Physical and mechanical properties of particleboard made from extracted black spruce and trembling aspen bark

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Abstract

Bark residues are mostly used for thermal energy production. However, a better utilization of that resource could be as raw material for particleboard (PB) manufacturing. Bark is also a source of numerous extractives used in several fields including pharmacology and adhesive production. This study aims at analyzing the effect of hot water extracted bark particle content and size on the physical and mechanical properties of bark PBs including the modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB), Janka hardness (HJ), thickness swelling (TS) and linear expansion (LE). Moreover, these properties were compared both to a control (100% wood particles) and to PB made from the same content of unextracted bark. The results showed that, while the mechanical properties of the PB made from extracted black spruce and trembling aspen bark decreased with increasing bark content, LE increased. PB made of fine particles often showed higher IB and lower TS values. Hot water extraction of the bark had a detrimental effect on all the physical and mechanical properties of the PBs produced except for the Janka hardness, where no significant decrease was found. The MOE and MOR of the PBs made from 50 percent black spruce and trembling aspen bark met the requirements of the ANSI standard for commercial (M–1) and underlayment (PBU) grades. In contrast, the dimensional properties (TS and LE) of all the boards did not fulfill the minimum requirements of the ANSI standard.

Large quantities of bark are produced by the forest industry and are mostly used for thermal energy production. In the Province of Québec, 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 (PB) manufacturing (Blanchet 1999, Blanchet et al. 2000, Villeneuve 2004, Ngueho Yemele et al. 2007).

Bark is also an important source of extractives used in several fields including pharmacology and adhesive production. Experimental studies support the significant role of the polyphenols as anti-inflammatory, antiallergic, and antiviral agents (Middleton 1998) as well as their effect in cancer prevention (Savouret and Quesne 2002) and cardiovascular diseases (Frankel et al. 1993). Recent developments in tannin-based adhesives were presented by Pizzi (2006).

Two major approaches to manufacture bark PBs can be identified in the literature. 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, NguehoYemele et al. 2007), isocyanates (Deppe and

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Hoffman 1972) and extractives-based adhesives (Anderson et al. 1974a, 1974b; Nemli et al. 2004b; Nemli and Colakoglu 2005) were used to bond bark particles. Villeneuve (2004) compared the strength of PBs made with UF and PF adhesives and found the MOE, MOR and IB of the boards made of PF adhesive higher than that of those made of UF adhesive. Therefore, PF adhesive can be use to improve the properties of bark PBs produced for interior applications.

The presence of extractives in the raw material impacts the PB in both negative and positive ways. Moslemi (1974) reported that extractives can have adverse effects on the setting of adhesives, thereby lowering the particle-particle bond strength. Extractives may cause blows and severely reduce the internal bond strength. In the other hand, phenolic extractives can react with formaldehyde and limit water absorption as well as improve thickness swelling resistance of the board (Moslemi 1974; Anderson et al. 1974a, 1974b, 1974c; Plackett and Troughton 1997; Nemli et al. 2004a, 2004b; Nemli and Colakoglu 2005; Nemli et al. 2006). For instance, Nemli et al. (2004a, 2006) found a significant improvement of thickness swelling, decay resistance and formaldehyde emission of PB made from wood particles impregnated with bark extractives. However, the mechanical properties of these boards were lower than for those made from unimpregnated particles. Similar results were reported by Nemli et al. (2004b) and Nemli and Colakoglu (2005) with addition of black locust and mimosa bark particles to the furnish. Anderson et al. (1974a, 1974c) found that paraformaldehyde added to wood sprayed with concentrated ponderosa pine and white fir bark extract reacted with phenolic compounds present in the extract and formed a waterproof bonding agent which improved the board water absorption resistance and thickness swelling. Therefore, extracted bark particles may lead to high moisture absorption and thickness swelling. The high content of condensed polyphenol present in bark and able to react with formaldehyde was pointed out as the main raison of the aforementioned improvement (Nemli et al. 2004b).

