast, the increasing cost of wood residues is because of the scarce supply from numerous sawmill closures, cost of transporting the residue over long distances, and competition with other sectors, such as the bio-energy industry, for available sawdust and shavings. For particleboard mills, this limited wood residue supply means that the mills will have to find material from several different locations near and far to prevent production curtailment. This results in non-uniform residue resources composed of a variety of wood species, increased transportation and furnish costs, and invariably, increased production costs.

Most of the time, to counteract the negative effect that a wide furnish variability has on the particleboard strength properties, more resin is incorporated during panel manufacturing, which further increases costs. A promising alternative to this issue is to investigate other lignocellulosic residues that are readily available and can efficiently substitute for wood residue in particleboard production. As a result, agricultural crops and plant residues have been of interest in recent years.

Numerous articles have been published concerning the use of branches, leaves, seeds, husks, roots, and/or fruits from agricultural crops and plant residues for particleboard manufacturing. Some examples include guar and sorghum stalks (Gabir *et al*. 1990), sunflower stalks (Khristova *et al*. 1996), waste tea leaves (Yalinkilic *et al*. 1998), castor stalks (Grigoriou and Ntalos 2001), coconut shells (Almeida *et al*. 2002), durian peels and coconut fibers (Khedari *et al*. 2003), almond shells (Gürü *et al*. 2006), tissue paper solid wastes and corn peels (Lertsutthiwong *et al*. 2008), wild rye (Li *et al*. 2009), rice straw (Li *et al*. 2010), corn cobs (Paiva *et al*. 2012), macadamia shells (Wechsler *et al*. 2013), and poppy husks (Keskin *et al*. 2015).

Particleboard has conventionally been manufactured with urea formaldehyde (UF) resin and, in some cases, phenol formaldehyde (PF) resin. However, most agricultural crop and plant residues have waxy outer stalk surfaces that hinder bonding with conventional resins, and this in turn results in poor interfacial interactions (Mwaikambo and Ansell 2002; Wasycliw 2005). The interfacial interaction is important because the waste residues may have high strength and stiffness properties, but if the bonding between them is poor, then the inherent strength of the residue has no impact and the resulting composite exhibits poor mechanical properties (Zhang *et al*. 2005; Ndazi *et al*. 2006). Polymeric diphenyl methane diisocyanate (pMDI) resin has been shown to successfully bond with agricultural crops and plant residues, such as miscanthus, wheat straw, corn pith, and rice straw, to produce panels that meet the required standards for specific applications (Tröger *et al*. 1998; Wang and Sun 2002; Mo *et al*. 2003; Halvarsson *et al*. 2010; Zhang and Hu 2014). Isocyanate resin cures rapidly and can be used in lower quantities (usually 3% to 6% mass resin loads) in comparison with UF and PF resins (6% to 14% mass resin load) (Frihart 2013). With the current concerns about formaldehyde emissions from conventional UF and PF resins, this adhesive type is a practical choice.

Presently pMDI resin, which costs $1.8-$2.2/kg, is expensive compared to UF ($0.9-$1.1/kg based on liquid UF) and PF ($1.45) resins. Even though lower dosages of pMDI are used for board manufacture compared to UF resin, its cost has been a major hindrance to its wider industrial acceptance and use in most particleboard plants, except for specialty products such as moisture resistant boards reserved for niche markets. Typically reducing the quantities of resin required for panel production is not preferred, since it leads to boards that do not meet the relevant standards. But moving forward it is essential to ascertain whether a reduction (no matter how minor) in the present quantities of pMDI used in particleboard production can be achieved without compromising board integrity.

In Canada, flax (*Linum usitatissimum*) and hemp (*Cannabis sativa* L.) crops are cultivated for the oil from their seeds and fiber from their stalks. Retting and decortication of the stalks lead to three main fractions: long staple fibers, short (tow) fibers, and woody core tissue. The woody tissue obtained from flax crop is called flax shive, and that from hemp crop is known as hemp hurd. Considering the wood residue shortage that plagues some particleboard mills, flax shive and hemp hurd residues, which are readily available, have been identified as alternative raw materials for particleboard production.

The main aim of this study was to investigate flax and hemp crop residues that are readily available in Canada as alternate natural resources which can supplement wood in particleboard production, and to determine whether there was room for further reduction of the current quantity of pMDI resin being used for particleboard production. The properties of low-density three-layered particleboards manufactured from 100% flax shive and hemp hurd residues using pMDI resin were comprehensively evaluated. Given the relatively high cost of isocyanate resin, it is important for economic reasons to identify the minimum amount of resin that can sufficiently bond with flax shive and hemp hurd residues. A low resin consumption of 2.5% (based on the oven-dry weight of the residue) and an upper limit of 5% was used for board production. The study consisted of two main parts: (1) characterization of the flax shive and hemp hurd residues; and (2) evaluation of the physical and mechanical strength properties of the flax shive and hemp hurd particleboards compared with those of wood particleboards.

EXPERIMENTAL

Materials

Flax shive and hemp hurd residues were purchased from the Alberta Innovates Technology Futures' pilot decortication facility in Vegreville, Alberta. These residues consisted of woody tissue and short fiber residues (Fig. 1). The materials were sieved into size fractions *via* a laboratory mechanical shaker using four standard sieves with 4.6-mm, 2-mm, 1-mm, and 0.5-mm openings. Three-layered particleboards with the face comprising of fine particles and the core consisting of the coarse particles were to be manufactured; this sandwich design provides a smooth board surface for lamination. After sieving, the oversized (on a 4.6-mm screen) and undersized (through a 0.5-mm screen) residues were discarded.

flax shive hemp hurd

Fig. 1. Flax shive and hemp hurd residues

Particles collected on the 2-mm sieve (100%) were used as core furnish only. A 50:50 mixture of particles on the 1-mm and 0.5-mm sieve were used as face furnish, with the exception of the hemp hurd residue, where only particles on the 1-mm sieve (100%) were used. This was done because those on the 0.5-mm sieve contained a larger proportion of short hemp fibers, which tend to agglomerate. This was not desired because the resulting fiber balls do not mix well with the woody particles nor the resin during board manufacture. For the purpose of comparison with the non-wood residues, industrial face and core wood particles consisting of softwood species, mostly spruce, firs, and pines, were supplied by the Roseburg Forest Products Company in Dillard, OR. For the manufacture of the particleboards, a commercial-grade pMDI resin, Lupranate® M20, was provided by BASF (Mississauga, Canada).

Residue Characterization

Bulk density measurements were taken for the flax shive, hemp hurd, and wood residues by freely pouring the residues into a box of known volume without compaction and subsequently weighing the box. Using image analysis software, Image J (National Institutes of Health, Bethesda, USA), the particle length and width ratios (aspect ratios), as well as the total surface areas, were measured for the face and core furnishes of all three residue types. Using a stage microtome, samples 20 µm thick were cut from cross-sections of the flax and hemp stalks and viewed under a Hitachi S3000N scanning electron microscope (SEM) (Vancouver, Canada) to provide information on the woody core tissue.

Differential Scanning Calorimetry (DSC)

The differential scanning calorimetry (DSC) technique was employed to observe the effect that the different residues (*i.e.*, wood, flax shive, and hemp hurd) had on the curing behavior of the pMDI resin. The residues were ground into powder using a ball mill, Retsch PM 200 (Vancouver, Canada), and sieved through an ASTM no. 60 sieve with 0.25-mm openings. The powder that went through the sieve was oven dried and then used for the DSC. High-volume stainless steel hermetic sample pans, which are commonly used with liquids and solids containing volatile compounds (such as water and formaldehyde), were used for the DSC measurements. The presence of moisture has been shown to increase the curing of pMDI resin by accelerating the curing time (He and Yan 2005, 2007). Moisture was therefore considered to be a factor in the analysis of the thermal properties of the wood, flax shive, and hemp hurd residues to replicate the exact conditions used in hot pressing the particleboards. To avoid any erroneous effects from the moisture and ensure detailed observations of only the effects of different residues on the curing behaviour of pMDI, all of the residues were oven dried at 103 ± 2 °C for 24 h, and a specified quantity of distilled water was added to bring all of the samples to a similar moisture content (MC) before testing. The specified quantity of distilled water was based on a mass ratio of 1:10 with residue and/or resin. The wood, flax shive, and/or hemp hurd powder were thoroughly mixed with the resin and distilled water at a 10:10:1 mass ratio immediately prior to testing. For samples without residues, the pMDI resin was mixed with distilled water at a mass ratio of 10:1.

