MECHANICAL PROPERTIES IN RELATION TO SELECTED WOOD CHARACTERISTICS OF BLACK SPRUCE

Jérôme Alteyrac†
Ph.D. Candidate

Alain Cloutier†
Professor
Département des sciences du bois et de la forêt
Université Laval
Québec City, Québec, Canada, G1K 7P4

Chhun-Huor Ung
Research Scientist
Natural Resources Canada, Canadian Forest Service
1055, rue du P.E.P.S., P.O. Box 3800
Sainte-Foy, Québec, Canada, G1V 4C7

and

S. Y. Zhang†
Senior Scientist/Group Leader and Adjunct Professor
Resource Assessment and Utilization Group, Forintek Canada Corp.
319 rue Franquet
Québec City, Québec, Canada, G1P 4R4

(Received April 2005)

ABSTRACT

The relation between ring width, ring density, microfibril angle, and bending properties was analyzed at 2.4-m height on twelve 80-year-old black spruce trees. The moduli of elasticity and rupture were measured in the southernmost radial direction on extracted specimens of size 10 × 10 × 150 mm^3 from pith to bark. Ring density and ring width were measured by X-ray densitometry, and microfibril angle was measured by the Silviscan technology. The impact of these three traits on the moduli of elasticity and rupture was evaluated by explicitly separating the radial variation from the variation among trees using a mixed model analysis. The results obtained show first that the modulus of elasticity is negatively correlated to microfibril angle. This result supports the assumption that the relation between modulus of elasticity and microfibril angle is not dependent on radial growth rate. Secondly, ring density has a lower contribution in predicting the modulus of elasticity than the modulus of rupture. In both cases, ring width was not a significant factor of variation of the moduli of elasticity and rupture.

Keywords: Microfibril angle, modulus of elasticity, modulus of rupture, ring density, ring width, cambial age, mixed model.

INTRODUCTION

The properties of forest products depend strongly on wood characteristics such as tracheid length, microfibril angle, and wood density. Traditionally, wood density is seen as the single most important factor, although other parameters (e.g. microfibril angle, spiral grain, compression wood, juvenile wood proportion, and ring width) may have an equal or greater effect. Wood density is of key importance in forest products manufacturing because it has a major impact on yield, quality, and value of wood-based composites and solid wood products and

† Member of SWST.

because it can be changed by silvicultural practices and genetic improvement (Zobel and van Buijtenen 1989; Walker and Woollons 1998). For instance, it is often admitted that wood density is a determinant factor of wood quality (Bamber and Burley 1983; Zobel and van Buijtenen 1989; Walker et al. 1993). However, microfibril angle (MFA) in the second cell-wall layer is known as one of the main determinants of stiffness (Cave 1968, 1969; Cave and Walker 1994; Walker and Butterfield 1996; Lindstrom et al. 2002) and longitudinal shrinkage (Harris and Meylan 1965).

Other wood characteristics such as ring width, cell structure, ring density, and latewood proportion can influence bending properties (Butterfield and Pal 1998). The early work of Wardrop (1951) showed that relationships exist between wood density, fiber length, MFA, and compression wood. More recently, Zhang and Zhong (1992) demonstrated that a large MFA in juvenile wood of oak was negatively correlated to fiber length and that the relationship between tensile strength and MFA was significant. Microfibril angle has been shown in several studies to decrease from pith to bark (Cowdrey and Preston 1966; Bendtsen and Senft 1986; Donaldson 1992; Butterfield and Pal 1998). Therefore, a large MFA in coniferous juvenile wood reduces the stiffness of young trees and gives flexibility to prevent breaking in strong winds (Barnett and Bonham 2004). The literature shows that ring density and microfibril angle are two of the most determinant characteristics of wood in terms of shrinkage and strength properties.

The objective of this study was to quantify the impacts of ring width, ring density, and microfibril angle on black spruce wood stiffness and strength. The approach adopted consists of separating explicitly the variation across the trees from the radial variation (within-trees) with a mixed model.

MATERIAL AND METHODS

Material

Thirty-six black spruce trees were harvested in the Chibougamau area, 400 km north of Quebec City, Canada, in a naturally regenerated stand after a fire in 1906 (Alteyrac et al. 2005). All mechanical, physical, and anatomical specimens were obtained from the same 30-cm-long bolt taken at 2.4 m high in every tree. A 10-mm-thick box-pith plank was cut from this bolt (Fig. 1). Two cross-sections were cut from this plank to produce specimens for the determination of the radial density and MFA profiles (specimen C about 20 mm long). The remaining part of the plank, part A, was used for the determination of bending properties and part B for anatomical measurements of lumen area and cell-wall thickness not presented in this paper.