Nevertheless, the use of bark in wood PB manufacturing is currently viewed negatively due to the fact that excessive bark content in the raw material produces significant adverse effects on strength and dimensional properties. Several examples given in the literature demonstrate a decrease of the modulus of elasticity (MOE), modulus of rupture (MOR) and internal bond (IB) with addition of bark while the linear expansion (LE) increased (Dost 1971, Lehmann and Geimer 1974, Wisherd and Wilson 1979, Muszynski and McNatt 1984, Blanchet et al. 2000, Ngueho Yemele et al. 2007). Muszynski and McNatt (1984) indicated that PBs 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 PBs. 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) pointed out the high significance of particle geometry in the development of board properties. 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 fiber 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 fiber surface area is higher for long fibers than for short fibers at a given adhesive content per unit ovendry mass of particles.

Only few studies examined the effect of bark particle geometry on the properties of PB. Gertjejansen and Haygreen (1973) compared properties of wafer and flake-type particles and found that the IB, the LE and the 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 the substitution of wood particles by wood fibers in the surface layer improved the MOE and the MOR of PBs made from black spruce bark.

Ngueho Yemele et al. (2007) found that the MOE, MOR, and IB of PB made from black spruce and trembling aspen unextracted bark decreased with increasing bark content. They also found that the IB of the boards often decreased with increasing bark particle size.

The objectives of this study were 1) to determine the effect of extracted bark particle content and size on the physical and mechanical properties of PB made from black spruce and trembling aspen bark; 2) to compare the physical and mechanical properties of PB made from extracted bark to those of unextracted bark.

Material and methods

Bark extraction and particle production

Fresh black spruce (*Picea mariana* (Mill.)) and trembling aspen (*Populus tremuloides* (Michx.)) bark was collected respectively from Arbec Forest Products Inc. softwood sawmill located in L'Ascension, Québec, Canada, and from the Louisiana Pacific Canada OSB mill located in Chambord, Québec, Canada. The raw bark was taken directly from the debarking units in each mill. Bark densities, wood content of bark residues, and the effective bark content (ebac) of the panels were determined according to the procedure described in Ngueho Yemele et al. (2007).

Hot water extraction was performed at a large scale in order to produce extracted particles for PB manufacturing. Bark was soaked into 55 °C water. The mean concentration was 35 and 28 g of dried weight per liter of hot water for black spruce and trembling aspen, respectively. The system was heated with water vapor and the average temperature maintained at 100 °C for 3 hours. The weight loss ratio was determined gravimetrically and the results were reported as a percentage of the dry raw material weight. Weight loss comprises the extracts and undesirable materials like sand, stone, etc. A weight loss after extraction and air-drying of 16.6 and 10.8 percent was obtained for black spruce and trembling aspen, respectively.

Table 1. — Factorial experimental design used for each species and adhesive content of core layer.

Species	Extracted bark content (percent)	Bark particle size class of core layer (mm)	Adhesive content of core layer (percent)
Black spruce	50	Fine	9
		Medium	7
		Coarse	6
	100	Fine	9
		Medium	5
		Coarse	3
Trembling aspen	50	Fine	9
		Medium	7
		Coarse	6
	100	Fine	9
		Medium	5
		Coarse	3

The air-dried extracted bark was crushed in a hammer mill and sieved in four groups: one for the surface layer and three for the core layer. Wood particles were added to the bark particles to produce mixed wood and bark PBs. The particle size distribution of each raw material type (extracted bark and wood) was determined with a CE Tyler testing sieve shaker.

Bark organic and inorganic extractive content

The bark was sampled and prepared according to Tappi T 257 (Tappi 2002). Total extractive contents, for both unextracted and extracted bark, were determined by successive extraction of bark flour with organic solvents (first with hexane and afterwards with denatured ethanol) and then with hot water, according to Tappi T 204 (Tappi 2007a) and T 207 (Tappi 1999) standards. The ash content was determined according to Tappi T 211 (Tappi 2007b). Two replicates were used for each sample.

Raw material pH value and buffering capacity measurement

Knowledge of pH and buffering capacity of the raw material (bark and wood) is important for the understanding of the adhesive curing process. For each particle size, the aqueous extract was prepared by refluxing 25 g of dry powdered bark in 250 mL of distilled water for 20 minutes. Two replicates for each sample were prepared. After refluxing, the mixture was filtered through a filter paper using a vacuum. The aqueous extract was cooled to room temperature in a 25 mL pipette and diluted to 50 mL before titration. After recording the initial pH, 50 mL of extract solution was titrated potentiometrically to a pH of 3 (for alkaline buffering capacity) and 7 (for acid buffering capacity) with nominal 0.025 N H_2SO_4 and 0.025 N NaOH solution respectively.