The sample sizes, which ranged from 15.0 to 15.5 mg, were placed in the high-volume sample pans and tightly sealed with a rubber O-ring seal and lid. The dynamic scan was conducted using a single heating rate of 10 °C/min within a temperature range of 40 to 230 °C in a TA Instruments DSC Q1000 machine (Vancouver, Canada). Three replicates were conducted per sample with a less than 4% deviation in the peak height between samples. All of the analyses and comparisons were conducted using TA Universal analysis software (Thermal Advantage Universal Analysis 2000 for Windows 2K/XP/Vista, New Castle, USA). For each sample, the onset temperature, peak temperature, and reaction heat/reaction enthalpy were determined from the DSC curves.

Board Manufacture

The main factors of interest in this experiment were the effect of the residue type (wood, flax shive, and hemp hurd) and quantity of resin (2.5% and 5%) on the particleboard properties.

Based on the experimental design outlined in Table 1, three-layered particleboards were made from flax shive, hemp hurd, and wood residues. The MCs of the flax shive and hemp hurd residues at the time of board manufacturing were determined by ASTM D1348-94 (2008) and were approximately 10% for the 2.5% resin load boards and 9.8% for the 5% resin load boards. The MCs of the wood particleboards were 9.1% for the 2.5% resin load boards and 8% for the 5% resin load boards.

Table 1. Design of Experiment for Low Density Particleboards

Factors		Levels	Response	Total specimens
Variables	Residue type	Wood	MOR/MOE IB TS LE	12
		Hemp hurd		32
		Flax shive		12
	Resin load (%)	2.5		20
		5		
Constants	Density (kg/m^3)	620		
	Thickness (mm)	12.7		
	Resin type	pMDI		
	Replicates	4		

The face and core furnishes were blended separately for 5 min with 2.5% and 5% pMDI resin loadings (oven dry weight) in a paddle-type particleboard blender. The mats were formed by hand in a forming box with internal dimensions of 635 mm by 635 mm and subsequently were pressed at 140 °C to a target board density of 620 kg/m^3 and panel thickness of 12.7 mm. The press cycle based on the mat displacement/thickness included a 16-s closing time, 415-s holding period at 2 MPa and 140 °C, and 200-s degassing time, before the mats were transferred to pressure control with a 50-s opening time.

Short-Term Property Testing

After the manufactured boards were cooled down to room temperature and trimmed to eliminate the edge effects, tests of the vertical density profile (VDP), internal bond (IB), bending strength (MOR), bending stiffness (MOE), thickness swell (TS), and linear expansion (LE) were performed on the samples. The samples were then conditioned to a constant weight and MC in a conditioning chamber maintained at 65 ± 5% relative humidity and 20 ± 3 °C for a minimum of two weeks before testing. The samples were evaluated in accordance with American standards for particleboards (ANSI A208.1-1999 (1999); ASTM D1037-06a (2006); ANSI A208.1-2009 (2009)). For some results, the strength properties were presented according to the ANSI A208.1-1999 (1999) standard, which permitted the calculation of the least significant differences between board types, unlike ANSI A208.1-2009 (2009), which was presented based on the lower 5th or upper 95th percentile limit. Other than those differences, the two ANSI versions, *i.e.*, 1999 and 2009, are essentially comparable. All of the statistical analysis was conducted with the JMP 11 software package (Cary, USA) at a 5% significance level. Using an analysis of variance test (ANOVA) and the Tukey-Kramer honest significant difference test, the test data obtained were analyzed for potential differences between the particleboard types.

RESULTS AND DISCUSSION

Residue Characterization

Table 2 presents the length to width ratios (aspect ratios) of the flax shive, hemp hurd, and wood residues. The flax shives were characterised by higher aspect ratios with longer, narrower, and needle-like particles compared with the hemp hurd particles, which were medium-sized and more rectangular in form, and the wood residue particles, which were shorter and thicker.

Table 2. Mean Aspect Ratio of Wood, Flax Shive, and Hemp Hurd Residues

Material		Aspect Ratio
Face	Wood	2.52 (1.25)
	Hemp hurd	4.48 (2.18)
	Flax shive	8.13 (4.28)
Core	Wood	3.48 (2.36)
	Hemp hurd	4.88 (1.89)
	Flax shive	10.76 (5.53)

n = 50 for each mean. The values in parentheses are the standard deviations.

Numerous studies conducted over the years on the effect of particle geometry on board properties have found that higher bending strength properties are obtained from longer particles because of the greater surface area it provides in terms of contact between particles (Maloney 1993; Juliana *et al*. 2012). Additionally, shorter and thicker particles usually improve the IB strength because they have the tendency to pack themselves together better during mat formation. Theoretically, at a set resin content, shorter and thicker particles are expected to have more resin coverage per unit area compared with longer, thinner particles because of the lower specific surface area.

Table 3 lists the bulk densities of the residues. In terms of core furnish, the hemp hurd residues yielded a significantly ($p < 0.0001$) lower bulk density compared with the flax shive and wood residues. The wood core furnish had a much higher bulk density. Similarly, for the face furnish, the wood residues yielded a significantly ($p < 0.0001$) higher bulk density compared with the hemp hurd and flax shive residues. For panel manufacturers, this means that on a weight basis, more flax shive and hemp hurd residues are required compared with wood residues to produce a particleboard of similar thickness.

Table 3. Bulk Density of Wood, Hemp Hurd, and Flax Shive Residues

Material		Bulk density (kg/m^3)
Face	Wood	200.90 (4.65)
	Hemp hurd	140.01 (1.61)
	Flax shive	88.13 (1.61)
Core	Wood	167.05 (2.99)
	Hemp hurd	89.87 (2.11)
	Flax shive	99.38 (0.67)

n = 3 for each mean. The values in parentheses are the standard deviations.

Mat Core Temperature

During hot pressing, the mat core temperature was monitored using a thermocouple positioned approximately at the center of the mat. The rate of heat transfer through the core of the flax shive, hemp hurd, and wood residues for the 5% resin load particleboards are presented in Fig. 2.

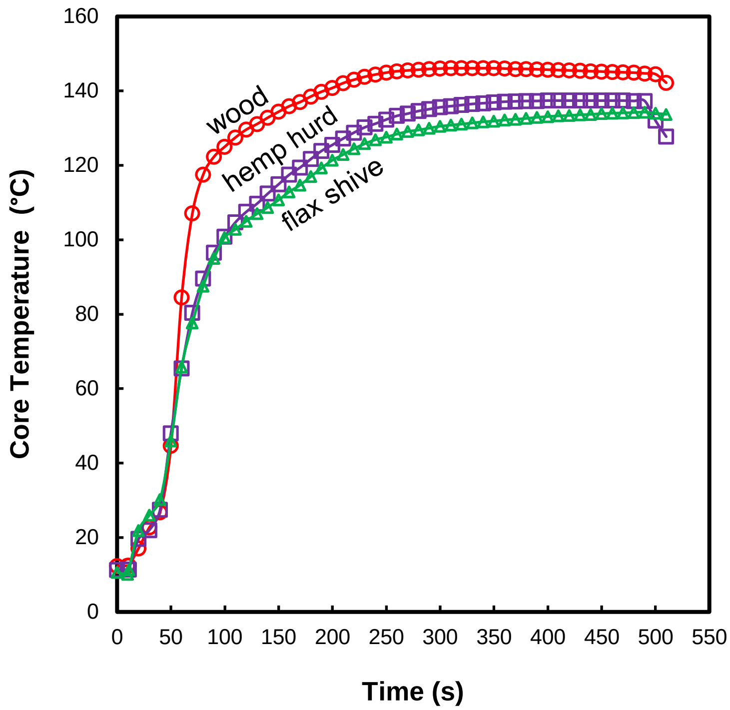


Fig. 2. Differences in the mat core temperature during hot pressing of the 5% pMDI load boards

In the first 50 s, there appeared to be no difference between the three particleboard types, as the core temperature steadily rose at approximately the same rate. The core of the wood mat quickly heated up to 100 °C after 70 s. This was faster compared with the flax shive and hemp hurd mats, which reached 100 °C after approximately 100 s. The core temperature then steadily increased until the maximum temperatures of 134 and 137 °C were reached for the flax shive and hemp hurd mats, respectively, while that of the wood mat was slightly higher, near 146 °C (*i.e.*, approximately the temperature of the press platen). This slower rate of heat transfer to the core for the hemp hurd and flax shive mats was attributed to the initial differences in the MC between the wood residues (8%) and hemp hurd/flax shive residues (9.8%) and to their lower bulk densities (Kelly 1977; Papadopoulos *et al*. 2002; Papadopoulos and Hague 2003; Dai *et al*. 2004; Papadopoulos *et al*. 2004). For granular-type particles, a positive linear relationship has been shown to exist between the press time and mat MC before the core mat temperature rises above 100 °C; that is, the lower the MC, the shorter the press time needed for the temperature to exceed 100 °C. This led to the faster heating rate in the wood core.