Ten-mm by 10-mm specimens were ripped from pith to bark in the southernmost radial direction in part A (Fig. 1) for the determination of the bending properties. Five or six specimens were produced this way depending on the bolt diameter. These specimens were trimmed to 150 mm long with special care in order to obtain specimens free of defects as much as possible. The resulting 10-mm × 10-mm × 150-mm (R × T × L) specimens were dried under restraint from green to 12% moisture content in a conditioning room (20°C, 65% HR).

The determination of MFA was carried out on specimens obtained from part C (Fig. 1) for 12 sample trees only. The specimens were cut to 10 mm long and placed into 95% and 100% ethanol for dehydration. They were then sent to the CSIRO Forestry and Forest Products Department, where they were further processed to 2

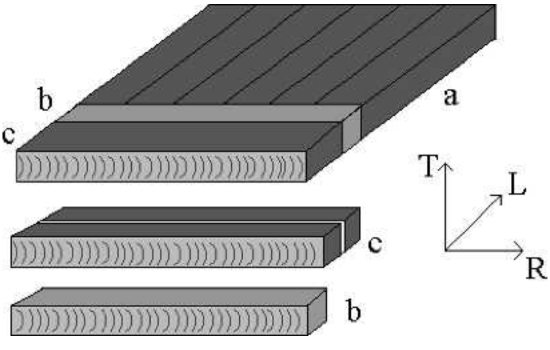

FIG. 1. Preparation of specimens for a) mechanical features, b) anatomical characteristics and c) densitometry.

mm by 7 mm (T × L) from pith to bark, and scanned.

From the remaining material of each radial section (part C), a 20-mm-long specimen was removed to obtain a radial segment from pith to bark of 10 mm × 20 mm (T × L) in the southernmost direction. The segments were cut into 5-mm by 1.57-mm (T × L) strips with a specially designed pneumatic-carriage twin-blade saw. The sawn strips were extracted with a cyclohexane/ethanol (2:1) solution for 24 h and then with hot water for another 24 h to remove extractive compounds. After extraction, the strips were air-dried under restraint to prevent warping.

Methods

Wood characterization.—The strips were scanned in the air-dried condition with an X-ray densitometer available at Forintek Canada Corp., Quebec City, Canada. The output data include ring density (RD) and ring width (RW).

Bending tests were also performed at Forintek Canada Corp. The specimens were tested according to the ASTM D-143 standard for small clear specimens in a conditioning room (20°C and 65% HR) at 12% equilibrium moisture content. The specimens were laid pith side up with growth rings in the horizontal position with a span of 110 mm. The bending tests were performed twice, below the elastic limit and until rupture.

The MFA measurements were done with the Silviscan technology, a method including optical microscopy, X-ray diffractometry, X-ray densitometry, and image analysis. The output is the MFA value associated to the distance from the pith in millimeters. The MFA was measured from pith to bark with a resolution of 2 mm that provided a MFA average value at each 2-mm step.

Statistical analysis.—The mixed model developed by the SAS Institute in 1992 is suitable for analyzing data with multiple hierarchical levels (Singer 1998). A mixed model was used by Guilley and Nepveu (2003) to determine the relation between ring density and ring width as a function of cambial age by considering three hierarchical levels: within-tree level (radial variation from pith to bark or longitudinal variation from stump to tree top), tree level (range of tree height or tree diameter), and stand level (stand density or site fertility).

Because of limited data, the stand level was not considered here. Based on the first two levels, i.e. within tree and between tree, the general relation between the response variable represented by MOE or MOR and the explanatory variables represented by MFA, RD, and RW can be written as follows:

$$y_{ij} = \mu + \beta_i + \gamma_j + \varepsilon_{ij} \tag{1}$$

where y_{ij} is the value of MOE or MOR for specimen i obtained from tree j; μ is the overall mean; β_i is the mean effect of MFA, RD, or RW measured on specimen i; γ_j is the random effect of tree j; and ε_{ij} is the error term following a normal distribution with a zero mean, and variance σ^2.

Nonsignificant explanatory variables were progressively removed from the model at $\alpha = 5\%$. Although 36 sample trees were collected, the statistical analysis was performed on 12 sample trees for which MFA measurements were done.

RESULTS AND DISCUSSION

Results

The average values obtained for MOE and MOR as a function of cambial age are presented in Fig. 2. Each ring of the specimen was given the value of MOE and MOR found for this specimen. Then, the results correspond to the average profile calculated for each ring of all sample trees. They clearly show a fast increase of MOE and MOR until a cambial age of 25 years, where a plateau is reached. The cambial age of 25 years seems to be the point for separating visually juvenile wood from mature wood.