Particleboard production

PBs 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 phenol formaldehyde adhesive from Dynea Company Ltd was used. The adhesive content shown in **Table 1** was determined by the procedure described by Ngueho Yemele et al. (2007) in order to maintain the adhesive content per unit specific surface (kg m^{-2}) constant. Panels were pressed at a platen temperature of 200 ± 0.1 °C and a maximum mat pressure of 5 MPa, 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 in the blender.

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. For the mechanical properties, an hydraulic test machine (MTS) with 5 kN capacity was used for load application, displacement measurement, and data acquisition. 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 PBs, the obtained values were adjusted (Garcia et al. 2005, Xing et al. 2007). Thus, other dependent variables such as the specific modulus of elasticity (MOE_{spec} = MOE/sample density), the specific modulus of rupture (MOR_{spec} = MOR/sample density), the specific 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 defined to perform statistical analyses. For comparison purposes, the ANSI standard property values for medium density PBs were divided by the target density (800 kg/m^3) to obtained specific values. For instance, the corresponding specific values for the 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 work is presented in **Table 1**. The factors chosen were species (black spruce and trembling aspen), extracted bark content (50 and 100%), and bark particle size of the core layer (fine, medium and coarse). For mixed extracted bark and wood PBs, a bark and wood content of 50 percent was used in both surface and core layers. The mixture of extracted 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 1**). Moreover, 3 control panels were manufactured in the same laboratory conditions with wood particles obtained from a PB 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). Finally, properties of PB made from extracted bark were compared to those made from unextracted bark from a previous study (Ngueho Yemele et al. 2007).

Results and discussion

Raw material characteristics and properties

Relevant characteristics and properties of raw material are summarized in **Figure 1** and **Tables 2**, **3**, and **4**. **Figure 1** shows the size distribution of extracted bark and wood particles used in the surface layer. The size classes distribution of extracted black spruce and trembling aspen bark particles as well as the industrial wood particles used in the core layer are presented in **Table 2** and indicate that the sizes of more than 77 percent of the industrial wood particles used in the core layer are below 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 PB manufacture.

Bark organic and inorganic extractive contents presented in **Table 3** show significant differences between the denatured ethanol solubility of unextracted and extracted bark of both species. There was also a significant difference between the hot water solubility of unextracted and extracted trembling aspen bark. In contrast, the hexane solubility indicated that there was no significant effect of the hot water extraction on the lipophilic extractives of the two species (**Table 3**). Nevertheless, both extracted and unextracted trembling aspen bark exhibited higher amount of lipophilic substances than the black spruce bark.

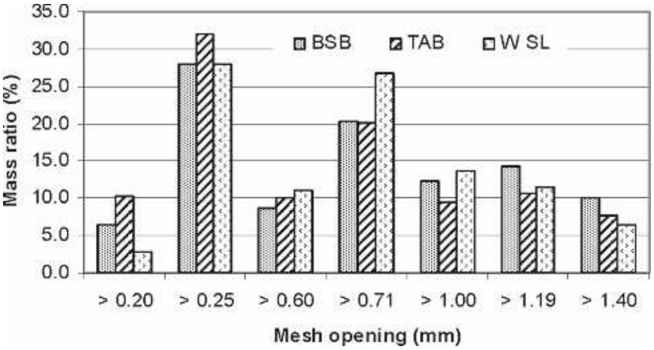

Figure 1. — Size distribution of extracted bark and wood particles used in the surface layer (BSB = extracted black spruce bark; TAB = extracted trembling aspen bark; W SL = industrial wood particles of surface layer).

Table 2. — Extracted bark particle size classes distribution for the core layer.

Particle class		Fine			Medium				Coarse	
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
					Mass ratio (percent)						
BSB		15.9	57.3	26.6	14.3	33.3	27.1	20.3	5.0	65.0	34.9
TAB		15.0	55.8	29.1	9.2	28.3	30.0	23.0	8.8	60.7	39.0
W CL	18.0	16.1	30.8	12.2		9.8	5.4		7.7		--

BSB = black spruce bark
TAB = trembling aspen bark
W CL = industrial wood particles of core

Table 3. — Bark organic and inorganic extractive content.