Furthermore, the lower bulk densities (increased void fraction) of the hemp hurd and flax shive residues coupled with the slightly higher MC (9.8%) compared with the wood residues delayed the heat flow to the mat core. This notion was corroborated by Papadopoulos *et al*. (2002, 2003) who, working on wood, coconut stem chips, and flax shive mats with a 10% MC and pressed to the same board thickness, observed similar trends of the heat flow to the core where the wood chips yielded a faster rate of heat transfer to the core compared with the flax shive and coconut chips.

Moisture Content, Average Board Density, and Vertical Density Profile

Statistically significant differences ($p < 0.0001$) were observed in the MC between the panel types for both the 2.5% and 5% resin loads (Table 4). This difference in the MC for both resin loads, which was more pronounced in the hemp hurd and flax shive boards, was the result of the moderately higher initial MCs of the residues compared with the wood residue.

Table 4. Average Board Density and MC of the Low Density Particleboards

	Wood	Hemp hurd	Flax shive
2.5% resin load boards			
Density (kg/m^3)	555 (36.72)	532 (25.02)	533 (17.69)
MC (%)	10.24 (0.13)	10.94 (0.08)	11.56 (0.40)
5% resin load boards			
Density (kg/m^3)	638 (35.60)	631 (26.53)	657 (18.15)
MC (%)	10.22 (0.11)	10.53 (0.12)	10.86 (0.12)

Each board density mean was computed from 12 samples. The mean MC was calculated from 12 samples for the 2.5% resin load boards and 11 samples for the 5% resin load boards. The values in parentheses are the standard deviations.

The average board density for the 2.5% resin load boards ranged from 532 to 555 kg/m^3, and values were not significantly different from each other. In contrast, for the 5% resin load boards, the average board density was significantly different ($p = 0.0401$) between the panel types, specifically between the flax shive and hemp hurd panels. From Table 4, it was evident that the average board density was lower for the 2.5% resin load boards compared with the 5% resin load boards. It is important to note that all of the boards were manufactured based on mass calculations for the same target density of 620 kg/m^3 and thickness of 12.7 mm. This difference was in part the result of the differences in the MCs of the residues prior to board manufacture, differences in resin content, and the non-uniform distribution of particles during mat formation by hand.

Figure 3 shows the peak face (F1, F2) and core (C) densities through the thickness of the wood, hemp hurd, and flax shive panels for both resin loads. On average, all of the board types portrayed the normal VDP observed in particleboards, *i.e.*, high-density faces and low core densities.

For the 2.5% resin load boards, significant differences were observed in the VDP between the wood, hemp hurd, and flax shive panel faces ($p = 0.0006$), which ranged from 586 to 709 kg/m^3, and the core densities ($p = 0.0017$), which ranged from 448 to 512 kg/m^3. The lowest face and core densities were observed in the wood panels. The VDP of the 5% resin load boards revealed no significant differences between the panel types in terms of their core densities, which ranged from 627 to 632 kg/m^3. Of the three panel types, the hemp hurd panel yielded the lowest core density. However, there was a significant difference ($p = 0.0014$) in the peak face densities, which ranged from 802 to 905 kg/m^3. The highest face density was observed in the panels manufactured from hemp hurd, and there was no difference seen between the wood and flax shive panels.

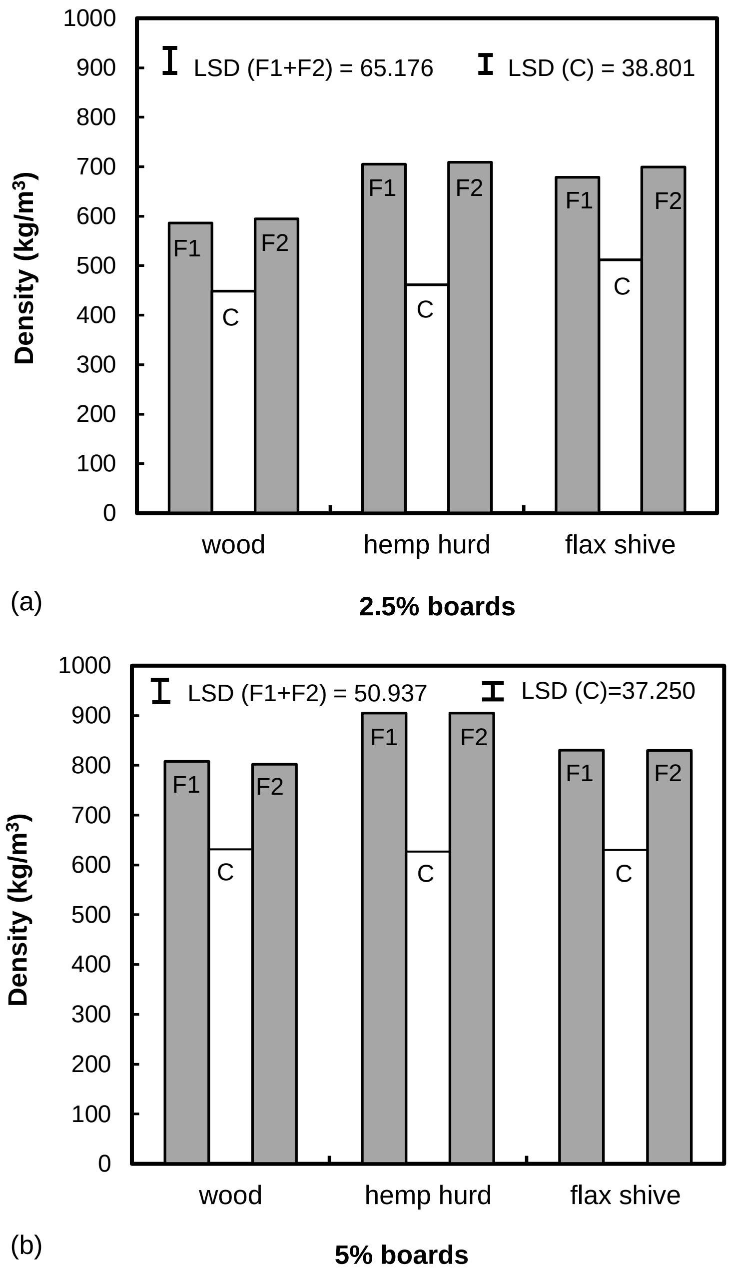
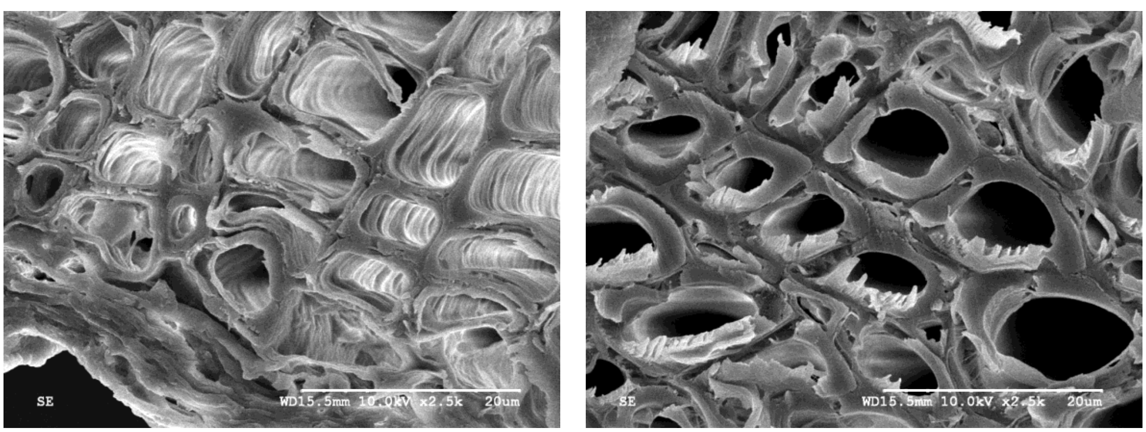


Fig. 3. Face and core density profiles of (a) 2.5% and (b) 5% resin load particleboards expressed as the peak face (F1, F2) and core densities (C). n = 6 for each mean. The error bars represent the least significant difference (LSD) i.e. the smallest significant difference between two means; pairs of means with a difference larger than the LSD are significant.

