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Effects of temperature and moisture content on selected wood mechanical properties involved in the chipping process

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Abstract The effects of temperature and moisture content on selected mechanical properties associated with the chipping process were evaluated. In chipping, mechanical properties such as shear parallel to the grain, cleavage, and bending are involved. Matched samples of heartwood and sapwood were obtained from freshly harvested logs of black spruce and balsam fir to determine the variation of the studied mechanical properties between −30 and 20 °C, at intervals of 10 °C. Moisture content (MC), basic density (BD), and annual ring width (RW) were measured for each sample. For both wood species, temperature had a significant effect on all mechanical properties under freezing conditions (below 0 °C). This effect was more important for sapwood than for heartwood, which was explained by the difference in MC between these two types of wood. Between 0 and 20 °C, temperature and type of wood did not show any significant effect on the mechanical properties. Multiple regression models were obtained to predict the mechanical properties. These regressions showed that MC was the most important factor to explain the mechanical properties below 0 °C. However, for temperatures of 0 °C and higher, BD was the principal factor to predict the mechanical properties. RW was not a significant factor to predict any mechanical property. Cleavage was the most sensitive one to changes in temperature followed by shear, modulus of rupture, and modulus of elasticity. These results could be of great importance in the chipping process.

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Introduction

It is known that the mechanical properties of wood are affected by several factors. The temperature and moisture content (MC) of wood are among the most important parameters affecting its mechanical behavior. Wood becomes more resistant as temperature decreases (Siimes 1967; Koran 1979; Gerhards 1982; Mishiro 1990; FPL 1999; Green et al. 1999; Deomano and Zink-Sharp 2004; Green and Evans 2008). The effect of MC on the mechanical strength of wood is especially important at MC below fiber saturation point (FSP). Above FSP, MC affects mechanical strength when temperature decreases below 0 °C. In this case, the portion of liquid water freezes, expands, and reinforces the strength of wood (Mishiro and Asano 1984; Mishiro 1990). For instance, Gerhards (1982) found that when MC is higher than the FSP, the MOR and MOE in bending are, respectively, 110 and 50 % greater at −50 °C than at 20 °C. In another work, the MOR and MOE were 130 and 86 % greater at 50 % MC, and 485 and 220 % greater at 210 % MC when temperature decreased from 20 to −30 °C (Mishiro and Asano 1984). This increase in wood strength under frozen conditions has positive impacts on several end uses of wood, particularly on those where high mechanical properties are required. However, in other cases, the effects of temperature and MC need to be taken more into consideration, as it is the case in wood chipping.

In the Province of Quebec, Canada, about half of the raw material used in pulp industries comes from chips (Parent 2013), which are mainly produced by chipper-canters (Hernández and Quirion 1993). These machines have been designed to obtain chips and cants from small diameter logs with very low sawdust production. The Comact (2014) and Sawquip (2014) chipper-canters are commonly used in this region. The dimensions of chips produced by chipper-canters are not inherently uniform making homogeneous pulping difficult to obtain. Chip classification improves chip homogeneity by removing undesirable parts, such as fines, pin chips, and overthick chips (overthicks). The latters are generally rechipped, while fines and pin chips are recycled for less profitable uses, such as fuel. Therefore, any improvement in the amount of pulpable chips is profitable for the sawmills.

The optimal chip dimensions required to obtain homogeneous pulping have been widely studied (Christie 1986, 1987). Uniform chip thickness is important in mechanical and chemi-mechanical pulping (Hoekstra et al. 1983; Robertsén and Lönnberg 1986), as well as in Kraft pulping (Olson et al. 1980; Tikka et al. 1993). It is therefore essential to understand the chip formation process in order to improve the fragmentation methods of logs (Hernández and Lessard 1997; Hernández and Boulanger 1997).

The chip formation by a chipper-canter is a complex process that involves several factors whose interactions are difficult to predict. The response to the change in a parameter of the chipping process depends on the values of other factors related to the wood and cutting parameters (McLauchlan and Lapointe 1979; Fuller 1983; Uhmeier 1995; Hellström et al. 2008, 2009). Hernández and Quirion (1993) studied the effect of the knife clamp on the formation of chips by a chipper-canter (Fig. 1). According to these authors, at the beginning of the process, the knife acts almost across the wood grain to cut a slice by shearing. This slice and the newly formed

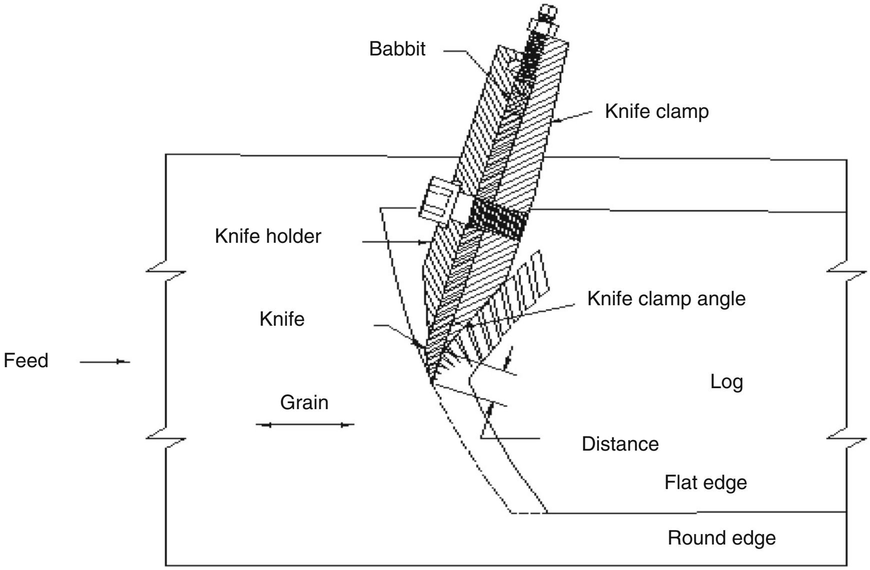

Fig. 1 Schematic representation of chipping by a chipper-canter (from Hernández and Quirion 1995)

wood surface undergo shear stresses parallel to the grain, which should produce cracks in both parts. The slice is then directed to the knife clamp placed at some distance of the knife edge. The change in the trajectory angle of the slice, caused by the knife clamp, produces other stresses that contribute to the slice fragmentation by parallel shearing or cleavage. The knife clamp angle and the distance between the knife edge and the knife clamp edge affect the development of these stresses and, consequently, the chip size. The cutting speed, which regulates the required time to cover the distance knife clamp/knife edge, also influences the chip size (Hernández and Boulanger 1997). It is also important that fragmentation takes place by parallel cleavage (lower energy consumption) than by parallel shearing (higher energy consumption). The chip formation in the case of disc chippers has a similar behavior (McLauchlan and Lapointe 1979).

As mentioned before, temperature and MC of wood have a significant impact on chipping, especially when using frozen and green logs. Hatton (1975) reported that production of pin chips and fines was two to three times greater in winter than in summer for three species and three types of chippers. Hernández and Quirion (1993) studied the distribution of black spruce chips produced by a Swecan chipper-canter. The results showed that a reduction of temperature from 21 to −8 °C produced nearly two times more fines and pin chips. Also, the acceptable chips increased at the expense of the overthick chips. According to these authors, the different sensitivity of the mechanical properties of wood to the temperature variation has an influence on the ratio of parallel-to-the-grain strength (bending) to perpendicular-to-the-grain strength (cleavage). This ratio will be higher at low temperatures and will create thinner chips in winter conditions. Hernández and Quirion (1993) hypothesized that the greater proportion of ice in sapwood plays an important role in the increase in mechanical properties of black spruce wood. Similar tendencies were reported later by Hernández and Lessard (1997) and Hernández and Boulanger (1997).