		Black spruce bark		Trembling aspen bark	
Solvent	Main groups	Unextracted	Extracted	Unextracted	Extracted
		(percent)			
Hexane	Fatty acids, fats, oils, waxes, resins, resin acids, sterols	3.7 (0.4)	3.5 (0.9)	6.5 (0.1)	6.6 (0.3)
Denatured ethanol	Coloring matter, stilbenes, polyphenols	8.2 (0.7)	4.0 (0.6)	6.5 (0.1)	2.4 (0.1)
Hot water	Carbohydrates, proteins, alkaloids, ash, tannins	9.5 (2.5)	8.1 (0.3)	13.3 (0.7)	6.1 (1.6)
Total		21.4	15.6	26.3	15.1
Ash	Inorganic extractives	1.8 (0.1)	1.9 (0.1)	5.1 (0.4)	5.4 (0.5)

SD is in parentheses.

Results on the pH value and buffering capacity of raw materials are presented in **Table 4**. Because of their important role for the understanding of the adhesive curing process, this topic is discussed in the last section.

Physical and mechanical properties of PBs

The ANOVA results are summarized in **Table 5**. Detailed analyses of the effect of extracted bark content and particle size on each physical and mechanical property as well as comparison with results obtained for unextracted bark particles of the same species (Ngueho Yemele et al. 2007) are discussed in the following sections.

Bending properties

ANOVA results presented in **Table 5** show a significant effect of extracted bark content on the static bending properties (MOE_{spec} and MOR_{spec}) at 0.01 probability level and a significant effect of species and bark particle size on the MOE_{spec} at 0.01 and 0.05 probability level respectively. **Figures 2** and **3** show that for both species, the MOE_{spec} and the MOR_{spec} obviously decreased with increasing extracted bark content. Likewise for PBs with 100 percent bark content, **Figure 2** shows an increase of MOE_{spec} with increasing particle size. All the boards produced with 50 percent extracted bark content exhibited higher values of MOE and MOR than that obtained with 100 percent bark content. Moreover, there was no significant difference of MOE and MOR among the PBs made from 50 percent extracted bark content of both species. In fact, Ngueho Yemele et al. (2007) reported a lower cellulose content of black spruce and trembling aspen bark compared to wood particles.

Because of its degree of polymerization and linear orientation, cellulose is responsible for strength in the wood fibers (Winandy and Rowell 1984). This involves lower bending properties of PB made from 100 percent bark content than that of those made from 50 percent bark content. In addition, Blanchet et al. (2000) also found that the tack of the bark particle furnish and the rate of heat transfer through bark particles furnish were lower than for a wood particles furnish. This may result in an incomplete adhesive cure and could explain the decrease noticed for MOE and MOR with increasing bark content. **Table 5** also shows a significant effect of the interaction between extracted bark content and bark particle size on the MOE_{spec} at 0.01 probability level and a significant effect of the interaction between species and extracted bark content on both MOE_{spec} and MOR_{spec} at 0.01 probability level. This may suggest that the effect of extracted bark content on the MOE_{spec} and MOR_{spec} depends on bark particle size and species. The MOE and MOR values of the boards made from 50 percent extracted bark content of black spruce and trembling aspen were 33 and 50 percent lower than the control. Nevertheless, those values of MOE and MOR still exceeded the minimum requirements for the commercial (M–1) and the underlayment (PBU) grades (**Figs. 2** and **3**). In contrast, no boards made from 100 percent bark content of both species met these requirements.

Table 4. — pH and buffering capacity of raw materials.

Type of raw material	Particle size class	pH	Acid buffering capacity	Alkaline buffering capacity
			(mmol/l)	(mmol/l)
NEBSB	SL	3.99	3.31	2.10
	Fine	3.92	3.24	2.30
	Medium	3.93	2.62	1.93
	Coarse	4.08	2.00	1.90
EBSB	SL	3.96	1.59	1.67
	Fine	3.86	1.99	1.89
	Medium	3.84	1.92	1.71
	Coarse	3.91	1.78	1.86
NETAB	SL	4.45	3.56	5.07
	Fine	4.27	4.12	4.96
	Medium	4.41	3.48	4.53
	Coarse	4.32	3.42	4.22
ETAB	SL	3.95	2.96	2.20
	Fine	4.05	2.17	2.32
	Medium	3.95	2.37	2.13
	Coarse	3.84	2.36	1.72
Wood particles	SL	4.69	2.96	2.20
	CL	4.60	2.17	2.32

NEBSB: unextracted black spruce bark; EBSB: extracted black spruce bark; NETAB: unextracted trembling aspen bark; ETAB: extracted trembling aspen bark; SL: surface layer; CL: core layer.

