Effects of bark content and particle geometry on the physical and mechanical properties of particleboard made from black spruce and trembling aspen bark

Martin Claude Ngueho Yemele* Pierre Blanchet* Alain Cloutier*
Ahmed Koubaa*

Abstract

Bark residues are mostly used for thermal energy production. However, a better utilization of that resource could be as raw material for particleboard manufacturing. The use of bark in wood particleboard manufacturing is currently viewed negatively due to the fact that an excessive bark content in the furnish produces significant adverse effects on strength properties and dimensional stability of the boards. Strategies could be found to improve some properties of particleboard made from bark. The effects of bark particle content and geometry on the physical and mechanical properties of the panels including the modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB), Janka hardness (HJ), thickness swelling (TS), and linear expansion (LE) were investigated. The best panels in terms of properties were compared to a control made of 100 percent wood particles. The results showed that, while the mechanical properties of the particleboard made from black spruce and trembling aspen bark decreased with increasing bark content, LE increased and TS increased slightly. The IB of particleboard made from 50 percent bark content decreased with increasing particle size. Particleboard made from 50 percent black spruce bark showed the highest MOE, MOR, and IB and the lowest LE with values 12, 37, and 54 percent lower and 45 percent higher than the control, respectively. The MOE, MOR, IB, and HJ of boards made from 50 percent black spruce and trembling aspen bark met the requirements of the ANSI A208.1 to 1999 standard. Particleboard made from trembling aspen bark showed the lowest TS.

Large quantities of bark are produced by the forest industry and are mostly used for thermal energy production. In the Province of Quebec, Canada, more than 3.5 million tons of anhydrous bark were produced in 2005 (Anonymous 2007). Research projects are carried out in order to foster the use of bark for higher value-added products such as alternative raw material for particleboard manufacturing.

In the literature, two main approaches to manufacture bark particleboard can be identified. The first one is based on bark plasticization and extractives polymerization for the self bonding of the bark particles (Burrows 1960, Chow and Pickles 1971, Wellons and Krahmer 1973, Chow 1975, Troughton and Gaston 1997). The second one focuses more on bark particles for their physical properties rather than their chemical properties. Synthetic adhesives including urea-formaldehyde (Dost 1971, Maloney 1973, Wisherd and Wilson 1979, Muszynski and McNatt 1984, Blanchet et al. 2000, Villeneuve 2004), phenol-formaldehyde (Deppe and Hoffman 1972, Maloney 1973, Lehmann and Geimer 1974, Place and Maloney 1977, Wisherd and Wilson 1979, Suzuki et al. 1994, Villeneuve 2004), isocyanates (Deppe and Hoffman 1972),

The authors are, respectively, Ph.D. Candidate, Centre de recherche sur le bois (CRB), Département des sciences du bois et de la forêt, Université Laval, Québec, Canada (martin-claude.ngueho-yemele.1@ulaval.ca); Research Scientist, FPInnovations–Forintek Division, and Adjunct Professor, Centre de recherche sur le bois (CRB), Département des sciences du bois et de la forêt, Université Laval, Québec, Canada (pierre.blanchet@fpinnovations.ca); Professor, Centre de recherche sur le bois (CRB), Département des sciences du bois et de la forêt, Université Laval, Québec, Canada (alain.cloutier@sbf.ulaval.ca); and Professor, Canada Research Chair on Wood Development, Characterization and Processing, Université du Québec en Abitibi-Témiscamingue,Rouyn-Noranda, Québec, Canada (ahmed.koubaa@uqat.ca). The authors are grateful to the Fonds québécois de la recherche sur la nature et les technologies (FQRNT) and to the Fonds de recherche forestière du Saguenay - Lac Saint Jean for funding this research. We also acknowledge the support of the Arbec Forest Products sawmill, L'Ascension, Québec, Canada, Louisiana Pacific Canada OSB plant, Chambord, Québec, Canada, and the Tafisa Canada particleboard plant in Lac-Megantic, Québec, Canada for bark residues and wood particles supply. We also thank the technicians of the Centre de recherche sur le bois for their support. This paper was received for publication in August 2007. Article No. 10392.
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and extractives-based adhesives (Anderson et al. 1974a, 1974b; Nemli et al. 2004, Nemli and Colakoglu 2005) were used to bond bark particles.

The use of bark in wood particleboard manufacturing is currently viewed negatively because the excessive bark content in raw material produces significant adverse effects on strength and dimensional properties. The possibility of manufacturing particleboards with black spruce and trembling aspen bark and a synthetic adhesive was demonstrated by Blanchet et al. (2000) and Villeneuve (2004). The work of Lehmann and Geimer (1974) indicated that the modulus of elasticity (MOE), the modulus of rupture (MOR) and the internal bond (IB) of particleboard decreased by 20 to 30 percent as a result of the addition of 25 percent Douglas-fir bark. Likewise, the linear expansion (LE) increased by almost 25 percent. Wisherd and Wilson (1979) reported a decrease of 4 to 17 percent and 7 to 24 percent of the MOE and the MOR of particleboards, respectively, when increasing bark content from 5 to 20 percent. Muszynski and McNatt (1984) indicated that particleboards suitable for furniture manufacturing could be made from up to 30 percent spruce bark content. Suzuki et al. (1994) found 35 percent as the tolerable limit of bark substitution for particleboards. Xing et al. (2006) included up to 40 percent bark fibers in MDF and found its effect on the physical and mechanical properties more detrimental for the MOE, MOR, IB, and LE than for thickness swelling (TS) and water absorption.