The main objective of this study was therefore to evaluate the effects of temperature and MC of wood on the mechanical properties associated with the fragmentation process by a chipper-canter. The species used were black spruce [*Picea mariana* (Mill.) B.S.P] and balsam fir [*Abies balsamea* (L.) Mill].

Materials and methods

Ten stems of black spruce [*Picea mariana* (Mill.) B.S.P] and ten stems of balsam fir [*A. balsamea* (L.) Mill.] from Saint-Lambert de Lauzon, in the Chaudière-Appalaches area of Quebec, were harvested for this experiment. These species are of great economic importance to the Quebec province, and they are used as building timber and pulpwood. The stems were crosscut into two 1.40-m logs obtained at 1.0 m from the base of the tree. Logs were kept with bark, and their ends were wrapped in polyethylene and stored at −4 °C until utilization. The logs were without crook or visible decay and had a minimum of knots. They also had straight grain and concentric growth rings.

Boards were obtained from each log with a bandsaw and then jointed and planed to obtain planks from heartwood and sapwood (Fig. 2). Three types of planks, each with a different width and all with 10 mm of thickness, were obtained. From each type of plank, matched samples for shear [10 mm (R) × 25 mm (T) × 35 mm (L)], cleavage [10 mm (R) × 45 mm (T) × 45 mm (L)], and static bending [10 mm (R) × 10 mm (T) × 190 mm (L)] tests were prepared. Dimensions were chosen to represent those chips obtained from a chipping process by a chipper-canter. The distribution of planks within a stem is shown in Fig. 2. Sequences of six adjacent samples were then selected within each plank in order to investigate six levels of wood temperature. By taking one sample from each sequence, six matched groups of 20 samples each were formed. Therefore, 240 samples for each mechanical property were obtained, 120 samples from sapwood and 120 samples from heartwood, making a total of 720 samples per species. They all had straight grain and were without any major defect. Growth rings were oriented parallel to the tangential plane of the samples. The preparation of samples from each type of plank is shown in Fig. 2. All samples were kept in green conditions at −4 °C and wrapped in a polyethylene protection until the beginning of mechanical tests.

Prior to mechanical tests, the samples were enveloped with an extruded polystyrene foam protection (Styrofoam®, minimum thickness of 7 mm, thermal conductivity of 0.033 W/mK) and put in a CSZ Z44 Plus cold room in order to attain the target temperature to each mechanical test. This protection was kept intact during the experiment, being useful to maintain the initial temperature of samples during the mechanical test. The temperatures of treatment were between −30 and 20 °C with a 10 °C interval. The cooling rate was variable according to the

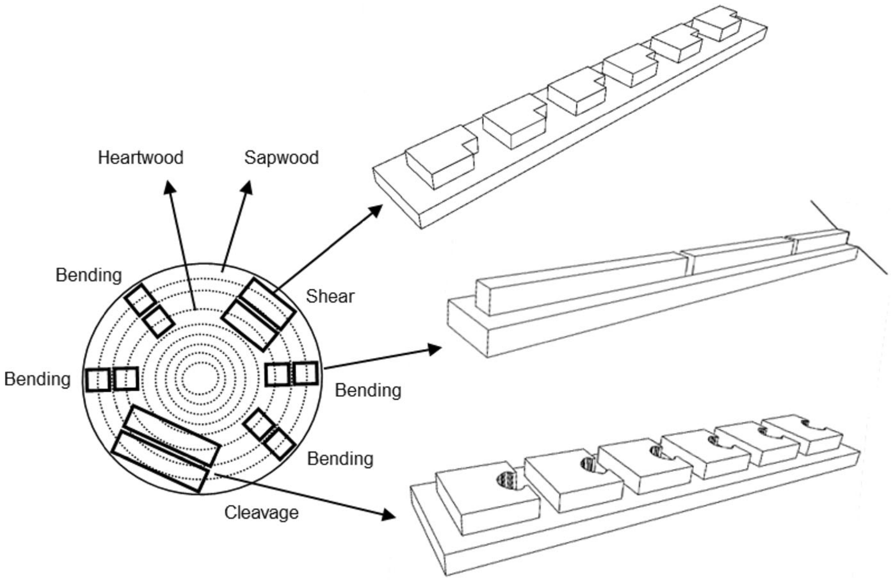

Fig. 2 Distribution of samples for the shear, cleavage, and static bending tests

temperature needed: 3.4 °C/min (20–10 °C), 4.7 °C/min (20–0 °C), 4.0 °C/min (20 to −10 °C), 3.1 °C/min (20 to −20 °C), and 1.7 °C/min (20 to −30 °C). The samples were kept at the target temperature at least 24 h before mechanical testing. The time spent between the removal of samples from the cold room and the end of mechanical testing was about 2 min. The three mechanical properties were determined according to ASTM D-143-94 standard (ASTM 1997), with some modifications in order to achieve the objectives of this work. The mechanical tests were performed on a universal testing machine equipped with a 5 kN load cell.

The shear strength parallel to the grain test was carried out in the radial–longitudinal failure plane. Load was applied at a rate of 5.0 mm per min until complete failure. There was no offset between the inner edge of the supporting surface and the specific plane along which the failure occurs. The calculated fracture area of each sample was 250 mm^2. The shear strength is defined as the load at failure (N) divided by the shear area (mm^2), expressed in MPa.

The cleavage was performed following the radial–longitudinal failure plane. Samples were fixed in the center of jaws before starting the test in order to distribute the forces equally. Load was applied at a rate of 5.0 mm per min until complete failure. The cleavage strength is the ratio of load at failure (N) divided by the sample width (mm), expressed in N/mm.

The static bending test was performed with a three-point loading system. Both the upper support, which carries the load, and the two lower supports were made with a dense wood to avoid changes in temperature between the sample and the external environment. These three supports had a radius of 15 mm. The span length was 140 mm, and load was applied at a crosshead rate of 30.0 mm per min until complete failure. MOR and MOE were computed from the data obtained with an acquisition hardware.

Green weight of each sample was taken immediately after each mechanical test to the nearest 0.0001 g. The green volume of the sample was then measured by immersion in water to the nearest 0.01 g. Samples were then oven-dried at 103 °C for at least 24 h to obtain their oven-dry weight, measured to the nearest 0.0001 g. MC at the time of mechanical tests as well as the basic density (oven-dry mass divided by green volume, BD) were calculated. The growth rings of each sample were counted and then divided by the thickness of sample, in order to calculate the average annual growth width (RW). RW was used as indicator of growth rate. This variable may influence BD and mechanical properties in some species (Zhang 1995).