Internal bond strength

Table 5 indicates a significant effect of species, extracted bark content and bark particle size on the specific internal bond (IB_{spec}) at 0.01 probability level. **Figure 4** shows that IB_{spec} of the PB made from extracted black spruce bark obviously decreased with increasing extracted bark content. For those panels made from extracted trembling aspen bark, the decrease is observed merely on fine and medium particle size classes. For coarse particles of trembling aspen bark, no significant difference of IB was noticed between 50 and 100 percent bark content. The highest value of IB was found on the PB made from 50 percent extracted fine bark particle of both species (**Fig. 4**). In fact, those particles showed a low slenderness (length-thickness) ratio. **Table 5** also shows a significant effect of all the interactions of the factors species, extracted bark content and bark particle size on the specific internal bond (IB_{spec}) at 0.01 probability level. However, the F-value of the factors extracted bark content and species were respectively 20 and six times that of bark particle size (**Table 5**). Thus, the variation observed on the IB_{spec} could be explained more by the difference of extracted bark content and species than on bark particle size. This may be due to a decrease of pH or/and a decrease of reactive materials like polyphenols, particularly bark tannin which can positively react with the adhesive and could have been extracted by hot water treatment. Although, the IB of the 50 percent bark boards of fine particles was 65 percent lower than the control, they met the requirement for M–1 and PBU grades of the ANSI standard as shown in **Figure 4**.

Hardness (Janka)

Table 5 shows a significant effect of the extracted bark content on specific Janka hardness (HJ_{spec}) at 0.01 probability level. **Figure 5** obviously shows that HJ_{spec} decreased with increasing bark content. There is also a significant effect of the triple interaction among species, extracted bark content and bark particle size on specific Janka hardness (HJ_{spec}) at 0.05 probability level. Moreover, the factor extracted bark content exhibited the highest F-value (**Table 5**). PB made from 100 percent extracted black spruce bark showed higher HJ than the PB made from 100 percent extracted trembling aspen bark. In contrast, all the boards made from 50 percent extracted trembling aspen bark showed higher HJ than the 50 percent extracted black spruce bark except those of medium size particles which was found to be not significantly different to those made from 50 percent trembling aspen bark (**Fig. 5**). The HJ of those boards were 9 percent higher than the control. All the PBs produced met the requirements of the ANSI A208.1–1999 standard except for those made from 100 percent extracted fine particles of trembling aspen bark (**Fig. 5**).

Thickness swelling

Table 5 indicates a significant effect of species, extracted bark content and bark particle size on specific thickness swelling (TS_{spec}) at 0.01 probability level. **Figure 6** obviously shows that TS_{spec} of PB made from trembling aspen bark is

Table 5. — Results of the analysis of variance (F-values) for physical and mechanical properties of PB made from extracted bark of black spruce and trembling aspen.

Source of variation	MOE_{spec}	MOR_{spec}	IB_{spec}	HJ_{spec}	TS_{spec}	LE_{spec}
Species	24.34**	1.07^{NS}	106.25**	2.75^{NS}	618.19**	0.14^{NS}
Extracted bark content (EBC)	733.79**	538.06**	365.11**	269.08**	28.57**	147.11**
Bark particle size (BPS)	4.56*	2.77^{NS}	17.59**	1.04^{NS}	20.33**	1.75^{NS}
Species × EBC	21.34**	9.27**	91.12**	15.91**	60.29**	1.95^{NS}
Species × BPS	1.19^{NS}	0.27^{NS}	6.69**	1.35^{NS}	5.58**	4.05*
EBC × BPS	6.74**	1.18^{NS}	13.94**	0.26^{NS}	2.57^{NS}	18.00**
Species × EBC × BPS	0.24^{NS}	0.06^{NS}	7.66**	3.98*	1.36^{NS}	1.93^{NS}

MOE = modulus of elasticity, MO*R* = 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 0.05 probability level. *: significant at 0.05 probability level. **: significant at 0.01 probability level.