Particle geometry is a prime parameter affecting both board properties and its manufacturing process (Moslemi 1974). Suchsland and Woodson (1990) suggested that particle geometry is of greater significance in the development of board properties than the actual mechanical properties of the fibers themselves. It has a definite relationship with the compression ratio, and thus it will influence the density of the composite (Brumbaugh 1960, Bhagwat 1971, Hoglund et al. 1976, Kelley 1977).

The type of particle, its geometry and the combination of particles of different type and geometry have significant impacts on board quality (Maloney 1993). The variation of particle geometry results in different fiber surface areas which have a direct impact on the adhesive content per unit particle surface area (kg/m^2) (Moslemi 1974). Generally, the specific surface area (m^2/kg) of longer fibers is lower than that of shorter fibers of the same species and thickness due to the higher surface of the fiber cross sections. Thus, the adhesive content per unit particle surface area is higher for long particles than for short particles at a given adhesive content per unit ovendry mass of particles.

Only a few studies examined the effect of bark particle geometry on the properties of particleboard. Gertjejansen and Haygreen (1973) compared properties of wafer and flake-type particles and found that IB, LE and TS were higher on waferboard made from 13 mm wide (1/2 inch) flakes than those made from 38 mm wide (1-1/2 inch) wafers. Blanchet (1999) found that substitution of wood particles by wood fibers in the surface layer improved the MOE and the MOR of particleboard made from black spruce bark.

The objectives of this study were 1) to determine the effects of bark content, and particle geometry (shape, size and distribution) on the physical and mechanical properties of particleboard made from black spruce and trembling aspen bark; and 2) to determine whether these boards could meet the usual performance requirements for wood particleboards through optimization of bark particle content and geometry.

Materials and methods

Bark particle production

Fresh black spruce (*Picea mariana* (Mill.)) and trembling aspen (*Populus tremuloides* (Michx.)) bark was collected, respectively, from the Arbec Forest Products Inc. softwood sawmill located in L'Ascension, Québec, Canada and from the OSB mill of Louisiana Pacific Canada, Québec-Chambord OSB Division located in Chambord, Québec, Canada. The raw bark was taken directly from the debarking units in each mill. A laboratory dry kiln was used to dry the bark at 60 °C to a final MC of 5 percent. The wood content of bark residues was determined in order to calculate the effective bark content (ebac) in the panel. The density of the different bark species was determined by a volumetric method.

After drying, the bark was crushed in a hammer mill and sieved in four groups. The first group with particle size of 0.2 to 1.5 mm was used for the surface layer. The three other groups, 1.5 to 2.6, 2.6 to 5.0 and 5.0 to 7.0 mm, were used as core layers in order to assess the effect of bark particle size on the properties of particleboard. Wood particles were added to the bark particles to produce mixed wood bark particleboards. The particle size distribution of each raw material type (bark and wood) was investigated with CE Tyler testing sieve shaker.

Chemical characterization of bark

The bark specimens were sampled and prepared according to the Tappi T257 cm–02 standard. The insoluble lignin content was determined by the conventional Klason method (Tappi T222 om–06) and the acid-soluble lignin was quantified using absorption spectroscopy at 205 nm (Tappi useful method UM–250). The holocellulose content of extractive-free samples was determined by the chlorite method (Wise et al. 1946) and was corrected for residual lignin after hydrolysis of holocellulose with sulphuric acid. The cellulose content was determined by the Kuschner and Hoffer nitric acid method (Browning 1967). Two replicates were used for each sample. Total bark extractive content was determined by successive extractions from powdered bark with organic solvents (hexane, denatured ethanol and hot water) according to Tappi T 204 cm–07 and T 207 cm–99 standards.

Adhesive content

The phenol-formaldehyde (PF) adhesive content in the core layer was determined in such a way that the adhesive take-up per unit surface area of particle (kilogram of adhesive per square meter of particle surface area) remains constant for all particle sizes and types of panel considered in this study.

The procedure described by Dunky (1988) was adapted and used for that purpose. Particle specific surface (S_S) represents the particle surface area per ovendry weight of particles (m^2/kg). It is assumed that the particles shape is square in cross section and the thickness classes are determined by screening. Therefore, the particle size distribution was used to calculate

Table 1. — Particle type, size, and adhesive content.

Particle						
	Size	Mean thickness	Mean density	Particle specific surface area S_S	Adhesive content per unit surface L_S	Specific adhesive content L
Type	---------- (mm) ----------		(kg/m^3)	(m^2/kg)	(kg/m^2)	(percent)
Bark	0.2 to 1.5	--	--	--	--	12
	1.5 to 2.6	2.07	673	1.44	0.060	9
	2.6 to 5.0	3.66	673	0.82	0.060	5
	5.0 to 7.0	5.97	673	0.50	0.060	3
Wood	0.2 to 2.8	--	--	--	--	12
	0.2 to 5.6	1.48	610	1.48	0.060	9

Table 2. — Factorial experimental design used for each species and adhesive content of the core layer.