Data were analyzed using Statistical Analysis System (SAS) software, version 9.2 (SAS Institute 2007). First, models of analysis of variance (ANOVA) of one or two factors were adjusted to data according to the variables of the study. The GLM procedure of SAS was initially used for analysis. When the assumption of normality was not found, a log or square root transformation was used. However, when no transformation was found that could improve the normality and the homogeneity of data, the MIXED procedure was applied. Multiple comparisons of means were made using the “Fisher Protected LSD” (least significant difference) method. This approach was carried out to verify significant effects of temperature and wood types (heartwood and sapwood) of samples on shear, cleavage, and static bending properties. Correlation analyses among these three mechanical properties, MC, BD, and RW were performed at probability levels of 0.05 and 0.01. Such analyses allowed to identify some independent variables that may explain the variation observed in the mechanical properties. Multiple regression analyses were then performed to determine the influence or not of each independent variable (MC, BD, and RW), on the dependent variable at each temperature of study. The stepwise method was used, with inclusion or exclusion of independent variables in the models set at the 0.10 probability level. The autonomy between independent variables was accomplished for the used model. The quantitative contribution of each independent variable to the three mechanical properties of wood was obtained by calculating the beta coefficients.

Results and discussion

Wood physical properties

The main results of average MC, BD, and RW for the two species and wood types (heartwood and sapwood) by pooling all specimens are shown in Table 1. MC was significantly higher for sapwood than for heartwood for both species. Balsam fir had a higher MC than black spruce wood. MC of black spruce logs is similar to those reported by Hernández and Quirion (1993, 1995), Hernández and Lessard (1997), and Hernández and Boulanger (1997).

Table 1 Means and standard error (in parentheses) of the mean of MC, BD, and RW of the two species studied

Species	MC (%)		BD (g/cm^3)		RW (mm)	
	H	S	H	S	H	S
Black spruce	50 A[a]	139 B	417 A	425 B	1.38 A	0.88 B
	(1)[b]	(2)	(2)	(3)	(0.02)	(0.02)
Balsam fir	105 A	178 B	357 A	351 B	1.51 A	1.43 A
	(2)	(2)	(2)	(1)	(0.03)	(0.03)

MC moisture content, *BD* basic density, *RW* annual ring width, *H* heartwood, *S* sapwood

[a] Means within a row followed by the same letter are not significantly different at 0.05 probability level, for each property tested separately

[b] Number in parentheses corresponds to the standard error of the mean

Black spruce wood had higher density than balsam fir wood (Table 1). Means of BD of the two species were slightly higher than those reported by Jessome (1977), 406 kg/m^3 for black spruce and 335 kg/m^3 for balsam fir, and by Laganière and Bédard (2009), 409 kg/m^3 and 326 kg/m^3, respectively.

There was a statistically significant difference in BD between heartwood and sapwood of black spruce. Sapwood was slightly denser than heartwood. RW was higher in heartwood than in sapwood for this species (Table 1). Density and RW are negatively correlated in black spruce (Koubaa et al. 2000, 2005). However, Koubaa et al. (2000) highlighted that for black spruce, this relationship is not clear yet and that it may be age-dependent, with a decrease when wood reaches maturity.

Despite of the statistically significant difference in BD found between heartwood and sapwood for balsam fir, values of RW for heartwood and sapwood were not statistically significant (Table 1). Zhang (1995) found that BD was negatively but not significantly correlated with RW for *Abies nephrolepis* and *Abies fabri*.

The higher RW for balsam fir wood was reported by Jessome (1977). He found values of 1.3 mm and 2.8 mm for black spruce and balsam fir, respectively. However, this author did not study the differences between heartwood and sapwood. As discussed later, the studied physical properties were considered to estimate the mechanical properties by regression analyses.

Shear strength

The temperature and wood type had a significant effect on shear strength for the two wood species (Table 2; Fig. 3). Shear strength increased as temperature decreased from 0 to −30 °C for samples of heartwood and sapwood. The increase in shear strength was higher in sapwood than in heartwood for the two wood species. Between −10 and −30 °C, the difference between sapwood and heartwood was statistically significant at 0.05 probability level for black spruce and balsam fir.

The influences of temperature and wood type on shear strength were negligible for temperatures of 0 °C and higher, except for sapwood of balsam fir at 10 °C (Table 2; Fig. 3). In this case, shear strength of heartwood samples was slightly

Table 2 Effects of temperature and type of wood on three mechanical properties of black spruce and balsam fir woods

Temperature (°C)	Shear (MPa)		Cleavage (N/mm)		Static bending			
					MOR (MPa)		MOE (MPa)	
	H	S	H	S	H	S	H	S
Black spruce								
−30	7.7 A[1]a[2]	10.3 Ba	n.a.	n.a.	89 Aa	140 Ba	10,045 Aa	15,012 Ba
	(0.2)[3]	(0.3)			(2)	(6)	(164)	(560)
−20	7.0 Ab	9.2 Bb	30 Aa	60 Bb	83 Aab	119 Bb	9,786 Aa	14,064 Ba
	(0.2)	(0.3)	(1)	(3)	(2)	(5)	(160)	(555)
−10	5.8 Ac	7.8 Bc	29 Aa	47 Bc	74 Abc	98 Bc	9,164 Aab	11,814 Bb
	(0.2)	(0.2)	(1)	(2)	(2)	(4)	(188)	(501)
0	4.2 Ade	4.1 Ad	20 Ab	24 Bd	68 Acd	68 Ad	8,671 Abc	8,630 Ac
	(0.1)	(0.1)	(1)	(1)	(2)	(2)	(160)	(238)
10	4.5 Ad	4.1 Ad	19 Ab	22 Bd	66 Ade	66 Ad	8,506 Abc	8,605 Ac
	(0.2)	(0.1)	(1)	(1)	(2)	(2)	(171)	(238)
20	3.9 Ae	4.0 Ad	18 Ab	21 Bd	61 Ae	62 Ad	8,121 Ac	8,345 Ac
	(0.1)	(0.2)	(1)	(1)	(2)	(2)	(195)	(249)
Balsam fir								
−30	9.6 A[1]a[2]	12.2 Ba	n.a.	n.a.	99 Aa	145 Ba	11,119 Aa	14,040 Ba
	(0.5)[3]	(0.4)			(4)	(5)	(507)	(552)
−20	8.3 Ab	10.3 Bb	41 Aa	64 Bb	83 Ab	113 Bb	9,864 Ab	12,413 Bb
	(0.3)	(0.3)	(2)	(3)	(4)	(5)	(469)	(482)
−10	6.9 Ac	8.3 Bc	35 Ab	49 Bc	76 Ab	90 Bc	9,482 Ab	11,089 Bc
	(0.3)	(0.2)	(1)	(2)	(3)	(3)	(414)	(485)
0	4.4 Ad	3.9 Ad	19 Ac	18 Ad	65 Ac	58 Bd	8,189 Ac	7,577 Ad
	(0.2)	(0.1)	(1)	(0.6)	(2)	(1)	(357)	(304)
10	4.7 Ade	3.9 Bd	17 Ac	18 Ad	60 Ac	60 Ad	7,867 Ac	7,486 Ad
	(0.2)	(0.2)	(1)	(0.3)	(2)	(1)	(291)	(247)
20	5.2 Ae	5.3 Ae	18 Ac	17 Ad	55 Ad	55 Ae	7,611 Ac	7,169 Ad
	(0.3)	(0.4)	(1)	(0.4)	(2)	(1)	(336)	(229)

H heartwood, *S* sapwood

[1] Means within a row followed by the same uppercase letter are not significantly different at 0.05 probability level. Means of each mechanical property tested separately

[2] Means within a column followed by same lowercase letter are not significantly different at 0.05 probability level

[3] Number in parentheses corresponds to the standard error of the mean

higher than that of sapwood. This difference is not important for practical purposes because the numerical difference between both types of wood (0.8 MPa) is low in comparison with the difference obtained under freezing temperatures. There was also an unexpected high value for shear strength at 20 °C for balsam fir heartwood and sapwood samples compared to temperatures of 0 and 10 °C. In this case, the