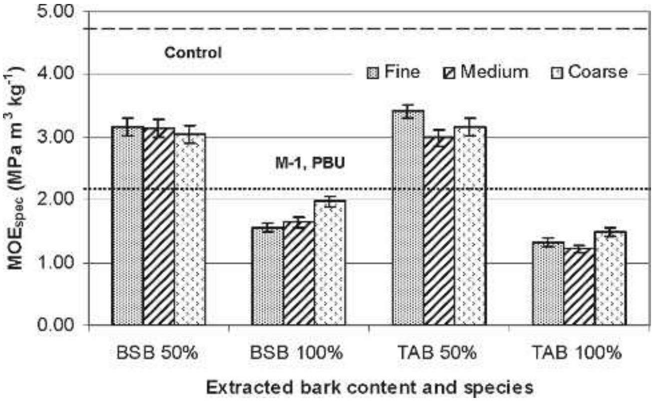

Figure 2. — Effect of extracted bark content and particle size on the specific modulus of elasticity (BSB = black spruce bark; TAB = trembling aspen bark. M–1, PBU: ANSI standard particleboard grades).

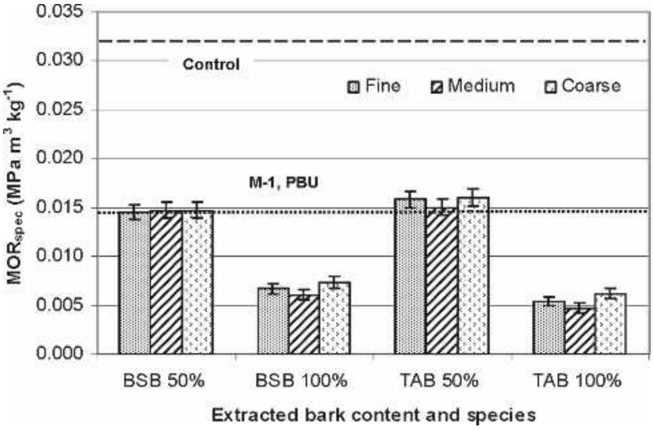

Figure 3. — Effect of extracted bark content and particle size on the specific modulus of rupture (BSB = black spruce bark; TAB = trembling aspen bark. M–1, PBU: ANSI standard PB grades).

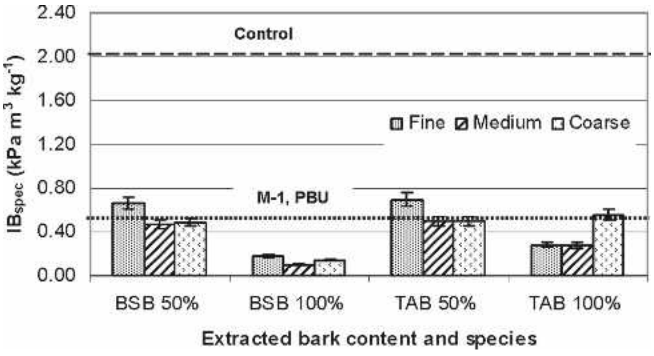

Figure 4. — Effect of extracted bark content and particle size on the specific internal bond (BSB = black spruce bark; TAB = trembling aspen bark. M–1, PBU: ANSI standard PB grades).

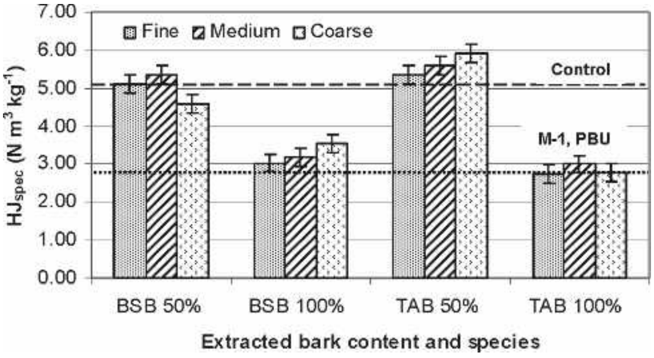

Figure 5. — Effect of extracted bark content and particle size on the specific Janka hardness (BSB = black spruce bark; TAB = trembling aspen bark. M-1, PBU: ANSI standard PB grades).