Moisture is one of the factors that influences the formation of a density gradient in particleboard. This is because it serves as a means of heat transfer from the mat faces in contact with the press platen to the mat core, which assists in the polymerization of the resin (curing/hardening) and consolidation of the mat. Prior to the manufacture of the 2.5% and 5% resin load boards, the MCs were determined for both the hemp hurd and flax shive residues, and were 10.10% and 9.8%, respectively. Regardless of the similar MCs for the same resin load (*i.e.*, 2.5% or 5%), higher face densities were consistently observed in the hemp hurd particleboards compared with the flax shive particleboards. A look at the maximum mat pressures observed for the particleboards during the hot-pressing operation revealed that the hemp hurd boards yielded the highest mat pressure, even though the same press cycle was used for the manufacture all of the particleboard types. This indicated that the hemp hurd and flax shive residues have more resistance to compaction compared with the wood residues, which are more easily compressed.

To eliminate the effect that differences in the MC have on the formation of the VDP, samples of wood, hemp hurd, and flax shive residues were conditioned to an 11% MC in a chamber held at 65 ± 5% relative humidity and 20 ± 3 °C for three weeks, and these conditioned residues were subsequently used for the manufacture of the 5% pMDI resin load boards. There were no significant differences in the average board density between the particleboard types manufactured with the conditioned furnish. The hemp hurd particleboards once again yielded a significantly higher average face density (872 kg/m^3), which resulted in a larger face to core density variation. This was closely followed by the flax shive particleboards (848 kg/m^3), and the lowest face density occurred in the wood particleboards (746 kg/m^3). In terms of the core density, a high value was observed in the flax shive boards (580 kg/m^3), but this was not significantly different from that of the hemp hurd (579 kg/m^3) and wood (553 kg/m^3) boards.

These results suggested that there were factors other than the MC that influenced the density gradient within the different particleboard types. In fact, other factors, such as the particle configuration within the layers of the formed mat, cellular structure, and compressive strength of the constituent residue, all impact the formation of the density gradient (Dai and Steiner 1993). A detailed look at the cellular structure of the hemp hurd tissue compared to the flax shive (Fig. 4) showed thicker cell wall vessels in the hemp hurd, which explained the greater force that was required to compress its mat to the same board thickness as the flax shive residue board.



flax shive hemp hurd

Fig. 4. SEM images of the vessels in the flax shive and hemp hurd residues

DSC Analysis

Figure 5 presents the compiled heat flux DSC graphs for the combination of wood, hemp hurd, and flax shive residues with pMDI resin, where the heat flow signal is measured as positive for an exothermic event (measured upward) and displayed as distinct single exothermic peaks representing the curing reaction. The results of the average onset temperatures, peak temperatures, and reaction heats that were determined from the graphs are listed in Table 5.

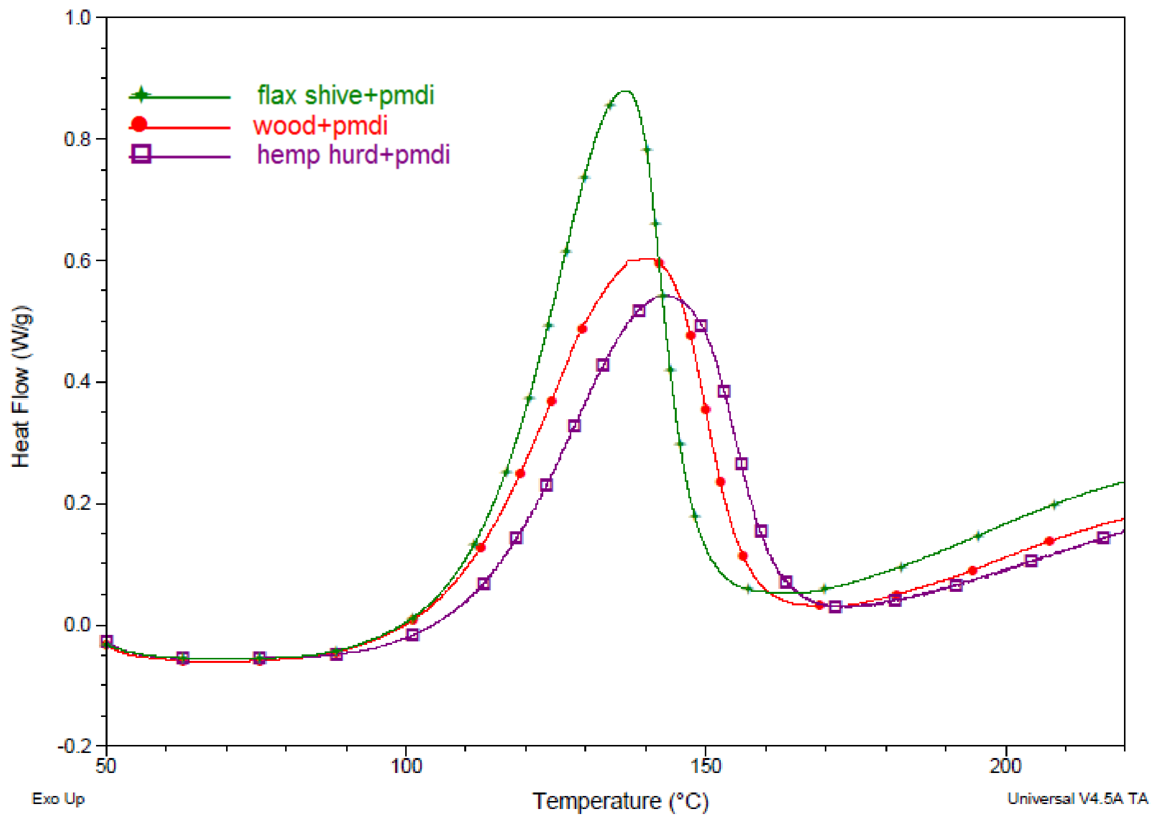


Fig. 5. DSC curves of the curing reaction between the wood, hemp hurd, and flax shive residues, combined with pMDI resin and distilled water

The effect of the residue type on the pMDI curing reaction was significant ($p < 0.0001$) compared with the neat pMDI resin. The addition of the different residues to the pMDI resin significantly reduced the reaction heat. It was expected that in the presence of moisture and with the introduction of residues that each contain cellulose, hemicelluloses, and lignin constituents with reactive hydroxyl groups, a greater number of bonds was likely to be formed in the residue and pMDI mixtures than in the neat pMDI samples. However, this was not the case. The ability of the pMDI resin to react with the reactive hydroxyl groups depends on their accessibility and reactivity. The hydroxyl groups in wood, for instance, have been reported to have a low mobility during their reaction with pMDI resin (He and Yan 2005). Because it has been established that the bonding mechanism between pMDI and wood flour is mainly mechanical interlocking (when it penetrates the cellular structure) (Wandler and Frazier 1996; Bao *et al*. 2003; Smith 2004; He and Yan 2007) with minor covalent bond formation, it was concluded that the reaction heat observed from the DSC analysis must have been from chemical bond formations between the pMDI resin molecules; therefore, the lower reaction heat values obtained for the residue and pMDI mixtures indicated a lower number of bond formations between the pMDI resin molecules. As can be seen in Table 5, there was a decrease in the percentage of reacted pMDI molecules, by as much as 50% in the case of the wood residue, 52% for the hemp hurd residue, and 47% for the flax shive residue. The significant decrease that was observed could have been the effect of the chemical components (extractives, silica, ash content) of the residues on the resin crosslinking, and the ease with which the pMDI resin was able to access the reactive sites (cellulose, lignin, hemicellulose) in the residues, which was dependent on the intrinsic anatomy. For instance, Das *et al*. (2007), using solid-state nuclear magnetic resonance (NMR) with nitrogen-labeled (N^{15}) pMDI resin bonded with two different wood species (southern yellow pine and yellow poplar), reported a minor, but statistically significant effect of the wood species on the cure chemistry. Also, Bao *et al*. (1999) reported that the wood species (southern pine and aspen) influenced the rate of reaction of the pMDI as a function of the temperature and MC.