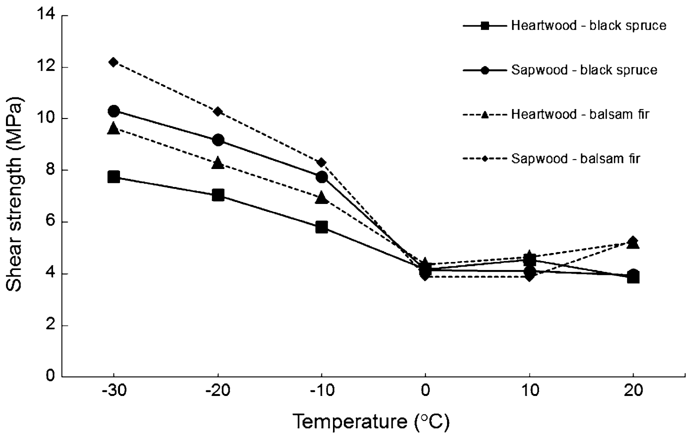

Fig. 3 Effect of wood temperature on shear strength of black spruce and balsam fir woods

high coefficients of variation observed (24 and 31 % for heartwood and sapwood, respectively) could explain this result. Below 0 °C, shear strength of balsam fir was higher than for black spruce despite of the higher BD of the latter species (Fig. 3). As discussed later, the higher MC of balsam fir wood was responsible for a more pronounced mechanical reinforcement with decreasing temperature.

Cleavage strength

Cleavage strength increased as temperature decreased from 0 to −20 °C (Table 2; Fig. 4). Values at −30 °C were removed from the analysis because temperature during tests was wrongly controlled. As for shear strength, the increase in cleavage strength was greater in sapwood than in heartwood for the two wood species.

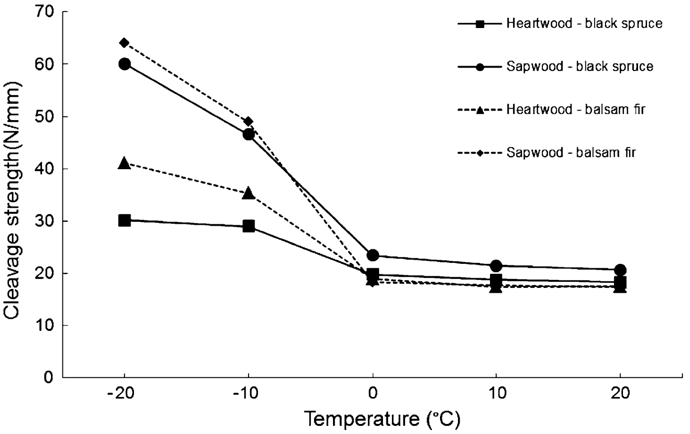

Fig. 4 Effect of wood temperature on cleavage strength of black spruce and balsam fir woods

Between −10 and −20 °C, the difference between sapwood and heartwood was statistically significant at 0.05 probability level for black spruce and balsam fir woods.

Cleavage strength of black spruce was significantly higher for sapwood than for heartwood for temperatures of 0, 10, and 20 °C (Table 2). Moreover, the numerical difference between cleavage strength of heartwood and sapwood for these temperatures for black spruce (4, 3 and 3 N/mm, respectively) compared to that of freezing temperatures is negligible. This fact could be explained in part by the slightly higher BD of sapwood (423 kg/m^3 at 0 °C; 424 kg/m^3 at 10 °C; 423 kg/m^3 at 20 °C) samples than heartwood ones (418 kg/m^3 at 0 °C; 421 kg/m^3 at 10 °C; 418 kg/m^3 at 20 °C). Thus, for practical purposes, after a careful observation of data, it may be admitted that the effect of temperature and MC in cleavage strength was negligible above 0 °C.

The higher MC of balsam fir wood in relation to black spruce wood was responsible for higher values of cleavage strength for freezing temperatures, despite of the higher BD of black spruce wood. As well as in shear strength, higher MC under freezing conditions provides greater reinforcement of wood due to a greater ice formation. In fact, it is known that the strength of ice increases as temperature decreases (Michel 1978). Changes in mechanical properties of cell walls themselves will also contribute to increase in wood strength. Thus, values obtained for cleavage strength at −20 °C were approximately two times higher than those achieved at 20 °C for heartwood and three times for sapwood for black spruce wood. This increase was approximately two and four times, respectively, for balsam fir wood.

Jessome (1977) obtained a cleavage strength of 31.5 and 25.7 N/mm for green samples of black spruce and balsam fir, respectively, that is, higher than the results presented in this work. The fact that small clear wood samples were used in this work compared with those studied by Jessome (1977) could explain this difference.

Literature concerning cleavage test under freezing temperatures is not available. However, some work has been done with tensile strength perpendicular to the wood grain. This test may shed some light on the effects of temperature and MC on a transverse mechanical test. Koran (1979) found a linear relationship between tensile stress perpendicular to the grain and temperature for black spruce green samples at temperatures ranging from −60 °C to about 100 °C. As temperature decreased from 20 to −30 °C, tensile strength increased by about only 30 %. However, values of MC were not reported in that work.

Bending strength

There was a gradual increase in MOR and MOE as temperature decreased below 0 °C for both species (Table 2; Figs. 5, 6). This increase in MOR and MOE was more pronounced for sapwood than for heartwood.

In general, there was not a statistically significant difference between heartwood and sapwood at 0.05 probability level for temperatures of 0, 10, and 20 °C for both species (Table 2). The exception was for MOR samples of balsam fir at 0 °C where a significant difference between the two types of wood was observed. However, the numerical difference between these values (7 MPa) compared with the other values

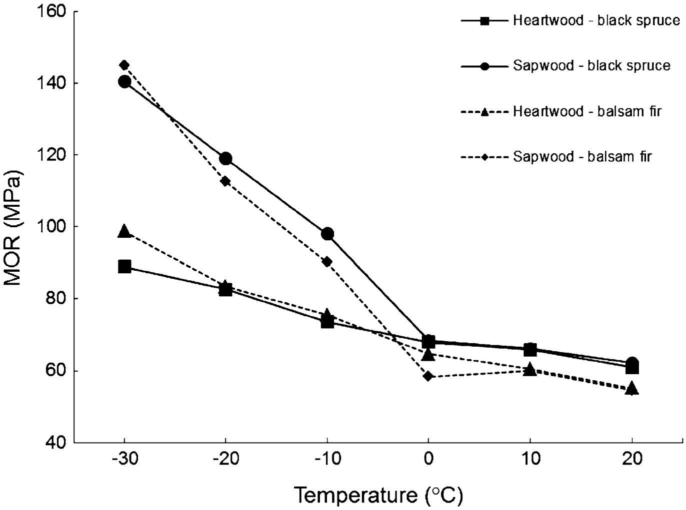

Fig. 5 Effect of wood temperature on MOR of black spruce and balsam fir woods

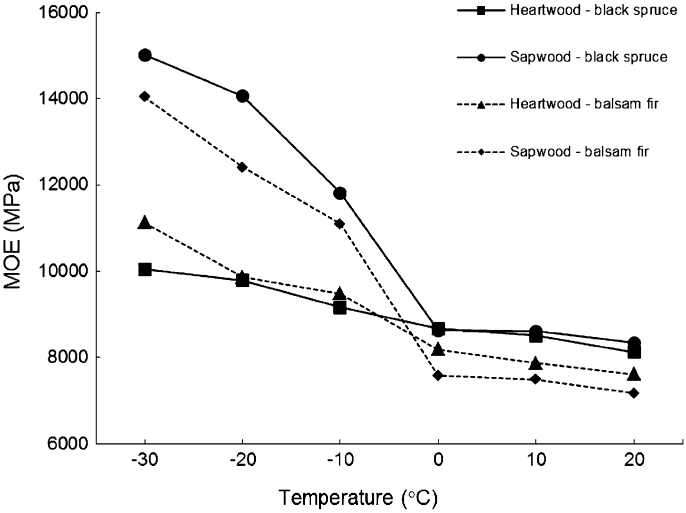

Fig. 6 Effect of wood temperature on MOE of black spruce and balsam fir woods

relative to the freezing temperatures indicate that this variation is not important for practical purposes.