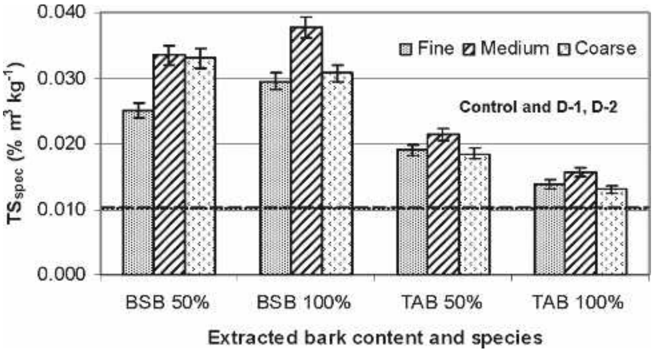

Figure 6. — Effect of extracted bark content and particle size on the specific thickness swelling (BSB = black spruce bark; TAB = trembling aspen bark. D–1, D–2: ANSI standard PB grades).

lower than for PB made from black spruce bark. In fact, trembling aspen bark contains much more lipophilic extractives (**Table 3**) than black spruce bark which can increase thickness swelling resistance. A similar trend was reported for unextracted bark particles (Ngueho Yemele et al. 2007). The TS$_{spec}$ value of PB of medium bark particle size was often higher than the two other size classes. **Table 5** also indicates significant interactions between species and bark particle size as well as species and extracted bark content on specific thickness swelling (TS$_{spec}$) at 0.01 probability level. This means that the effect of species on TS depends on the extracted bark content and bark particle size. Boards made from fine and coarse extracted trembling aspen bark particles exhibited the lowest TS value which was 29 percent higher than the control and also exceeded the maximum value required by the ANSI standard for manufactured home decking (D–2 and D–3) grades as shown in **Figure 6**.

Linear expansion

Table 5 shows a significant effect of extracted bark content on the specific linear expansion (LE$_{spec}$) at 0.01 probability level respectively. **Figure 7** indicates that the LE$_{spec}$ increased with increasing bark content for both species. There are also a significant effect of the interactions between extracted bark content and bark particle size on the one hand, and between species and bark particle size on the other hand on the specific linear expansion (LE$_{spec}$) at 0.01 and 0.05 probability level, respectively. Thus, the LE$_{spec}$ of the PB made from 50 percent extracted bark content, increased with increasing bark particle size. The trend seems to be opposite for boards made from 100 percent extracted trembling aspen bark content (**Fig. 7**). In contrast, no significant difference was found between the LE of the PBs made from 100 percent black spruce and the LE of PBs made from other extracted bark contents and species.

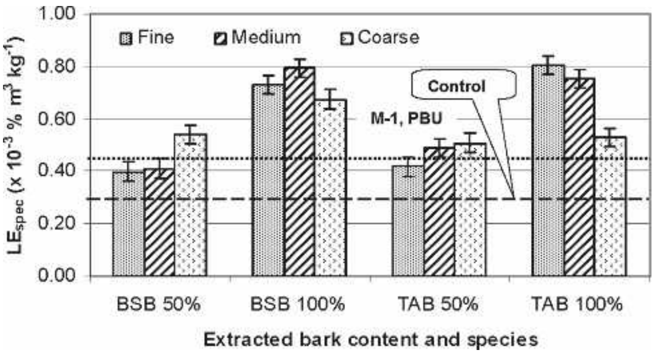

Figure 7. — Effect of extracted bark content and particle size on the specific linear expansion (BSB = black spruce bark; TAB = trembling aspen bark. M–1, PBU: ANSI standard PB grades).

Table 6. — Variation in percentage of the physical and mechanical properties of PB made from extracted bark vs. those made from unextracted bark.

	Particleboard of			
	Black spruce bark content		Trembling aspen bark content	
Property	50 percent	100 percent	50 percent	100 percent
MOE (MPa)	−25	−22	−9	−34
MOR (MPa)	−25	−22	NS	−38
IB (kPa)	NS on coarse		−16	
	−30 to −67 on the others			
HJ (N)	NS		+22	NS
TS (percent)	+57		+67	NS
LE (percent)	+30 on coarse		NS	
	NS on the others			

NS: not significant at 0.05 probability level
Negative value (−): decrease in percentage
Positive value (+): increase in percentage

Low LE value was obtained for the boards made from 50 percent of fine and medium extracted black spruce bark particle, which was 52 percent higher than the control. Some of the boards produced fulfilled the LE requirements of the ANSI A208.1 standard but not all of them as shown in **Figure 7**.