Bark species	Bark content	Bark particle size	Adhesive content per unit surface of particles L_s	Adhesive content L	Replications
	(percent)	(mm)	(kg/m^2)	(percent)	
Black spruce	50	1.5 to 2.6	0.060	9	3
		2.6 to 5.0	0.060	7	3
		5.0 to 7.0	0.060	6	3
	100	1.5 to 2.6	0.060	9	3
		2.6 to 5.0	0.060	5	3
		5.0 to 7.0	0.060	3	3
Trembling aspen	50	1.5 to 2.6	0.060	9	3
		2.6 to 5.0	0.060	7	3
		5.0 to 7.0	0.060	6	3
	100	1.5 to 2.6	0.060	9	3
		2.6 to 5.0	0.060	5	3
		5.0 to 7.0	0.060	3	3

the mean thickness of each particle type with the following formula:

$$Mean\ thickness = \Sigma\, x_i f_i \qquad [1]$$

where x_i represents the median of a particle size class i (m) and f_i the corresponding weight ratio of the particle size class i (kg/kg).

By assuming that particles lateral and end surfaces do not contribute significantly to the adhesion, the particle specific surface was calculated as follows:

$$S_S = \frac{2}{mean\ thickness \times density} \qquad [2]$$

The specific adhesive content (%) is defined as follows:

$$L = \frac{\text{dry mass of adhesive}}{\text{ovendry mass of wood particles}} \times 100 \qquad [3]$$

and the adhesive content per unit surface area of particle (kg/m^2) is defined as:

$$L_S = \frac{(L/100)}{S_S} = \frac{\text{dry mass of adhesive}}{\text{unit surface of wood particles}} \qquad [4]$$

Based on the study of Lehmann (1974) and industrial practice, a L value of 3 percent PF was attributed to the coarse bark particles (5.0 to 7.0 mm) and the corresponding L_S was calculated. This L_S value was then kept constant for all particle size classes and used as a reference to determine the L value of the other particle size classes used in the core layer. **Table 1** summarizes the results obtained. For the core layer of mixed particles (bark and wood), the mean adhesive content of the two types of particles was used. The adhesive content used in the core layer of all particleboard types is presented in **Table 2**.

Particleboard production

Particleboards measuring 560 by 460 by 8 mm with a target density of 800 kg/m^3 were manufactured using a 1000 by 1000 mm Dieffenbacher hot-press equipped with a PressMAN control system manufactured by Alberta Research Council. A liquid PF adhesive from Dynea Company Ltd. was used. The adhesive contents used are shown in **Table 2**. Panels were pressed at a platen temperature of 200±0.1 °C for a press closing time of 20 seconds, curing time of 200 seconds and an opening time of 60 seconds which resulted in a total press cycle of 280 seconds. One and 0.5 percent of wax were added respectively to the surface and core layer particles.

Determination of physical and mechanical properties

The panels were conditioned at 20±3 °C and 65±1 percent relative humidity for 1 week. Physical and mechanical properties were determined according to the American National Standards Institute (ANSI) standard A.208.1–1999. The properties determined were the modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending, internal bond (IB), Janka hardness (HJ), thickness swelling (TS), and linear expansion (LE). However, in order to consider the impact of the sample density on the mechanical and physical properties of particleboards, the obtained values were adjusted according to the procedure used by Garcia et al. (2005) and Xing et al. (2007). Therefore, the specific modulus of elasticity (MOE_{spec} = MOE/sample density), the specific modulus of rupture (MOR_{spec} = MOR/sample density), the specific

Table 3. — Bark anhydrous density of each kind of raw material and the nominal and effective bark content in the panel.

Species	Code	Bark density (kg/m^3)	Nominal bark content	Effective bark content in the panel (ebac*)
			(percent)	
Black spruce bark	BSB	639 (17)	50	32.0
			100	82.0
Trembling aspen bark	TAB	707 (67)	50	38.1
			100	88.1

*calculation based on the ovendry weight.
SD is in brackets.

internal bond (IB_{spec} = IB/sample density), the specific hardness (HJ_{spec} = HJ/sample density), the specific thickness swelling (TS_{spec} = TS/sample density), and the specific linear expansion (LE_{spec} = LE/sample density) were used for statistical analyses. For comparison purposes, the ANSI standard property values for medium density particleboards were divided by the target density (800 kg/m^3) to obtain the corresponding specific values. For instance, the corresponding specific properties for MOE, MOR, IB, HJ, TS, and LE are 2.16 MPa m^3 kg^{-1}, 0.014 MPa m^3 kg^{-1}, 0.50 kPa m^3 kg^{-1}, 2.78 N m^3 kg^{-1}, 0.01 percent m^3 kg^{-1}, and 0.44 × 10^{-3} percent m^3 kg^{-1}, respectively.