The higher BD of black spruce wood was responsible for its higher MOR and MOE than balsam fir for temperatures of 0, 10, and 20 °C. However, the mean values obtained for these properties were close below 0 °C (Table 2; Figs. 5, 6). Thus, the stiffening of wood cells carried out by the ice formed in cell lumens was more important for balsam fir than for black spruce wood. Similar results for MOE were reported by Onwona-Agyeman et al. (1995). The MOE of *Cryptomeria japonica* branches with higher moisture content increased more than that of *Chamaecyparis obtusa* and *Larix leptolepis* branches under freezing temperatures. Moreover, the increase in MOR and MOE with decreasing temperature was more uniform than those for shear and cleavage strength. This uniformity may be due to the fact that the bending test is simple to conduct and generally undeviating (Bodig and Jayne 1982). Thus, the errors induced by the complexity of performing mechanical tests are minimized.

The values obtained for MOR at −30 °C were approximately two times higher than those achieved at 20 °C for heartwood and three times for sapwood in black spruce wood (Table 2). For balsam fir wood, this increase was approximately two and four times higher, respectively (Table 2). However, for MOE, this same increase was less pronounced, being not higher than two times for both species and types of wood (Table 2). In *Picea*, Mishiro and Asano (1984) also showed that MOR is more sensitive than MOE to changes in temperature and MC.

Sensitivity of mechanical properties to temperature variation

The studied mechanical properties appeared to have different responses to changes in temperature. The wood species and types of wood also showed different sensitivity to temperature. To evaluate that, the mean values at −10 °C were divided by a mean that pooled the results obtained at 0, 10, and 20 °C. This ratio, called frozen/unfrozen strength ratio, was calculated for each property, wood species, and type of wood (Table 3). Values obtained at −10 °C were used to minimize probable effects of the Styrofoam® protections at −20 and −30 °C on mechanical properties. The average of 0, 10, and 20 °C was used because, in general, as discussed earlier, the effects of temperature in this temperature range were not significant at 0.05 probability level.

The mechanical properties of balsam fir wood were more influenced by temperature changes than those of black spruce wood (Table 3). This was expected because MC of balsam fir was higher than black spruce. Thus, the effects of ice reinforcement were more evident in the case of higher MCs. The ratios also confirmed that sapwood was more sensitive to temperature changes than heartwood. Again, the higher MC of sapwood was responsible for this behavior. Consequently, these differences in MC and sapwood thickness among wood species should be taken into account when, for instance, chipper-canters are operating under winter

Table 3 Mean frozen (−10 °C)/unfrozen (0 °C to −20 °C) ratio calculated for each property, wood species, and type of wood

Species	Shear		Cleavage		MOR		MOE	
	H	S	H	S	H	S	H	S
Black spruce	1.4	1.9	1.5	2.1	1.1	1.5	1.1	1.4
Balsam fir	1.5	1.9	2.0	2.8	1.3	1.6	1.2	1.5

H heartwood, *S* sapwood

conditions. The variation in the frozen/unfrozen strength ratios will certainly affect size distribution of chips produced by these machines.

For both species, the most sensitive mechanical property to temperature decrease was cleavage, followed by shear, MOR, and MOE (Table 3). The higher sensitivity to temperature changes for MOR than MOE was already noted by Mishiro and Asano (1984). They obtained ratios of 1.65 and 1.16, respectively, at 150 % MC, for the same temperature conditions of those of Table 3. Koran (1979) studied the effect of temperature on tensile strength perpendicular to the grain for green wood samples of black spruce. For the same temperature variation, this author found a lower ratio (1.14) compared to those obtained for the same species in the present work (1.5 for heartwood and 2.1 for sapwood). However, the levels of MC were not reported in that work.

According to Panshin and de Zeeuw (1980), wood is an orthotropic material and the tubular forms of the cells and the orientation of the cellulose in the cell walls are responsible for the higher strength parallel to the grain than perpendicular to the grain. Thus, compressive, tensile, and shear strengths are quite variable in these two directions. Tension perpendicular to the grain is only a small fraction of that parallel to the grain and is closely related to the cleavage strength (Wangaard 1950). It can be admitted that cleavage, as a perpendicular mechanical property, is more prone to be influenced by ice reinforcement than the other parallel mechanical properties studied. In this case, the role played by the ice in the wood-ice composite is more evident when a perpendicular property is tested.

The different sensitivity of the mechanical properties of black spruce and balsam fir to temperature changes affects the chipping process. As discussed earlier, shear, cleavage, and bending are involved in this process. A modification in this relationship among these three properties due to the temperature change leads to a variation in chip size. The relationship of mechanical properties obtained in this work face with the temperature change is contrary to the discussion of Hernández and Quirion (1993), Hernández and Lessard (1997), and Hernández and Boulanger (1997). From the literature review, they hypothesized that the ratio parallel to the grain and perpendicular to the grain is higher under frozen conditions and as a consequence, thinner chips will be produced under these conditions. In the present work, it is suggested that as the cleavage and shear strength increase with decreasing temperature, the knife penetration in wood would be lower and thinner chips should be formed. Wood in freezing conditions becomes also more brittle (Lunstrum 1985).

Relationships among mechanical properties and MC, BD, and RW

Linear correlation analyses were performed among mechanical properties (shear, cleavage, MOR, and MOE) and MC, BD, and RW for each type of wood and each species separately. This was made in order to find general tendencies in the data and to detect relationships among variables (not shown). These analyses were made with two different groups, one for the treatments −10, −20, and −30 °C (group I) and another for the treatments 20, 10, and 0 °C (group II). It was hypothesized that, contrary to group I, in group II, there was not an effect of freezing by the ice in cell lumens. Samples from heartwood had lower MC than sapwood samples. Thus, data analysis by pooling heartwood and sapwood results was another approach used in this work. In general, the correlation analyses showed that MC positively affected the strength properties under frozen conditions (group I). Ring width negatively affected some of the wood properties. BD significantly affected strength properties of both groups (I and II). Multiple regression models were then performed to estimate mechanical properties from MC, BD, and RW as independent variables. These models were made for each species and temperature condition.

Shear strength

The multiple regression equations and the beta coefficients indicating their respective individual contribution to each independent variable on shear strength are shown in Table 4.

The models could explain from 19 to 68 % of the total variation in shear strength for black spruce, and from 9 to 81 % for balsam fir. A high coefficient of variation (COV) was obtained in equations relatively to 20 °C for both species and for 10 °C for balsam fir (Table 4). It means that these equations may not be used for predictive purposes. It is desirable that the COV be lower than 15 % to represent an accurate model to explain the dependent variable.