Effect of extracted vs. unextracted bark particles on the properties of PBs

Physical and mechanical properties of PB made from extracted bark were compared to those obtained by Ngueho Yemele et al. (2007) for PBs made from unextracted bark. **Table 6** shows that the hot water extraction applied in this study had a detrimental effect on the physical and mechanical properties of PB made from black spruce and trembling aspen bark. However, the effect of the extraction was light on the bending properties (MOE and MOR) of boards made from 50 percent trembling aspen bark. The IB of the boards made from extracted bark was significantly reduced (from 16 to 67%) except for PB made from 50 percent of coarse particles of black spruce bark probably due to its low effective bark content ratio. The TS of boards made from extracted bark was higher than that of those made from unextracted bark except for those made from 100 percent trembling aspen bark as shown in **Table 6**. In fact, for those boards, the high lipophillic content of both extracted and unextracted trembling aspen bark acts as a barrier to reduce water absorption and thickness swelling. No significant difference was found between the LE of furnish made from extracted and unextracted bark of both species except for those made from coarse black spruce raw material which showed an increase of 30 percent. No significant decrease of the extraction process implemented was found on the HJ of the boards (**Table 6**). Furthermore, an improvement of 22 percent was observed on the HJ value of the PB made from 50 percent extracted trembling aspen bark.

He and Riedl (2004) reported that pH and buffering capacity are important factors influencing PF adhesive curing. A decrease of the PF/particle system pH led to a decrease of the adhesive functional group reactivity. Therefore, both the quality of the interactions (PF adhesive/particles) and the mechanical properties of the boards decrease. Significant differences were found between the average pH values of extracted and unextracted bark of both species presented in **Table 4**. In addition, the values of acid and alkaline buffering capacity increased and doubled. This suggests a positive correlation between the alkaline buffering capacity and the mechanical properties (MOE, MOR, and IB) of the PBs. In fact, the higher the alkaline buffering capacity, the longer the delay for PF acidification. A decrease of the pH observed on extracted bark particles of the two species led to the alteration of the adhesive reticulation conditions and its interaction with bark particles.

The decrease of the mechanical properties of PB made from extracted (or hydrothermally treated) bark could also be explained by the kind of interactions between particles and PF adhesive. Previous studies have shown that the interactions between PF adhesive and wood are of secondary nature and mainly based on hydrogen bonds (He and Riedl 2004, Laborie and Frazier 2006). Hot water extractives are essentially polyphenols including tannins that can react with formaldehyde, free sugars and ash. Extracted bark particles after hot water treatment exhibit less secondary interactions than unextracted bark due to a decrease of the functional groups (hydroxyl, carbonyl, carboxylic). These groups involved in the hydrogen bonds were removed together with the hydrophilic compounds during the hot water extraction process. Therefore, the mechanical properties (MOE, MOR and IB) of the boards made from extracted bark particles should be lower than that of those made from unextracted bark. This is confirmed by the results obtained in the current study as presented in **Table 6**.

Table 6 also shows an increase of TS value of PB made from extracted bark particles compared to that of those made from unextracted bark. In fact, during the extraction process, extractives soluble in alcohol and water are released from the rhytidome cells (Srivastava 1964, Martin and Crist 1970). Thus, the porosity of extracted bark particles and the whole furnish might increase and they became less resistant to water absorption and thickness swelling.

The significant impact of bark acidity on the curing of PF adhesive suggests that the properties of PB made from bark could be further improved by using an appropriate adhesive formulation as well as more specific manufacturing parameters for each kind of raw material.

Conclusions

In this study, the physical and mechanical properties of PB made from extracted black spruce and trembling aspen bark were investigated. The effect of the hot water extraction on these properties was evaluated. The following conclusions can be drawn:

1. The mechanical properties including modulus of elasticity (MOE), modulus of rupture (MOR), internal bond (IB) and Janka hardness (HJ) decreased with increasing extracted bark content. In contrast, an increase in extracted 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 and TS. PB made from fine particles often showed higher IB and lower TS values.
3. The hot water extraction applied on black spruce and trembling aspen bark had detrimental effect on all the physical and mechanical properties of the PBs produced except for the Janka hardness.
4. Bark extracts are highly desired in pharmacology and for adhesive production. Therefore, it becomes necessary to carry out studies in order to manufacture value-added products with the residues remaining after the extraction process. Although, extracted bark boards showed lower physical and mechanical properties than unextracted ones, the high hardness exhibited by extracted bark boards suggests that some of them could be suitable for flooring products where hardness is the main property required.

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