Experimental design and data analyses

The factorial design used in this study is presented in **Table 2**. The factors considered were species (black spruce and trembling aspen), bark content (50 and 100%), and bark particle size of the core layer (1.5 to 2.6 mm, 2.6 to 5.0 mm, and 5.0 to 7.0 mm). For mixed bark and wood particleboards, a bark content of 50 percent was used in both surface and core layers. The mixture of bark and wood particles was made in a cylindrical rotary blender in order to obtain a homogeneously mixed furnish material. This led to 12 combinations with 3 replicates resulting in a total of 36 panels (**Table 2**). Moreover, 3 control panels were manufactured in the same laboratory conditions with wood particles obtained from a particleboard mill.

The Statistical Analysis System (SAS) software 9.1 was used for statistical analyses. The analysis of variance (ANOVA) was performed at 13 levels (12 levels of treatments and 1 level of control). Contrasts were performed to determine interactions between the factors studied. Finally, comparisons between treatments and control were performed in order to identify the best treatments following the method of Scott and Knott (1974).

Results and discussion

Raw material characteristics and properties

The anhydrous bark density and the nominal and effective bark content ratio of bark residues are presented in **Table 3**. The wood content of black spruce bark (BSB) residues is higher than that of trembling aspen bark (TAB) residues. **Figure 1** shows the size distribution of bark and wood particles used in the surface layer. The size distribution of black spruce and trembling aspen bark particles as well as the industrial wood particles used in the core layer are presented in **Table 4** and indicate that the sizes of more than 77 percent of the industrial wood particles used in the core layer are below

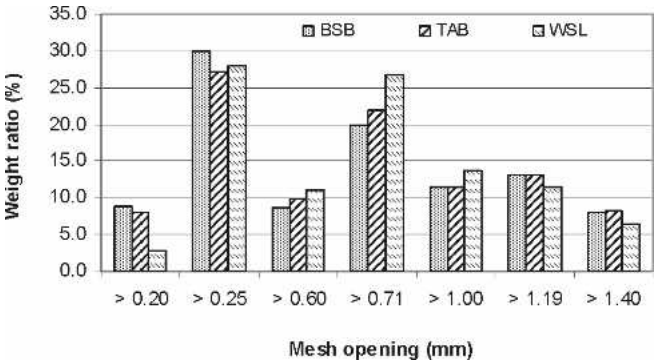

Figure 1. — Size distribution of particles used in the surface layers (BSB = black spruce bark; TAB = trembling aspen bark; WSL = industrial wood particles of surface layer).

2.80 mm. Therefore, only the bark particles of size 1.5 to 2.6 mm almost fit that optimum size range used in wood particleboard manufacture.

The chemical composition of BSB and TAB is presented in **Table 5**. The holocellulose of BSB and TAB was higher than reported by Harun and Labosky (1985). In contrast, the lignin content of BSB and TAB was significantly lower than that of most American softwoods and hardwoods bark (Harun and Labosky 1985). **Table 5** also shows significant differences between BSB and TAB in terms of hexane and denatured ethanol content as well as hot-water solubility. Trembling aspen bark showed a higher amount of lipophilic extractives and higher total extractive content than BSB.

Physical and mechanical properties of particleboards

The mean values of the physical and mechanical properties of particleboards made from black spruce and trembling aspen bark are presented in **Table 6**. A typical vertical density profile of particleboards made from bark is presented in **Figure 2**. A 1000 by 1000 mm Dieffenbacher hot-press equipped with a modern PressMAN control system provided repetitive experimental conditions and the vertical density profile of particleboards did not significantly change between treatments. ANOVA results are summarized in **Table 7**. Detailed analysis of the effects of bark content and particle size on the physical and mechanical properties are discussed in the following sections.

Bending properties

ANOVA results presented in **Table 7** show a significant effect of species, bark content and bark particle size on the static bending properties (MOE_{spec} and MOR_{spec}) at the 0.01 probability level. **Figures 3** and **4** show that MOE_{spec} and MOR_{spec} decreased with increasing bark content. Therefore, the MOE and MOR of the particleboards made from 50 percent black spruce and trembling aspen bark content were higher than that of the particleboards made from the same species at 100 percent bark content. Particleboards made from 50 percent black spruce bark showed the highest bending properties. However, the MOE and MOR values obtained for these boards were respectively 12 and 37 percent lower than that of the control. This can be explained by the low cellulose content of bark (**Table 5**) as compared to wood. This is in agreement with the data reported by Fengel and Wegener (1984). As a result, bark particleboards strength and stiffness

Table 4. — Size distribution of particles used in the core layer.

Particle size (mm)	1.50 to 2.60				2.60 to 5.00					5.00 to 7.00	
Mesh opening (mm)	<1.50	>1.50	>1.70	>2.38	>2.60	>2.80	>3.35	>4.00	>4.76	>5.00	>6.30
	Weight ratio (percent)										
BSB		19.8	59.9	20.0	13.0	28.2	28.2	21.8	8.6	77.1	22.9
TAB		17.9	57.7	24.0	7.7	23.6	28.1	26.0	14.4	65.7	34.2
WCL	18.0	16.1	30.8	12.2[a]		9.8	5.4		7.7[b]		

BSB = black spruce bark. TAB = trembling aspen bark. WCL = wood particles of core layer.
Weight ratio of wood particles from size (a) 2.38 to 2.80 mm, and (b) 4.00 to 5.60 mm.