The MC was the most important factor contributing to the variation in shear strength for freezing temperatures in both species, with BD having a secondary role (Table 4). Therefore, shear strength increases as MC and BD increase. A previous study showed that wood density had positive effects on shear strength of tropical hardwoods (Hernández and Almeida 2003).

There was a tendency of higher R^2 and lower COV for models concerning temperatures below 0 °C for both species, showing a better relationship between independent and dependent variables (Table 4). This confirms that MC had a great role in the increase in shear strength under freezing temperatures. The effect of other factors not studied on shear strength would be minor. For temperatures higher than 0 °C, other independent variables besides those studied (MC, BD, and RW) might influence shear strength.

The RW was not an important factor to estimate shear strength for all temperature levels in both species. RW had some impact only on balsam fir shear at −30 °C (Table 4).

The beta coefficients of MC in shear strength for all temperatures below 0 °C pooled show that this independent variable, on average, had greater contribution in the variation of shear strength explained by the models for black spruce than balsam fir (72 and 75 %, respectively). BD was the main element to predict shear strength for black spruce for temperatures of 0 °C or higher. BD contributed, on average, for 77 % of shear strength variation represented by the equations of 0, 10, and 20 °C pooled. MC was the main significant factor to predict shear strength, and it was negatively correlated with this property for temperatures of 0 and 10 °C for balsam fir wood. The model for the temperature of 20 °C was not statistically significant at 0.05 probability level (Table 4).

Table 4 Regression equations predicting shear strength obtained from independent variables MC, BD, and RW for black spruce and balsam fir woods

Equations	R^2	COV (%)
Black spruce		
$SH_{(-30\,^\circ C)} = -0.2 + \underset{\underset{(73\%)^{b}}{(0.07)^{a}}}{0.025}\ MC + \underset{\underset{(27\%)}{(0.26)}}{16}\ BD$	0.56	13.4
$SH_{(-20\,^\circ C)} = -4 + \underset{\underset{(65\%)}{(0.71)}}{0.023}\ MC + \underset{\underset{(35\%)}{(0.38)}}{22}\ BD$	0.65	11.9
$SH_{(-10\,^\circ C)} = -3 + \underset{\underset{(67\%)}{(0.76)^{a}}}{0.022}\ MC + \underset{\underset{(33\%)}{(0.37)}}{19}\ BD$	0.68	11.9
$SH_{(0\,^\circ C)} = -1 + \underset{\underset{(64\%)}{(0.53)}}{11}\ BD + \underset{\underset{(36\%)}{(0.29)}}{0.4}\ RW$	0.26	12.5
$SH_{(10\,^\circ C)} = -2 + \underset{\underset{(67\%)}{(0.57)}}{17}\ BD - \underset{\underset{(33\%)}{(-0.27)}}{0.005}\ MC$	0.43	14.6
$SH_{(20\,^\circ C)} = -0.7 + \underset{\underset{(100\%)}{(0.43)}}{11.0}\ BD$	0.19	16.7
Balsam fir		
$SH_{(-30\,^\circ C)} = 0.03 + \underset{\underset{(62\%)^{b}}{(0.76)^{a}}}{0.041}\ MC - \underset{\underset{(21\%)}{(0.29)}}{0.8}\ RW + \underset{\underset{(18\%)}{(0.22)}}{17}\ BD$	0.81	9.9
$SH_{(-20\,^\circ C)} = -3 + \underset{\underset{(62\%)}{(0.75)}}{0.028}\ MC + \underset{\underset{(38\%)}{(0.45)}}{24}\ BD$	0.73	9.2
$SH_{(-10\,^\circ C)} = -3 + \underset{\underset{(56\%)}{(0.73)}}{0.020}\ MC + \underset{\underset{(44\%)}{(0.57)}}{22}\ BD$	0.70	8.7
$SH_{(0\,^\circ C)} = 5.0 - \underset{\underset{(100\%)}{(-0.46)}}{0.006}\ MC$	0.21	12.3
$SH_{(10\,^\circ C)} = 3 - \underset{\underset{(62\%)}{(-0.46)}}{0.008}\ MC + \underset{\underset{(38\%)}{(0.27)}}{7}\ BD$	0.32	16.7
$SH_{(20\,^\circ C)} = 0.3 + \underset{\underset{(100\%)}{(0.30)}}{14}\ BD$	0.09	26.4

SH shear strength, *MC* moisture content, *BD* basic density, *RW* annual ring width, R^2 coefficient of determination, *COV* coefficient of variation (%)

[a] Number in parentheses corresponds to beta coefficients of the regression

[b] Quantitative contribution of the independent variable on the mechanical property (%)

Cleavage strength

Multiple linear regressions and the beta coefficients with their respective percentage of contribution on cleavage strength for the two species are shown in Table 5. The models retained explained from 62 to 90 % of total variation in cleavage strength for black spruce and from 20 to 82 % for balsam fir.

Despite high values of R^2, the COV of models for both species was high (more than 15 %) (Table 5). These values highlight the great variation of results obtained for the cleavage tests. Previous work had confirmed the high values of COV in cleavage strength in relation to the other mechanical properties of wood (Jessome

Table 5 Regression equations predicting cleavage strength obtained from independent variables MC, BD, and RW for black spruce and balsam fir woods

Equations	R^2	COV (%)
Black spruce		
$\mathrm{CL}_{(-30\,^{\circ}\mathrm{C})} = -70 + \underset{\substack{(0.92)^{a}\\(79\%)^{b}}}{0.44}\ \mathrm{MC} + \underset{\substack{(0.25)\\(21\%)}}{178}\ \mathrm{BD}$	0.90	16.1
$\mathrm{CL}_{(-20\,^{\circ}\mathrm{C})} = -59 + \underset{\substack{(0.84)^{a}\\(75\%)^{b}}}{0.33}\ \mathrm{MC} + \underset{\substack{(0.28)\\(25\%)}}{172}\ \mathrm{BD}$	0.80	19.0
$\mathrm{CL}_{(-10\,^{\circ}\mathrm{C})} = -39 + \underset{\substack{(0.82)\\(68\%)}}{0.20}\ \mathrm{MC} + \underset{\substack{(0.38)\\(32\%)}}{138}\ \mathrm{BD}$	0.79	14.2
$\mathrm{CL}_{(0\,^{\circ}\mathrm{C})} = -30 + \underset{\substack{(0.77)\\(69\%)}}{116}\ \mathrm{BD} + \underset{\substack{(0.35)\\(31\%)}}{0.032}\ \mathrm{MC}$	0.67	12.7
$\mathrm{CL}_{(10\,^{\circ}\mathrm{C})} = -24 + \underset{\substack{(0.77)\\(70\%)}}{97}\ \mathrm{BD} + \underset{\substack{(0.32)\\(30\%)}}{0.029}\ \mathrm{MC}$	0.63	13.2
$\mathrm{CL}_{(20\,^{\circ}\mathrm{C})} = -22 + \underset{\substack{(0.73)\\(71\%)}}{92}\ \mathrm{BD} + \underset{\substack{(0.30)\\(29\%)}}{0.025}\ \mathrm{MC}$	0.62	12.9
Balsam fir		
$\mathrm{CL}_{(-30\,^{\circ}\mathrm{C})} = -41 + \underset{\substack{(0.84)^{a}\\(67\%)^{b}}}{0.23}\ \mathrm{MC} + \underset{\substack{(0.41)\\(33\%)}}{158}\ \mathrm{BD}$	0.55	19.6
$\mathrm{CL}_{(-20\,^{\circ}\mathrm{C})} = -75 + \underset{\substack{(1.05)\\(68\%)}}{0.32}\ \mathrm{MC} + \underset{\substack{(0.50)\\(32\%)}}{231}\ \mathrm{BD}$	0.82	14.2
$\mathrm{CL}_{(-10\,^{\circ}\mathrm{C})} = -26 + \underset{\substack{(0.96)\\(69\%)}}{0.18}\ \mathrm{MC} + \underset{\substack{(0.43)\\(31\%)}}{123}\ \mathrm{BD}$	0.64	15.2
$\mathrm{CL}_{(0\,^{\circ}\mathrm{C})} = 22 - \underset{\substack{(-0.45)\\(100\%)}}{2.5}\ \mathrm{RW}$	0.20	13.0
$\mathrm{CL}_{(10\,^{\circ}\mathrm{C})} = 21 - \underset{\substack{(-0.48)\\(100\%)}}{2.5}\ \mathrm{RW}$	0.23	13.3
$\mathrm{CL}_{(20\,^{\circ}\mathrm{C})} = 12 + \underset{\substack{(0.37)\\(53\%)}}{20}\ \mathrm{BD} - \underset{\substack{(0.33)\\(47\%)}}{1.1}\ \mathrm{RW}$	0.32	8.8