Table 5. Thermal Properties of the Curing Reaction Between the pMDI Resin and Residues

Sample	Onset Temp. (°C)	Peak Temp. (°C)	Reaction heat (J/g)
pMDI	106.7	130.5	235.3
wood + pMDI	107.9	138.5	118.7
hemp hurd + pMDI	112.7	142.5	112.8
flax shive + pMDI	111.2	136.2	125.0

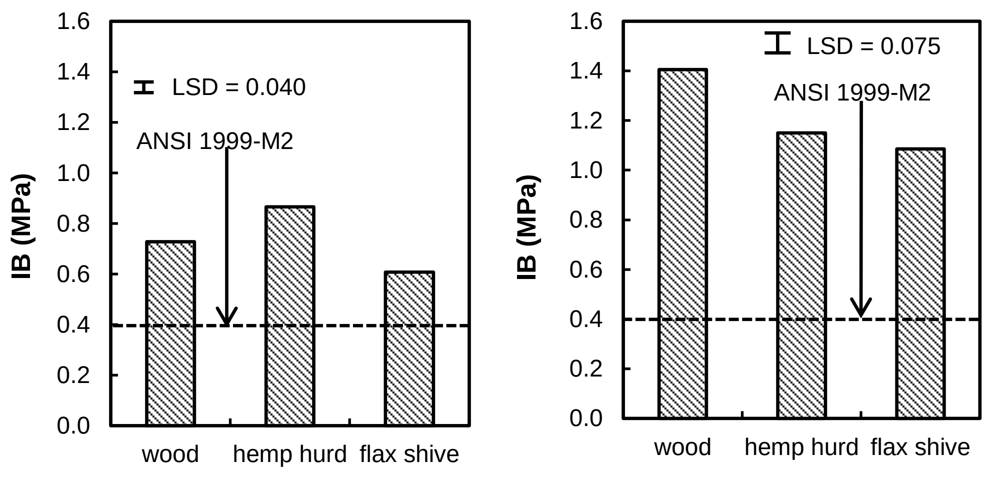
The peak temperatures for the residue and pMDI mixtures also shifted to higher values, and were significant ($p = 0.0010$) in comparison with the neat pMDI sample, which signified slower cure rates, and provided information on the typical press platen temperatures that should be employed during the hot-pressing operation that ensures crosslinking of the pMDI resin. In terms of the onset temperature, the neat pMDI (107 °C), and wood and pMDI mixture (108 °C) had an early onset of curing, and were significantly different ($p = 0.0014$) from the hemp hurd and pMDI (113 °C), and flax shive and pMDI (111 °C) mixtures. These onset temperatures suggested that the curing reaction proceeded easily and at lower temperatures for the pMDI resin in the presence of the flax shive and wood residues.

The reactivity of the pMDI resin in the presence of the residues was also confirmed by the peak temperatures, which represented the rate of curing of the resin. Lower temperatures, and hence, faster reaction cure rates, were once again observed in the flax shive and wood samples. A significant difference ($p = 0.0029$) was observed in the peak temperature between all three samples. The amount of heat produced at the end of the curing process (*i.e.*, reaction heat) was the highest in the flax shive samples and lowest in the hemp hurd samples, which indicated a greater resin cure in the flax shive and pMDI mixture compared with the wood and hemp hurd samples. The hemp hurd and pMDI mixture therefore exhibited the lowest degree of resin cure. It is important to note that the term “degree of cure” does not refer to the extent of the resin cure, because, the upper temperature range (230 °C) used during testing ensured that the resin was highly crosslinked and incapable of further reactions. Rather, the term “degree of cure” refers to the quantity of bonds formed between the resin molecules, as some reactions are unproductive reactions.

In summary, the DSC results indicated that of the three lignocellulosic residues, the hemp hurd had a significantly prohibitive effect on the curing of the pMDI resin. For particleboard manufacturers, this implied the need to increase press temperatures during particleboard production when using hemp hurd residues in order to ensure efficient bonding of the pMDI resin with the residue. The reaction heat results observed based on the residue type remains unexplained, and can be the emphasis for further studies.

Internal Bond (IB) Strength

The IB strength for the different particleboard types is shown in Fig. 6. Research has shown that, for particleboard panels, an increase in board density is associated with a corresponding increase in the IB strength. This is the result of more contact between the particles; hence, there are fewer voids in the mat as it is being compressed to a higher density in the pressing operation. For the 2.5% resin load boards (Fig. 6a), significant differences ($p < 0.0001$) were observed between all of the panel types. Within the same density range (500 to 600 kg/m^3), the hemp hurd panels yielded the highest IB strength. There was a wide variation in the IB strength for the wood panels. Approximately 19% of the wood samples yielded the lowest density, and hence, had low IB strength. In contrast, for the 5% resin load boards within a density range of 600 to 750 kg/m^3, the wood panels yielded a significantly ($p < 0.0001$) higher IB strength (Fig. 6b). There were no statistically significant differences between the panels manufactured from the flax shive and hemp hurd residues.



(a) (b)

Fig. 6. IB strength of (a) 2.5% and (b) 5% resin load particleboards. The horizontal line indicates the minimum value stipulated by ANSI A208.1-1999 (1999) for the medium density (M2) boards. n = 32 for each mean. The error bars represent the LSD i.e. the smallest significant difference between two means; pairs of means with a difference larger than the LSD are significant.

The lowest IB strength was consistently observed in the flax shive panels for both the 2.5% and 5% resin load boards. Although all of the particleboard types exceeded the 0.15 MPa and 0.45 MPa minimum IB strengths required by ANSI A208.1-1999 (1999) for the low-density (LD2) and medium-density (M2) grade particleboards, respectively, there was an indication that factors other than the reactivity of the resin during the curing reaction, such as the rate of heat transfer to the mat core and residue cellular structure, affected the cohesive strength properties of the particleboard. Using image analysis (Image J), the core densities of the wood, hemp hurd, and flax shive residues that had been previously measured for their aspect ratios were analyzed in terms of their surface area, which were recorded as 20.58 mm^2 for hemp hurd, 17.96 mm^2 for wood, and 13.55 mm^2 for flax shive. The medium sized rectangular hemp hurd particles yielded the largest surface area available for resin coverage, while the shorter and thicker wood particles had the second largest, and hence, the bond strengths were higher for the hemp hurd and wood residues in the 2.5% and 5% resin load boards. Because of their short and fine particle geometry, the wood residues had the extra advantage of better packing, as the particles easily filled the voids created during mat formation; therefore, greater particle-particle contact during the wood residue mat densification was ensured (Maloney 1993; Sackey *et al*. 2008).

As was expected with an increase in the resin content, the IB values were higher for the 5% resin load boards compared with the 2.5% resin load boards. Regardless, the values observed in the flax shive and hemp hurd boards were found to be superior and/or comparable to particleboards manufactured from similar residues in other studies, after taking into consideration the differences in some processing parameters, such as resin type, resin content, press time, and board densities. Papadopoulos and Hague (2003) manufactured single-layer flax shive particleboards to a target density of 750 kg/m^3 and thickness of 17.5 mm using a 13% UF resin load, and the boards yielded IB values of 0.09 MPa, which were quite low. Balducci *et al*. (2008) manufactured 16-mm thick single-layer hemp hurd boards with densities of 400 kg/m^3 and a 6% isocyanate resin load, and reported an IB strength of 0.32 MPa, which given the lower density when extrapolated (linear best fit) from the data of this study for both the 2.5% and 5% resin load pMDI boards (Fig. 6), was still quite low compared with the current results.