Table 5. — Bark chemical composition.

Component	Black spruce	Trembling aspen
	(percent)	
Holocellulose*	43.1	48.8
Cellulose	26.8	25.4
Total lignin	25.1	22.6
Lipophilic extractives	3.7	6.5
Ethanol soluble extractives	8.2	6.5
Hot water extractives	9.5	13.3
Total extractive content	21.4	26.3

*Holocellulose are hemicelluloses and a part of cellulose content.

are lower than that of wood particleboards. Moreover, the density of black spruce bark used in this study was lower than that of trembling aspen bark (**Table 3**). The higher is the bark density, the lower is the compression ratio (C_r). A higher C_r for black spruce bark mats led to significantly higher MOE and MOR (**Figures 3** and **4**). Particleboards made at 100 percent bark content of size 5.0 to 7.0 mm exhibited higher MOE and MOR values than those of the other size classes probably due to their higher wood content. **Table 7** also shows a significant effect of the interaction between bark content and bark particle size on both MOE_{spec} and MOR_{spec} at the 0.01 probability level and a significant effect of the interaction between species and bark content on the MOE_{spec} at the 0.01 probability level. These interactions mean that the effect of bark content is dependent on bark particle size and species. In spite of the difference in bark and adhesive contents, the results obtained for the MOE and MOR of particleboard made from black spruce and trembling aspen bark were in accordance with the findings of Blanchet et al. (2000) and Villeneuve (2004). The MOE and the MOR values of the panels made from 50 percent bark of both species exceeded the minimum requirements of the ANSI standard A208.1–1999 for commercial (M-1) and underlayment (PBU) panels. In addition, the MOE values of particleboard made from 100 percent black spruce (particle sizes: 1.5 to 2.6 mm and 5.0 to 7.0 mm) and trembling aspen (particle size: 5.0 to 7.0 mm) fulfilled the requirements of the ANSI standard. In contrast, the MOR values of all the boards made from 100 percent bark of the two species were lower than the minimum requirement of the same standard (**Figures 3** and **4**).

Internal bond

Table 7 shows a significant effect of bark content on the specific internal bond (IB_{spec}) at the 0.01 probability level. The IB_{spec} of the two species decreased with increasing bark content as shown in **Figure 5**. Blanchet et al. (2000) noticed that the tack of the blended furnish is lower for bark particles than for wood particles. They also found a decrease of the rate of heat transfer with an increase of the bark content. This may affect adhesive cure and could explain why the mechanical properties and especially the IB of the boards made from 100 percent bark content was lower than those of the ones made from 50 percent bark content. There was also a significant effect of the interactions between bark content and bark particle size, and between species and bark content on the specific internal bond (IB_{spec}) at the 0.01 probability level (**Table 7**). This implies that the effect of bark content on IB depends on the species and particle size. When particle size increases, the IB_{spec} of the boards made at 50 percent bark content decreases and that of those made at 100 percent bark content increases (**Fig. 5**). In fact, the IB decreased with an increase in the slenderness (length/thickness) ratio of the particles used in the core layer (Maloney 1973, Moslemi 1974). In addition, because of the trend of the bark to produce finer particles than wood during the refining process, the effective bark content of particle size class 5.0 to 7.0 mm was lower than that of the other size classes as well as the mean value shown in **Table 3**. Also, the higher length of those particles and consequently their higher slenderness ratio are a shortcoming for the IB of boards made at 50 percent bark content. The particleboards made at 50 percent black spruce bark of size 1.5 to 2.6 mm showed the highest IB value. However, the IB value obtained was 54 percent lower than that of the control. In fact, the bark particles of size 1.5 to 2.6 mm almost fit the optimum size range used in wood particleboard manufacture. This result is in accordance with that reported by Lehmann and Geimer (1974). They found a decrease of 20 to 30 percent on the IB following an addition of 25 percent Douglas-fir bark. All the boards made from mixed bark and wood particles met the requirements of the ANSI A208.1–1999 standard for M-1 and PBU grades. In contrast, all the boards made from 100 percent bark content did not meet the requirements of that standard except for those of trembling aspen bark of particle size range 5.0 to7.0 mm.

Hardness

Statistical analysis showed a significant effect of species and bark content on the specific Janka hardness (HJ_{spec}) at the 0.01 probability level (**Table 7**). **Figure 6** shows that HJ_{spec} of particleboard made from black spruce bark was higher than that of particleboard made from trembling aspen bark. In fact, a higher compression ratio of the black spruce bark mat due to the lower density of black spruce bark increased the hardness of the boards produced. In addition, the higher is bark content, the lower is HJ_{spec}. Particleboard made from 50 percent black spruce bark showed the highest HJ_{spec} value which was not significantly different than the control. Although HJ_{spec} was not significantly different due to bark particle size, particleboard made from 100 percent trembling aspen bark of 1.5 to

Table 6. — Means values of physical and mechanical properties of particleboards made from black spruce and trembling aspen bark.