CL cleavage strength, *MC* moisture content, *BD* basic density, *RW* annual ring width, R^2 coefficient of determination, *COV* coefficient of variation (%)

[a] Number in parentheses corresponds to beta coefficients of the regression

[b] Quantitative contribution of the independent variable on the mechanical property (%)

1977). The sample must be correctly placed in the jaws to allow an equal distribution of forces during the test. However, even if the sample is well fitted, an even distribution of forces is not always reached, thus creating greater variability in the results.

The same tendencies obtained for shear strength were observed for cleavage strength (Table 5). MC was the most important factor involved in the variation of cleavage strength under freezing temperatures for both species. A less important role was played by BD. Therefore, cleavage strength increases as MC and BD increase.

The BD was the more important factor to explain cleavage strength variation for black spruce for temperatures of 0 °C and higher, with MC playing a minor role. The most important variable for this temperature range was RW for balsam fir. However, the R^2s of these equations were relatively low, which indicates that there are other factors implicated in cleavage strength than those included in this regression analysis (Table 5).

The analysis of the beta coefficients of the different models for treatments below 0 °C pooled shows that MC, on average, had a higher contribution to the variation in cleavage strength for black spruce than for balsam fir (74 and 68 %, respectively) (Table 5).

BD was the main factor to predict cleavage strength for black spruce for temperatures of 0 °C or higher, with an average contribution of 70 %. RW was negatively correlated with cleavage strength for all temperatures of 0 °C and higher for balsam fir. This variable was the main factor to explain cleavage strength variation (100 % of contribution), for the equations concerning 0 and 10 °C. However, for 20 °C, BD was the most important factor to predict cleavage strength (53 %), with RW playing a secondary role (47 %).

Bending strength

MOR

The multiple regression equations for MOR are shown in Table 6. The models obtained may explain from 51 to 86 % of the total variation for black spruce and from 51 to 81 % for balsam fir. These values, together with the low COVs obtained, indicate that these equations may be used for predictive purposes.

MC and BD were the main variables to explain MOR variation for both species (Table 6). MC was the main responsible for this variation under freezing temperatures, whereas BD was the main factor for temperatures of 0, 10, and 20 °C for both species. BD was always present in all models for both species, but it played a secondary role under temperatures below the freezing point of water. Moreover, RW was not an important factor to estimate MOR for both species in the studied temperature range.

An analysis of the beta coefficients of MC in MOR equations for treatments below 0 °C pooled shows that this independent variable, on average, had greater contribution in the variation of MOR explained by the models to black spruce than to balsam fir (65 and 53 %, respectively) (Table 6).

BD was the main element to predict MOR for black spruce and balsam fir for temperatures of 0 °C or higher, with an average contribution of 87 versus 94 % for balsam fir (Table 6).

MOE

The multiple regression equations for MOE are shown in Table 7. The models obtained may explain from 17 to 87 % of the total variation for black spruce and from 36 to 71 % for balsam fir wood. These values, together with the low COV obtained, demonstrated that these equations may be useful for predictive purposes, except for the case of the model of 0 °C for black spruce. In this case, the R^2 was too low (0.17) indicating that other factors not included in the model may play an important role in this property. Further investigations are needed. Moreover, the equation for 10 °C for black spruce was not significant at 0.05 probability level.

Table 6 Regression equations predicting MOR obtained from independent variables MC, BD, and RW for black spruce and balsam fir woods

Equations	R^2	COV (%)
Black spruce		
$\mathrm{MOR}_{(-30\,^\circ\mathrm{C})} = -153 + \underset{\substack{(0.95)^{a}\\(64\%)^{b}}}{0.58}\ \mathrm{MC} + \underset{\substack{(0.37)\\(25\%)}}{471}\ \mathrm{BD} + \underset{\substack{(0.16)\\(11\%)}}{14}\ \mathrm{RW}$	0.86	11.2
$\mathrm{MOR}_{(-20\,^\circ\mathrm{C})} = -103 + \underset{\substack{(0.82)\\(69\%)}}{0.40}\ \mathrm{MC} + \underset{\substack{(0.37)\\(31\%)}}{396}\ \mathrm{BD}$	0.85	9.8
$\mathrm{MOR}_{(-10\,^\circ\mathrm{C})} = -70 + \underset{\substack{(0.72)\\(61\%)}}{0.26}\ \mathrm{MC} + \underset{\substack{(0.45)\\(39\%)}}{311}\ \mathrm{BD}$	0.78	10.3
$\mathrm{MOR}_{(0\,^\circ\mathrm{C})} = -41 + \underset{\substack{(0.71)\\(100\%)}}{262}\ \mathrm{BD}$	0.51	10.2
$\mathrm{MOR}_{(10\,^\circ\mathrm{C})} = -34 + \underset{\substack{(0.70)\\(61\%)}}{265}\ \mathrm{BD} - \underset{\substack{(-0.25)\\(22\%)}}{6}\ \mathrm{RW} - \underset{\substack{(-0.19)\\(17\%)}}{0.03}\ \mathrm{MC}$	0.70	7.7
$\mathrm{MOR}_{(20\,^\circ\mathrm{C})} = -51 + \underset{\substack{(0.81)\\(100\%)}}{269}\ \mathrm{BD}$	0.66	7.5
Balsam fir		
$\mathrm{MOR}_{(-30\,^\circ\mathrm{C})} = -159 + \underset{\substack{(0.93)^{a}\\(60\%)^{b}}}{0.57}\ \mathrm{MC} + \underset{\substack{(0.63)\\(40\%)}}{562}\ \mathrm{BD}$	0.81	11.5
$\mathrm{MOR}_{(-20\,^\circ\mathrm{C})} = -59 + \underset{\substack{(0.83)\\(56\%)}}{0.38}\ \mathrm{MC} + \underset{\substack{(0.49)\\(33\%)}}{325}\ \mathrm{BD} - \underset{\substack{(-0.16)\\(11\%)}}{6}\ \mathrm{RW}$	0.81	10.8
$\mathrm{MOR}_{(-10\,^\circ\mathrm{C})} = -10 + \underset{\substack{(0.60)\\(43\%)}}{0.20}\ \mathrm{MC} + \underset{\substack{(0.43)\\(31\%)}}{223}\ \mathrm{BD} - \underset{\substack{(-0.35)\\(26\%)}}{10}\ \mathrm{RW}$	0.76	9.6
$\mathrm{MOR}_{(0\,^\circ\mathrm{C})} = -15 + \underset{\substack{(0.83)\\(86\%)}}{226}\ \mathrm{BD} - \underset{\substack{(-0.14)\\(14\%)}}{0.03}\ \mathrm{MC}$	0.76	7.5
$\mathrm{MOR}_{(10\,^\circ\mathrm{C})} = -17 + \underset{\substack{(0.86)\\(100\%)}}{216}\ \mathrm{BD}$	0.74	6.5
$\mathrm{MOR}_{(20\,^\circ\mathrm{C})} = -3 + \underset{\substack{(0.71)\\(100\%)}}{162}\ \mathrm{BD}$	0.51	9.5