Bending Properties (MOR and MOE)

Particleboard is a random blend of residues that requires no material orientation during mat formation. In this study, the mats were formed by hand in a square forming box, and no bias towards the forming direction (*i.e.*, parallel to the normal axis of the panel) was expected. Test samples for the MOR and MOE properties were taken parallel and perpendicular to the forming direction. Analysis of the test data revealed no significant difference between samples from the parallel and perpendicular directions. The MOR and MOE presented in Table 6 for the 2.5% and 5% resin load particleboard types were therefore the pooled data of both sample directions. The particleboard VDP and residue aspect ratio have been reported to remarkably influence the MOR and MOE of particleboard panels (Kelly 1977; Maloney 1993). The high density faces observed in the vertical density analysis of the boards denoted highly compact regions that were developed because of the plasticization and compression of the residues. As the face density increased, the higher the compaction within the board was, which implied greater inter-particle contact and a better ability to resist the bending stresses that were applied.

Table 6. Static Bending Properties of the pMDI-Bonded Particleboards

Board Type	MOR (MPa)		MOE (GPa)	
	2.5%	5%	2.5%	5%
wood	4.07 (1.54)	7.06 (1.56)	1.06 (0.29)	1.50 (0.26)
hemp hurd	12.40 (1.83)	17.90 (2.27)	2.09 (0.28)	2.72 (0.34)
flax shive	10.01 (2.32)	18.24 (1.83)	2.14 (0.32)	3.29 (0.24)
ANSI LD2	5.0		1.03	
ANSI M2	14.5		2.25	

The data are based on ANSI A208.1-1999 (1999) panel averages. n = 12 for each mean. The values in parentheses are the standard deviations.

As discussed previously, the residues that had longer and thinner particles tended to have more potential bonding sites; therefore, they provided greater contact area/overlap between the particles for bonding. This helped to resist the stresses developed during bending, which resulted in stronger and stiffer particleboards.

The hemp hurd and flax shive particleboards consistently exhibited higher face densities compared with the wood particleboards, even when all of the furnish types were conditioned to the same MC. This coupled with their high aspect ratios resulted in boards with significantly ($p < 0.0001$) greater bending strength, approximately 60% higher, compared with the wood boards within the same resin load category. The difference in the MOR and MOE values for similar particleboard types (wood, hemp hurd, or flax shive) in the 2.5% and 5% resin load boards was further attributed to the increase in the board density (Table 4). For the reduced pMDI resin load of 2.5%, only the flax shive and hemp hurd panels exceeded the standards for LD2 grade particleboards in terms of the MOR. For the MOE, all of the panel types met the ANSI A208.1-1999 (1999) requirements for LD2 particleboards. Both the 5% resin load hemp hurd and flax shive boards surpassed the stipulated ANSI specifications for the LD2 and M2 grade particleboards. In contrast, the panels manufactured from the wood residues only met the standards for the LD2 particleboards in terms of the MOR and MOE values.

Linear Expansion (LE)

When exposed to high humidity, particleboards absorb moisture and expand in volume. These dimensional changes are the result of the hygroscopic nature of the constituent materials, and the release of the compressive stresses, which were set in the boards during the hot-pressing operation. These changes are not entirely reversible upon drying, and become a great concern in applications where particleboards will be exposed to large changes in moisture, such as to liquid water or water vapor.

The linear expansion (LE) for the wood, hemp hurd, and flax shive boards with different resin contents and with changes in the MC at 20 ± 3 °C and between 50% and 90% relative humidity is presented in Fig. 7.

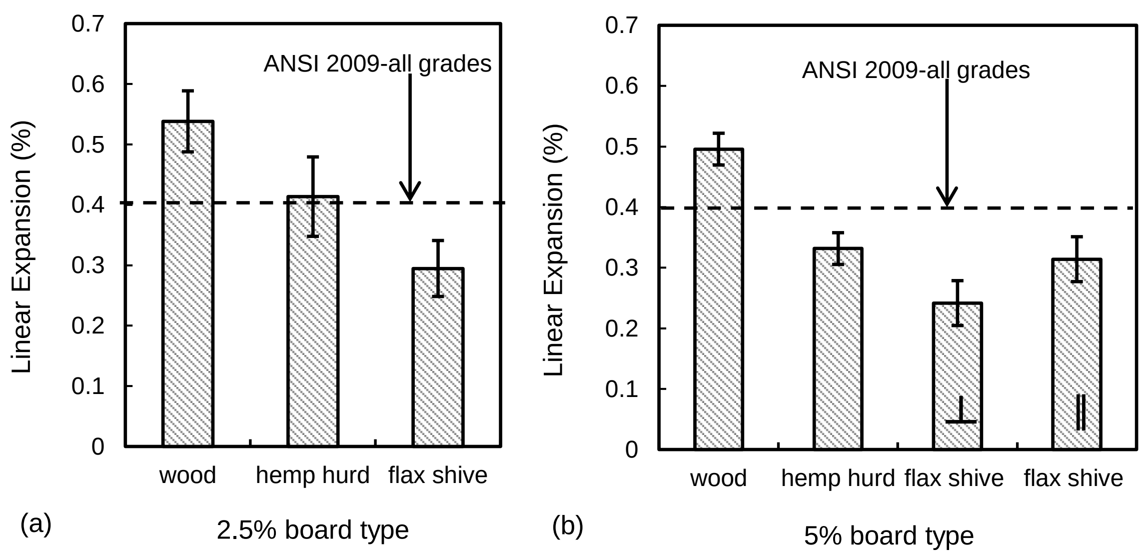


Fig. 7. LE of (a) 2.5% and (b) 5% resin load particleboards with changes in the MC between 50% and 90% relative humidity. ‖ and ⊥ indicate parallel and perpendicular to the forming direction, respectively. The horizontal line indicates the maximum value stipulated by ANSI A208.1-2009 (2009). Each mean was computed from 16 samples for the 2.5% resin load boards, 20 samples for the 5% resin load wood and hemp hurd boards, and 10 samples for the 5% resin load flax shive (‖ and ⊥) boards. The error bars represent a two-sided 95% confidence interval of each mean.

Particleboards manufactured from the wood residues yielded the significantly ($p < 0.0001$) highest LE compared with the flax shive and hemp hurd panels. This was expected because the LE is more dependent on the particle geometry and particle alignment than on the board density. As such, an increase in the particle length typically results in a decrease in the LE (Miyamoto *et al*. 2002), which is due to the fact that longer particles are more likely to have longer longitudinal sections where less dimensional changes occur. The geometry of the flax shive particles (Table 2) confirmed its lower LE values. Because the mats were randomly formed, the LE was expected to be equal in the directions parallel and perpendicular to the forming direction. The comparison of test samples from both directions for each particleboard type revealed no significant differences for the 2.5% and 5% resin load boards, with the exception of the flax shive particleboards manufactured with the 5% resin load, where changes to the length were greater in the direction parallel to the forming direction than in the perpendicular direction. This was not surprising, as it has been suggested that, despite the random orientation employed during mat formation in the manufacture of the particleboards, some particles tend to orient themselves at angles to the forming plane (Kelly 1977); therefore, greater changes to the length occurred in the plane parallel to the forming direction for the 5% resin load flax shive boards.

Increasing the resin content of the particleboard types appeared to have a slight, but not significant reduction effect on the LE values. The boards manufactured with the 5% resin load compared with the 2.5% resin load boards had LE values that were reduced by approximately 5% for the wood and hemp hurd particleboards, and were decreased by 10% in the case of the flax shive particleboards parallel to the normal axis of the board. The LE values observed in the flax shive and hemp hurd particleboards manufactured with the 5% resin load were within the limits stipulated by ANSI A208.1-2009 (2009). In the case of the 2.5% resin load boards, only the flax shive particleboards (a pooled effect of samples parallel and perpendicular to the forming direction) yielded values within the ANSI limits, while the hemp hurd boards, at 0.41%, just exceeded the stipulated 0.40% maximum average percent. The values observed for the wood particleboards in both the 2.5% and 5% resin load boards exceeded the maximum permitted LE value outlined in ANSI A208.1-2009 (2009).