Factorial design			Physical and mechanical properties						
	Bark content	Bark particle size of core layer	Density	MOE	MOR	IB	HJ	TS	LE
Species	(percent)	(mm)	(kg/m^3)	------- (MPa) -------		(kPa)	(N)	----- (percent) -----	
Control			812	3867	26.5	1724	4224	8.2	0.22
			(31)	*(460)*	*(3.0)*	*(200)*	*(214)*	*(0.3)*	*(0.03)*
BSB	50	1.5 to 2.6	802	3198	15.7	758	3948	15.2	0.34
			(16)	*(17)*	*(0.7)*	*(61)*	*(49)*	*(2.4)*	*(0.02)*
		2.6 to 5.0	806	3404	16.4	608	3889	18.1	0.32
			(8)	*(117)*	*(0.4)*	*(51)*	*(219)*	*(0.4)*	*(0.03)*
		5.0 to 7.0	804	3378	15.7	499	4159	14.8	0.32
			(29)	*(296)*	*(1.3)*	*(178)*	*(131)*	*(2.7)*	*(0.01)*
	100	1.5 to 2.6	734	1579	7.4	227	2248	13.6	0.57
			(18)	*(97)*	*(0.3)*	*(67)*	*(89)*	*(0.8)*	*(0.06)*
		2.6 to 5.0	705	1327	5.4	131	2591	22.2	0.58
			(27)	*(154)*	*(1.3)*	*(14)*	*(371)*	*(3.1)*	*(0.04)*
		5.0 to 7.0	885	2376	9.7	383	2935	11.4	0.48
			(4)	*(199)*	*(1.0)*	*(60)*	*(144)*	*(1.9)*	*(0.06)*
TAB	50	1.5 to 2.6	738	2519	13.0	532	3403	10.1	0.33
			(7)	*(117)*	*(0.5)*	*(47)*	*(353)*	*(0.5)*	*(0.02)*
		2.6 to 5.0	727	2484	12.9	518	3046	9.1	0.33
			(15)	*(127)*	*(1.5)*	*(65)*	*(177)*	*(1.1)*	*(0.02)*
		5.0 to 7.0	705	2323	11.1	379	3218	8.7	0.35
			(10)	*(17)*	*(0.7)*	*(94)*	*(263)*	*(1.2)*	*(0.03)*
	100	1.5 to 2.6	737	1340	5.9	344	1761	9.5	0.66
			(24)	*(116)*	*(0.6)*	*(62)*	*(218)*	*(0.2)*	*(0.07)*
		2.6 to 5.0	727	1355	5.0	280	1888	11.0	0.68
			(7)	*(64)*	*(0.1)*	*(62)*	*(125)*	*(1.7)*	*(0.08)*
		5.0 to 7.0	868	2117	9.3	548	2461	10.0	0.49
			(7)	*(35)*	*(0.0)*	*(49)*	*(385)*	*(1.1)*	*(0.01)*

Standard error is in parentheses. BSB = black spruce bark, TAB = trembling aspen bark, MOE = modulus of elasticity, MO*R* = modulus of rupture, IB = internal bond, HJ = Janka hardness, TS = thickness swelling, LE = linear expansion.

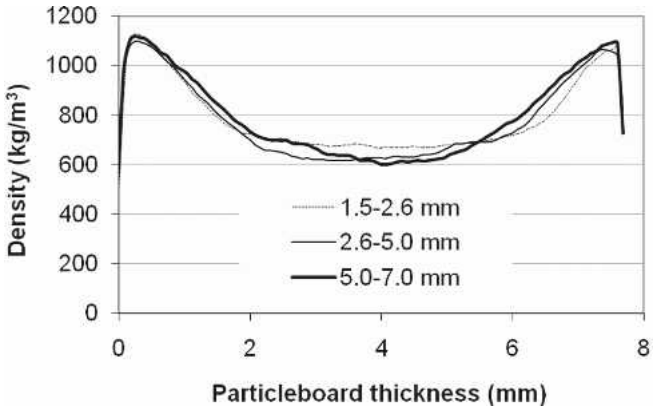

Figure 2. — Typical vertical density profile of particleboard made from bark.

2.6 mm and 2.6 to 5.0 mm particle size need a slight improvement to meet the minimum requirement of the ANSI A208.1–1999 standard for flooring products (**Fig. 6**).

Thickness swelling

Table 7 shows a significant effect of species and bark particle size on the specific thickness swelling (TS_{spec}) at the 0.01 probability level. **Figure 7** shows that TS_{spec} of particleboard made from trembling aspen bark is lower than for those made from black spruce bark. An extraction with hexane revealed 6.5 and 3.7 percent lipophilic extracts content in trembling aspen and black spruce bark, respectively (**Table 5**). The hydrophobic property of the lipophilic extractives increased the thickness swelling resistance of the boards made from trembling aspen bark. Boards made from black spruce bark particles of size 2.6 to 5.0 mm exhibit a higher TS values (**Fig. 7**). Thickness swelling values obtained for all the boards made from trembling aspen bark were not significantly different from the control except for those made from 100 percent bark particles of size 2.6 to 5.0 mm. In addition, the TS of particleboards made from 100 percent black spruce bark particles of size 5.0 to 7.0 mm was not significantly different from the control. Thus, with a slight improvement of the panel manufacturing process, these boards could fulfill the ANSI standard requirement (**Fig. 7**). In contrast, the TS values of the other boards were significantly higher than the control. **Table 7** also shows a significant effect of the triple interaction among species, bark content and bark particle size on TS_{spec} at 0.05 probability level and a significant effect of the interactions between species and bark particle size and between bark content and bark particle size on TS_{spec} at 0.01 probability level. These interactions suggest that the effect of bark particle size on the TS depends on the species and the bark

Table 7. — Results of the analysis of variance (F-values) for physical and mechanical properties of particleboard made from black spruce and trembling aspen bark.