MOR modulus of rupture, *MC* moisture content, *BD* basic density, *RW* annual ring width, R^2 coefficient of determination, *COV* coefficient of variation (%)

[a] Number in parentheses corresponds to beta coefficients of the regression

[b] Quantitative contribution of the independent variable on the mechanical property (%)

MC and BD were the main variables to explain MOE variation for both species (Table 7). MC was the most important factor for this variation under temperatures below 0 °C, whereas BD was the main factor for temperatures of 0 °C and higher for both species. BD was always present in all models for both species, but it played a secondary role under temperatures below the freezing point of water. Moreover, RW was a minor contributor to estimate MOE for both species, especially for freezing temperatures.

The analysis of the beta coefficients of MC for temperatures below 0 °C showed that this independent variable generally had a greater contribution in the variation of MOE for black spruce than for balsam fir (70 and 48 %, respectively) (Table 7).

Table 7 Regression equations predicting MOE obtained from independent variables MC, BD, and RW for black spruce and balsam fir woods

Equations	R^2	COV (%)
Black spruce		
$\mathrm{MOE}_{(-30\,^\circ\mathrm{C})} = -9082 + \underset{\underset{(67\%)^{b}}{(0.99)^{a}}}{57}\ \mathrm{MC} + \underset{\underset{(19\%)}{(0.29)}}{34364}\ \mathrm{BD} + \underset{\underset{(14\%)}{(0.20)}}{1747}\ \mathrm{RW}$	0.87	9.3
$\mathrm{MOE}_{(-20\,^\circ\mathrm{C})} = -8654 + \underset{\underset{(68\%)}{(0.91)}}{52}\ \mathrm{MC} + \underset{\underset{(21\%)}{(0.28)}}{34755}\ \mathrm{BD} + \underset{\underset{(11\%)}{(0.16)}}{1126}\ \mathrm{RW}$	0.85	9.4
$\mathrm{MOE}_{(-10\,^\circ\mathrm{C})} = -354 + \underset{\underset{(76\%)}{(0.75)}}{31}\ \mathrm{MC} + \underset{\underset{(24\%)}{(0.24)}}{19016}\ \mathrm{BD}$	0.66	12.1
$\mathrm{MOE}_{(0\,^\circ\mathrm{C})} = 2546 + \underset{\underset{(100\%)}{(0.41)}}{14612}\ \mathrm{BD}$	0.17	10.0
$\mathrm{MOE}_{(10\,^\circ\mathrm{C})} = \mathrm{MC, BD, RW\ n.s.}$	0.10	10.3
$\mathrm{MOE}_{(20\,^\circ\mathrm{C})} = -360 + \underset{\underset{(100\%)}{(0.50)}}{20609}\ \mathrm{BD}$	0.25	10.3
Balsam fir		
$\mathrm{MOE}_{(-30\,^\circ\mathrm{C})} = -12827 + \underset{\underset{(56\%)^{b}}{(0.79)^{a}}}{43}\ \mathrm{MC} + \underset{\underset{(44\%)}{(0.69)}}{54613}\ \mathrm{BD}$	0.68	12.7
$\mathrm{MOE}_{(-20\,^\circ\mathrm{C})} = -3129 + \underset{\underset{(48\%)}{(0.68)}}{33}\ \mathrm{MC} + \underset{\underset{(33\%)}{(0.46)}}{32181}\ \mathrm{BD} - \underset{\underset{(19\%)}{(-0.27)}}{1014}\ \mathrm{RW}$	0.71	12.3
$\mathrm{MOE}_{(-10\,^\circ\mathrm{C})} = -624 + \underset{\underset{(39\%)}{(0.47)}}{22}\ \mathrm{MC} - \underset{\underset{(32\%)}{(-0.40)}}{1517}\ \mathrm{RW} + \underset{\underset{(29\%)}{(0.36)}}{24982}\ \mathrm{BD}$	0.64	13.1
$\mathrm{MOE}_{(0\,^\circ\mathrm{C})} = -4725 + \underset{\underset{(100\%)}{(0.80)}}{35676}\ \mathrm{BD}$	0.64	11.5
$\mathrm{MOE}_{(10\,^\circ\mathrm{C})} = 2323 + \underset{\underset{(51\%)}{(0.45)}}{18289}\ \mathrm{BD} - \underset{\underset{(49\%)}{(-0.43)}}{834}\ \mathrm{RW}$	0.66	9.3
$\mathrm{MOE}_{(20\,^\circ\mathrm{C})} = -1299 + \underset{\underset{(100\%)}{(0.60)}}{24161}\ \mathrm{BD}$	0.36	14.1

MOE modulus of elasticity, *MC* moisture content, *BD* basic density, *RW* annual ring width, R^2 coefficient of determination, *COV* coefficient of variation (%)

[a] Number in parentheses corresponds to beta coefficients of the regression

[b] Quantitative contribution of the independent variable on the mechanical property (%)

BD was the main factor to predict MOE for black spruce and balsam fir for temperatures of 0 °C or higher pooled, with an average contribution of 100 versus 84 % for balsam fir (Table 7).

Conclusion

This study showed that temperature and moisture content of black spruce and balsam fir woods influence significantly the mechanical properties involved in the chip formation process by a chipper-canter. The results confirmed that the effect of moisture content must be taken into account only for temperatures below 0 °C. At higher temperatures, there were no important effects of moisture content on wood strength for the two softwoods. Furthermore, the effects of changes in temperature below 0 °C were more evident under higher moisture content conditions for both species. Thus, the higher strength values were obtained at −30 °C for sapwood. The multiple regression analyses showed that under temperatures below 0 °C, moisture content was the most important factor to explain all mechanical properties, with basic density playing a secondary role. However, for temperature of 0 °C and higher, basic density was the principal factor, with moisture content playing a minor role. Growth rate did not affect significantly the mechanical properties for all temperatures. Moreover, mechanical properties of balsam fir wood were more sensitive to changes in temperature below 0 °C than black spruce wood. Among the studied mechanical properties, cleavage was the most sensitive to changes in temperature, followed by shear, MOR, and MOE for both species. This fact could play an important role in the chip formation process and could generate a significant variation in size distribution of chips produced by chippers. Finally, physical and mechanical properties of wood should be taken into account in summer and winter conditions in order to enhance the chipping process in sawmills by obtaining higher proportions of acceptable chips.

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