Thickness Swell (TS) and Water Absorption (WA)

Table 7 shows the 2 h and 24 h TS and water absorption (WA) properties of the wood, hemp hurd, and flax shive particleboards. For the 2.5% resin load boards, the wood particleboards yielded significantly ($p < 0.0001$) lower TS (approximately 60% lower) and WA (approximately 45% lower) values for both the 2 h and 24 h measurements compared with the flax shive and hemp hurd particleboards, which had relatively similar values. In contrast, the high TS values attained by the flax shive and hemp hurd particleboards was attributed to their highly absorbent nature, which has been well documented by Papadopoulos and Hague (2003), Nguyen *et al*. (2009), and Arnaud and Gourlay (2012).

In boards manufactured with the 5% resin load, the wood particleboards swelled the most in thickness (7%) in the first 2 h of submersion, and absorbed twice the amount of water (28%), which was significant ($p = 0.0014$) compared with the flax shive and hemp hurd particleboards (11.5% and 12%, respectively). After 24 h of submersion, the flax shive particleboards recorded the highest TS (16.7%), and significant ($p < 0.0001$) differences were observed between all three particleboard types. Overall, no significant differences were observed between the percentages of water uptake by the wood, hemp hurd, and flax shive particleboards with the 5% resin load. The unusually high TS and WA values observed within the wood particleboards for the 5% resin load was likely the result of the non-uniform particle distribution during the hand formation of the mats.

Table 7. Thickness Swell and Water Absorption Properties of the pMDI-Bonded Particleboards

Board Type	2 h TS (%)		24 h TS (%)	
	2.5%	5%	2.5%	5%
Wood	2.53 (0.57)	7.02 (3.28)	6.67 (0.77)	10.87 (2.72)
Hemp Hurd	6.11 (0.54)	5.78 (1.28)	16.54 (0.76)	14.13 (1.83)
Flax Shive	6.11 (1.59)	5.86 (0.63)	18.44 (3.97)	16.67 (1.25)
	2 h WA (%)		24 h WA (%)	
Wood	7.02 (0.69)	28.02 (18.54)	26.75 (2.63)	39.48 (18.30)
Hemp Hurd	15.85 (0.89)	12.01 (2.60)	48.47 (1.87)	33.51 (3.95)
Flax Shive	15.57 (2.58)	11.46 (1.03)	45.76 (7.76)	33.80 (2.16)

Each mean was computed from 12 samples for the 2.5% resin load boards and 11 samples for the 5% resin load boards. The values in parentheses are the standard deviations.

It is important to note that no wax was used in the manufacturing of the boards. A comparison of the 2.5% and 5% resin load boards revealed that, with exception of the wood particleboard, the 2.5% resin load particleboards yielded the highest TS and WA values. This was likely because the boards with the higher resin load had better inter-particle bonding, and enhanced dimensional stability. This was contrary to the conventional understanding that boards of a higher average density (in this case, the 5% resin load boards as seen in Table 3) tend to have higher compressive stresses set within the panels during manufacturing, and these stresses are released upon submersion into water, which results in greater spring back. This theory held true for the wood particleboards, which consistently yielded higher TS values for the 5% resin load boards compared with the lower 2.5% resin load boards.

The ANSI standards do not stipulate maximum values for the TS or WA for medium or low density particleboards, so there was no benchmark for evaluation. The results obtained were however much lower than those observed by Balducci *et al*. (2008), who reported 28.3% TS for a 6% isocyanate-bonded hemp hurd particleboard with a lower density (400 kg/m^3). Considering the fact that boards with relatively higher densities tend to have more relaxation of compressive stresses and spring back after submersion into water (Kelly 1977), it was expected that the hemp hurd boards from this study with lower resin contents (2.5% and 5%) and higher densities ranging from 540 kg/m^3 to 662 kg/m^3 would show higher TS values compared to the results reported by Balducci *et al*. (2008). However, this was not the case.

CONCLUSIONS

1. Hemp hurd and flax shive residues were observed to be longer and narrower compared with wood residues.
2. Hemp hurd residues substantially prohibited the curing reaction of pMDI resin.
3. The hemp hurd and flax shive particleboards manufactured with both the 2.5% and 5% pMDI resin loads produced panels with approximately 60% higher bending strength and stiffness compared to wood particleboards.

4. Flax shive and hemp hurd residues had higher thickness swelling (TS) compared to wood residues.
5. The flax shive and hemp particleboards exhibited low linear expansions between 50% and 90% relative humidity at 20 ± 3 °C.
6. pMDI quantities as low as 2.5% (mass resin load) can be used to produce flax shive and hemp hurd particleboards of comparable properties to wood boards.

ACKNOWLEDGMENTS

The authors acknowledge the support of Roseburg Forest Products Company for providing the industrial grade wood particles, BASF for providing the pMDI resin, and NSERC Discovery Grant Program for funding this study.

REFERENCES CITED

Almeida, R. R., Del Menezzi, C. H. S., and Teixeira, D. E. (2002). "Utilization of the coconut shell of babaçu (*Orbignya sp.*) to produce cement-bonded particleboard," *Bioresource Technol.* 85(2), 159-163. PMID: 12227540

ANSI A208.1-1999 (1999). "Particleboard," Composite Panel Association, Leesburg, VA.

ANSI A208.1-2009 (2009). "Particleboard," Composite Panel Association, Leesburg, VA.

ASTM D1348-94 (2008). "Standard test methods for moisture in cellulose," ASTM International, West Conshohocken, PA.

ASTM D1037-06a (2006). "Standard test methods for evaluating properties of wood-base fiber and particle panel materials," ASTM International, West Conshohocken, PA.

Arnaud, L., and Gourlay, E. (2012). "Experimental study of parameters influencing mechanical properties of hemp concretes," *Constr. Build. Mater.* 28(1), 50-56. DOI: 10.1016/j.conbuildmat.2011.07.052

Balducci, F., Harper, C., Meinlschmidt, P., Dix, B., and Sanasi, A. (2008). "Development of innovative particleboard panels," *Drvna Industrija* 59(3), 131-136.

Bao, S., Daunch, W. A., Sun, Y., Rinaldi, P. L., Marcinko, J. J., and Phanopoulos, C. (1999). "Solid state NMR studies of polymeric diphenylmethane diisocyanate (PMDI) derived species in wood," *J. Adhesion* 71(4), 377-394. DOI: 10.1080/00218469908014549

Bao, S., Daunch, W. A., Sun, Y., Rinaldi, P. L., Marcinko, J. J., and Phanopoulos, C. (2003). "Solid state two-dimensional NMR studies of polymeric diphenylmethane diisocyanate (PMDI) reaction in wood," *Forest Prod. J.* 53(6), 63-71.

Dai, C., and Steiner, P. R. (1993). "Compression behaviour of randomly-formed wood flake mats," *Wood Fiber Sci.* 25(4), 349-358.

Dai, C., Wasylciw, W., and Jin, J. (2004). "Comparison of the pressing behaviour of wood particleboard and strawboard," *Wood Sci. Technol.* 38(7), 529-537. DOI: 10.1007/s00226-004-0256-2

Das, S., Malmberg, M. J., and Frazier, C. E. (2007). "Cure chemistry of wood/polymeric isocyanate (PMDI) bonds: Effect of wood species," *Int. J. Adhes. Adhes.* 27(3), 250-257. DOI: 10.1016/j.ijadhadh.2006.05.002

Frihart, C. R. (2013). "Wood adhesion and adhesives," in: *Handbook of Wood Chemistry and Wood Composites*, Second Ed., R. M. Rowell (ed.), CRC Press, Boca Raton, FL, pp. 255-319.