Source of variation	Physical and mechanical properties					
	MOE_{spec}	MOR_{spec}	IB_{spec}	HJ_{spec}	TS_{spec}	LE_{spec}
Species	60.85**	26.39**	0.49^{NS}	33.35**	94.28**	11.18**
Bark content	912.28**	730.83**	86.46**	419.08**	3.38^{NS}	195.69**
Bark particle size (BPS)	23.91**	6.37**	3.12^{NS}	1.79^{NS}	24.96**	17.36**
Species x bark content	8.36**	2.37^{NS}	25.84**	2.67^{NS}	0.02^{NS}	0.13^{NS}
Species x BPS	1.12^{NS}	0.23^{NS}	0.73^{NS}	0.23^{NS}	14.64**	0.50^{NS}
Bark content x BPS	27.99**	20.86**	18.58**	2.70^{NS}	12.07**	22.59**
Species x bark content x BPS	3.18^{NS}	2.45^{NS}	0.12^{NS}	0.28^{NS}	4.47*	1.18^{NS}

MOE = modulus of elasticity, MOR = modulus of rupture, IB = internal bond, HJ = Janka hardness, TS = thickness swelling, LE = linear expansion, MOE_{spec} = MOE divided by sample density, MOR_{spec} = MOR divided by sample density, IB_{spec} = IB divided by sample density, HJ_{spec} = HJ divided by sample density, TS_{spec} = TS divided by sample density, LE_{spec} = LE divided by sample density. NS = not significant at the 0.05 probability level. *significant at the 0.05 probability level. **significant at the 0.01 probability level.

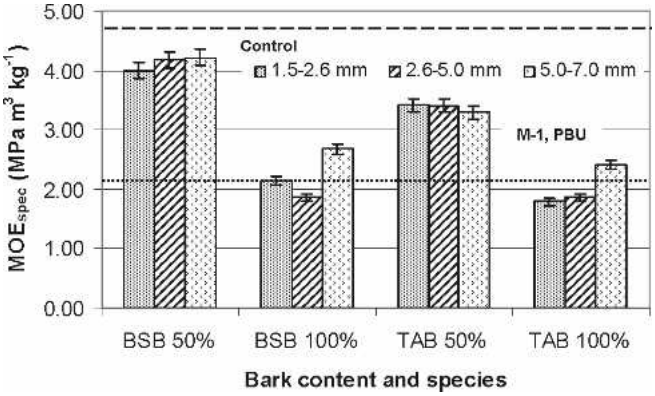

Figure 3. — Effect of bark content and particle size on the specific modulus of elasticity (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard particleboard grades).

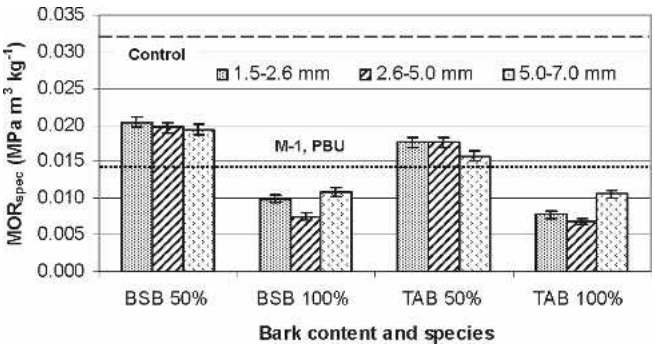

Figure 4. — Effect of bark content and particle size on the specific modulus of rupture (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard particleboard grades).

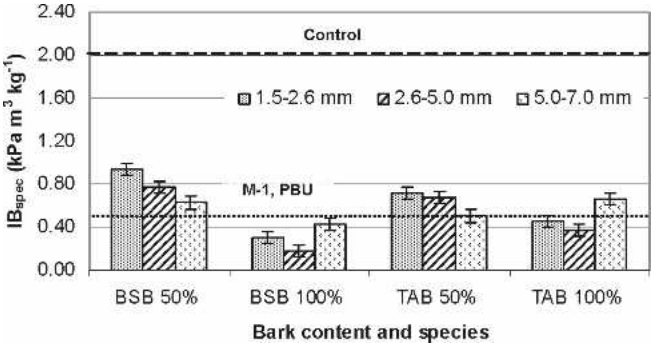

Figure 5. — Effect of bark content and particle size on the specific internal bond (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard particleboard grades).

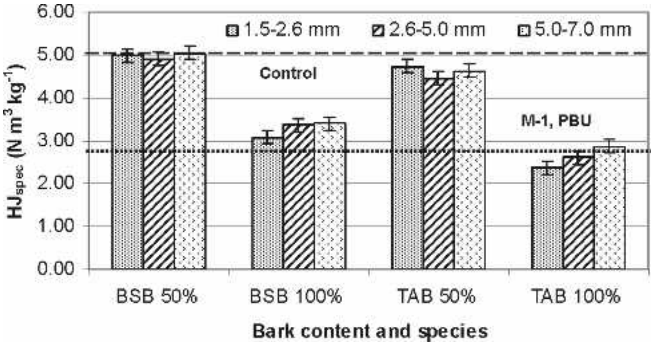

Figure 6. — Effect of bark content and particle size on the specific Janka hardness (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard particleboard grades).

content. This result is similar to the findings of Xing et al. (2006) who indicated a less detrimental effect of bark content on the TS of the MDF panels.

Linear expansion

Table 7 shows a significant effect of species, bark content and bark particle size on the specific linear expansion (LE_{spec}) at the 0.01 probability level. **Figure 8** shows that LE_{spec} increased with increasing bark content. Also, LE_{spec} of the particleboards made from 100 percent coarse bark particles (5.0 to 7.0 mm) was lower than that of the other particle size classes due to a lower bark content ratio for the coarse particles. The lower values of LE_{spec} were obtained for boards made from 50 percent black spruce bark and 50 percent wood particles, which was 45 percent higher than for the control. **Table 7** also shows a significant effect of the interaction between bark content and bark particles size on the LE_{spec} at 0.01 probability level. This means that the effect of bark content on LE depends on bark particles size. Even though LE was not significantly different between particleboards made of 50 percent trembling aspen bark, two of them (2.6 to 5.0

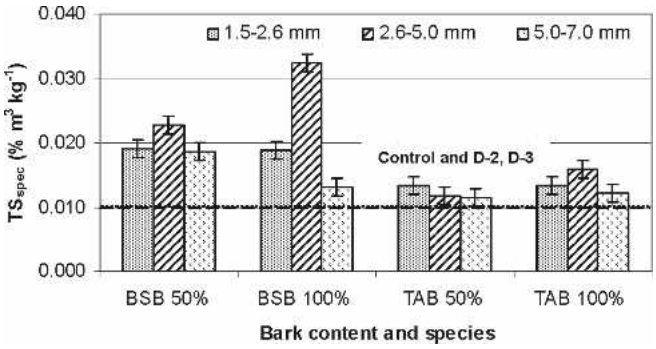

Figure 7. — Effect of bark content and particle size on the specific thickness swelling (BSB = black spruce bark; TAB = trembling aspen bark. D-2, D-3: ANSI standard particleboard grades).

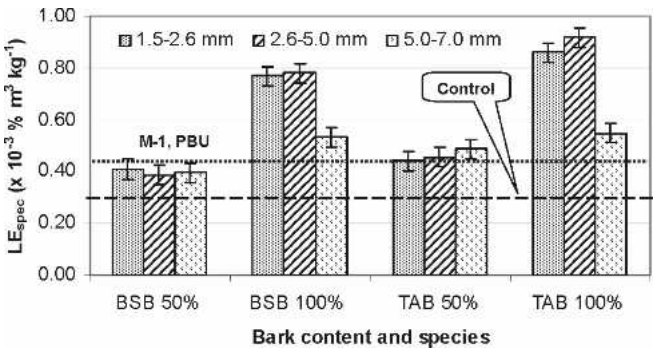

Figure 8. — Effect of bark content and particle size on the specific linear expansion (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard particleboard grades).

and 5.0 to 7.0) would require a slight improvement to fulfill the requirement of ANSI A208.1 standard for LE (**Fig. 8**).

The significant impacts of bark origin, bark particle morphology and bark content on most of the physical and mechanical properties of the particleboard suggest that these properties could be further improved by optimizing the bark fragmentation methods and using specifically designed panel-manufacturing processes for each kind of raw material.

Comparison of the physical and mechanical properties of bark-based particleboards produced in this study to ANSI Standard requirements suggests that most of them are suitable for furniture, cabinet making, floor underlay and substrates.

Conclusions

The results obtained in this study lead to the following conclusions:

1. The mechanical properties including the modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending, the internal bond (IB) and the Janka hardness (HJ) decreased with increasing bark content. In contrast, an increase in bark content resulted in an increase in linear expansion (LE) and a slight effect on thickness swelling (TS).
2. The effect of particle size was observed mostly on IB. In spite of the low effective bark ratio of the coarse particles, the IB of the boards often decreased with increasing bark particle size. For the other properties, the boards made of 100 percent bark seem to be more affected by particle geometry than those made of 50 percent bark.
3. Particleboards made of 50 percent black spruce bark showed the best MOE, MOR, IB, HJ, and LE. However, the results obtained for the MOE, MOR, IB, and LE of the 50 percent black spruce bark particleboards were respectively 12, 37, 54, and 45 percent lower than for the 100 percent wood particleboard control.
4. Particleboards made from trembling aspen bark showed low TS value which was not significantly different from the 100 percent wood particleboard control.
5. All the boards made from 50 percent bark of black spruce and trembling aspen met the requirements of the ANSI A208.1–1999 for commercial (M-1) and underlayment (PBU) panels for the MOE, MOR, and HJ.

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