Gabir, S., Khristova, P., and Yossifov, N. (1990). "Composite boards from guar and sorghum (dura) stalks," *Biol. Waste.* 31(4), 311-314. DOI: 10.1016/0269-7483(90)90088-A

Grigoriou, A. H., and Ntalos, G. A. (2001). "The potential use of *Ricinus communis* L. (Castor) stalks as a lignocellulosic resource for particleboards," *Ind. Crop. Prod.* 13(3), 209-218. DOI: 10.1016/S0926-6690(00)00078-9

Gürü, M., Tekeli, S., and Bilici, İ. (2006). "Manufacturing of urea–formaldehyde-based composite particleboard from almond shell," *Mater. Design* 27(10), 1148-1151. DOI: 10.1016/j.matdes.2005.03.003

Halvarsson, S., Edlund, H., and Norgen, M. (2010). "Manufacture of high-performance rice-straw fiberboards," *Ind. Eng. Chem. Res.* 49(3), 1428-1435. DOI: 10.1021/ie901272q

He, G., and Yan, N. (2005). "Effect of moisture content on curing kinetics of pMDI resin and wood mixtures," *Int. J. Adhes. Adhes.* 25(5), 450-455. DOI: 10.1016/j.ijadhadh.2004.12.002

He, G., and Yan, N. (2007). "Curing kinetics of polymeric diphenylmethane diisocyanate with different wood species," *Int. J. Adhes. Adhes.* 27(3), 244-249. DOI: 10.1016/j.ijadhadh.2006.04.003

Juliana, A. H., Paridah, M. T., Rahim, S., Nor Azowa, I., and Anwar, U. M. K. (2012). "Properties of particleboard made from kenaf (*Hibiscus cannabinus* L.) as function of particle geometry," *Mater. Design* 34, 406-144. DOI: 10.1016/j.matdes.2011.08.019

Kelly, M. W. (1977). *Critical Literature Review of Relationships Between Processing Parameters and Physical Properties of Particleboard* (General technical report FPL-10), U.S. Department of Agriculture Forest Products Laboratory Forest Service, Madison, WI.

Keskin, H., Kucuktuvek, M., and Guru, M. (2015). "The potential of poppy (*Papaver somniferum* Linnaeus) husk for manufacturing wood-based particleboards," *Constr. Build. Mater.* 95, 224-231. DOI: 10.1016/j.conbuildmat.2015.07.160

Khedari, J., Charoenvai, S., and Hirunlabh, J. (2003). "New insulating particleboards from durian peel and coconut coir," *Build. Environ.* 38(3), 435-441. DOI: 10.1016/S0360-1323(02)00030-6

Khristova, P., Yossifov, N., and Gabir, S. (1996). "Particle board from sunflower stalks: Preliminary trials," *Bioresource Technol.* 58(3), 319-321. DOI: 10.1016/S0960-8524(96)00112-5

Lertsutthiwong, P., Khunthon, S., Siralertmukul, K., Noomun, K., and Chandrkrachang, S. (2008). "New insulating particleboards prepared from mixture of solid wastes from tissue paper manufacturing and corn peel," *Bioresource Technol.* 99(11), 4841-4845. DOI: 10.1016/j.biortech.2007.09.051

Li, B., Zheng, Y., Pan, Z., and Hartsough, B. (2009). "Improved properties of medium-density particleboard manufactured from saline creeping wild rye and HDPE plastic," *Ind. Crop. Prod.* 30(1), 65-71. DOI: 10.1016/j.indcrop.2009.01.006

Li, X., Cai, Z., Winandy, J. E., and Basta, A. H. (2010). "Selected properties of particleboard panels manufactured from rice straws of different geometries," *Bioresource Technol.* 101(12), 4662-4666. DOI: 10.1016/j.biortech.2010.01.053

Maloney, T. M. (1993). *Modern Particle Board and Dry Process Fiberboard Manufacturing, Updated ed.*, Miller Freeman, San Francisco, CA.

Miyamoto, K., Nakahara, S., and Suzuki, S. (2002). "Effect of particle shape on linear expansion of particleboard," *J. Wood Sci.* 48, 185-190. DOI: 10.1007/BF00771365

Mo, X., Cheng, E., Wang, D., and Sun, X. S. (2003). "Physical properties of medium-density wheat straw particleboard using different adhesives," *Ind. Crop. Prod.* 18(1), 47-53. DOI: 10.1016/S0926-6690(03)00032-3

Mwaikambo, L. Y., and Ansell, M. P. (2002). "Chemical modification of hemp, sisal, jute, and kapok fibers by alkalization," *J. Appl. Polym. Sci.* 84(12), 2222-2234. DOI: 10.1002/app.10460

Ndazi, B., Tesha, J. V., and Bisanda, E. T. N. (2006). "Some opportunities and challenges of producing bio-composites," *J. Mater. Sci.* 41, 6984-6990. DOI: 10.1007/s10853-006-0216-3

Nguyen, T.-T., Picandet, V., Amziane, S., and Baley, C. (2009). "Influence of compactness and hemp hurd characteristics on the mechanical properties of lime and hemp concrete," *Eur. J. Environ. Civil Eng.* 13(9), 1039-1050. DOI: 10.1080/19648189.2009.9693171

Paiva, A., Pereira, S., Sá, A., Cruz, D., Varum, H., and Pinto, J. (2012). "A contribution to the thermal insulation performance characterization of corn cob particleboards," *Energ. Buildings* 45, 274-279. DOI: 10.1016/j.enbuild.2011.11.019

Papadopoulos, A. N., and Hague, J. R. B. (2003). "The potential for using flax shiv (*Linum usitatissimum* L.) as a lignocellulosic raw material for particleboard," *Ind. Crop. Prod.* 17(2), 143-147. DOI: 10.1016/S0926-6690(02)00094-8

Papadopoulos, A. N., Traboulay, E. A., and Hill, C. A. S. (2002). "One layer experimental particleboard from coconut chips – (*Cocos nucifera* L.)," *Holz Roh. Werkst.* 60(6), 394-396. DOI: 10.1007/s00107-002-0332-y

Papadopoulos, A. N., Hill, C. A., and Gkaraveli, A. (2004). "Bamboo chips (*Bambusa vulgaris*) as an alternative lignocellulosic raw material for particleboard manufacture," *Holz Roh. Werkst.* 62(1), 36-39. DOI: 10.1007/s00107-003-0447-9

Sackey, E. K., Semple, K. E., Oh, S.-W., and Smith, G. D. (2008). "Improving core bond strength of particleboard through particle size redistribution," *Wood Fiber Sci.* 40(2), 214-224.

Smith, G. D. (2004). "The effect of some process variables on the lap-shear strength of Aspen strands uniformly coated with pMDI resin," *Wood Fiber Sci.* 36(2), 228-238.

Tröger, F., Wegener, G., and Seemann, C. (1998). "*Miscanthus* and flax as raw material for reinforced particleboards," *Ind. Crop. Prod.* 8(2), 113-121. DOI: 10.1016/S0926-6690(97)10017-6

Wandler, S. L., and Frazier, C. E. (1996). "The effects of cure temperature and time on the isocyanate-wood adhesive bondline by the ^{15}N CP/MAS NMR," *Int. J. Adhes. Adhes.* 16(3), 179-186. DOI: 10.1016/0143-7496(95)00044-5

Wang, D., and Sun, X. S. (2002). "Low density particleboard from wheat straw and corn pith," *Ind. Crop. Prod.* 15(1), 43-50. DOI: 10.1016/S0926-6690(01)00094-2

Wasycliw, W. (2005). "Methods of straw fiber processing," U. S. Patent No. 6929854 B2.

Wechsler, A., Zaharia, M., Crosky, A., Jones, H., Ramírez, M., Ballerini, A., Nuñez, M., and Sahajwalla, V. (2013). "Macadamia (*Macadamia integrifolia*) shell and castor (*Rícinos communis*) oil based sustainable particleboard: A comparison of its properties with conventional wood based particleboard," *Mater. Design* 50, 117-123. DOI: 10.1016/j.matdes.2013.03.008
Yalinkilic, M. K., Imamura, Y., Takahashi, M., Kalaycioglu, H., Nemli, G., Demirci, Z., and Ozdemir, T. (1998). "Biological, physical and mechanical properties of particleboard manufactured from waste tea leaves," *Int. Biodeter. Biodegr.* 41(1), 75-84. DOI: 10.1016/S0964-8305(98)80010-3
Zhang, L., and Hu, Y. (2014). "Novel lignocellulosic hybrid particleboard composites made from rice straws and coir fibers," *Mater. Design* 55, 19-26. DOI: 10.1016/j.matdes.2013.09.066
Zhang, M. Q., Rong, M. Z., and Lu, X. (2005). "Fully biodegradable natural fiber composites from renewable resources: All-plant fiber composites," *Compos. Sci. Technol.* 65(15-16), 2514-2525. DOI: 10.1016/j.compscitech.2005.06.018

Article submitted: March 9, 2017; Peer review completed: May 16, 2017; Revised version received and accepted; June 21, 2017; Published: June 26, 2017.
DOI: 10.15376/biores.12.3.5715-5735