The radial profiles of MFA, RD, and RW are presented in Fig. 3 and show the average value of those traits calculated in each ring for all sample trees. These results show that only MFA presents a strong relationship with MOE and MOR radial profiles. This similar but reverse

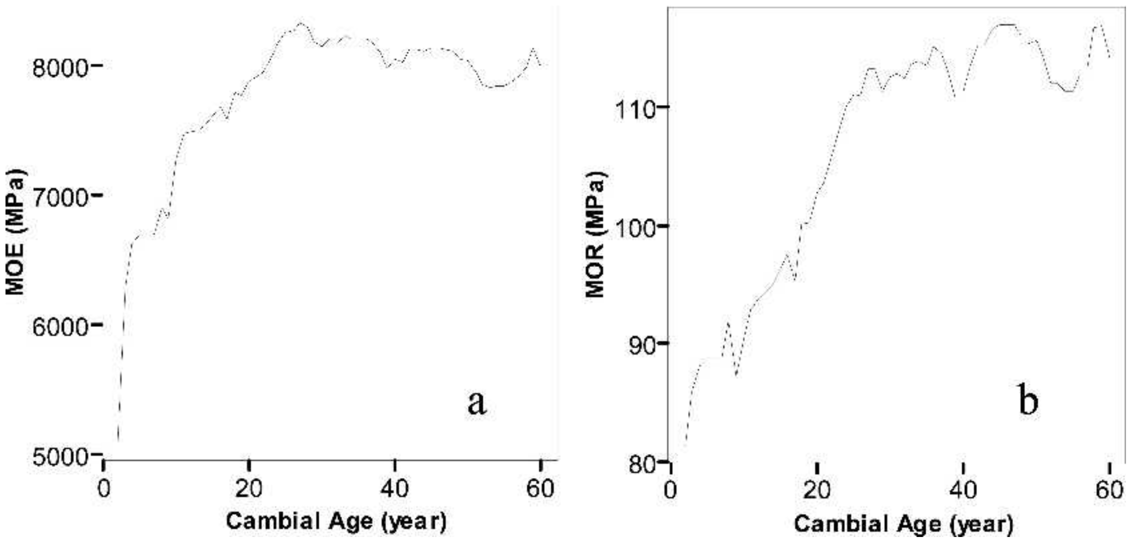

FIG. 2. Radial variation (measurement averages) from pith to bark of a) MOE and b) MOR as a function of cambial age.

profile between MFA and MOE/MOR is also shown in Figs. 4a and 4b where a strong relation is visible and is somewhat consistent with the relation between MFA and MOE as found for radiata pine by Downes et al. (2002).

In the present study, a high MFA value is observed near the pith (Fig. 3a), while rings closer to the cambium have a lower MFA in agreement with results obtained by Butterfield and Pal (1998) for radiata pine. The RD pattern (Fig. 3b) is of type II as described by Panshin and De Zeeuw (1980). Ring density decreases until ring 10 and then increases outward. In contrast, the radial profile of MOE (Fig. 2a) presents a positive slope until ring 25 and then stays fairly constant thereafter. Thus, the variations of the bending properties in the radial direction are small in mature wood, implying that this wood presents more stable mechanical properties than juvenile wood. The two different radial patterns of MOE and RD are also represented in the graph of Fig. 4c which shows no relation between these two wood characteristics. A nonsignificant correlation is found between RD and MOE, while RD/MOR presents a weak but significant correlation of 0.29. Finally the RW profile (Fig. 3c) presents a constant decrease after ring 4, showing a pattern strongly different from the MFA and RD radial profiles. From Fig. 4e and 4f, a possible link between RW and MOE is observed as well as between RW and MOR. A correlation of −0.47 was found between RW and MOE, while −0.42 was found between RW and MOR.

The first mixed model considered included the three independent variables MFA, RD, and RW, which are the wood characteristics that most likely will modify MOE. The nonsignificant effect of RD and RW on MOE leads to removal of those two variables from the model. Table 1 presents the final model showing that MOE decreases by 120 MPa when MFA increases by one degree in the radial direction. Moreover, the model indicates that, at a given MFA value, the MOE is different from one tree to another because of the tree effect, γ. However, this between-tree variation is weak with only 7.5% of the variation of MOE. Consequently, the within-tree variation is much more important than the between-tree variation.

The modulus of rupture was modeled with the same approach used for MOE, considering a starting model with MFA, RD, and RW variables which are likely to have an effect on MOR. The final model obtained is given in Table 2. This model suggests that the variation of MOR is dependent on both RD and MFA. As was the case for the MOE model (Table 1), RW was not

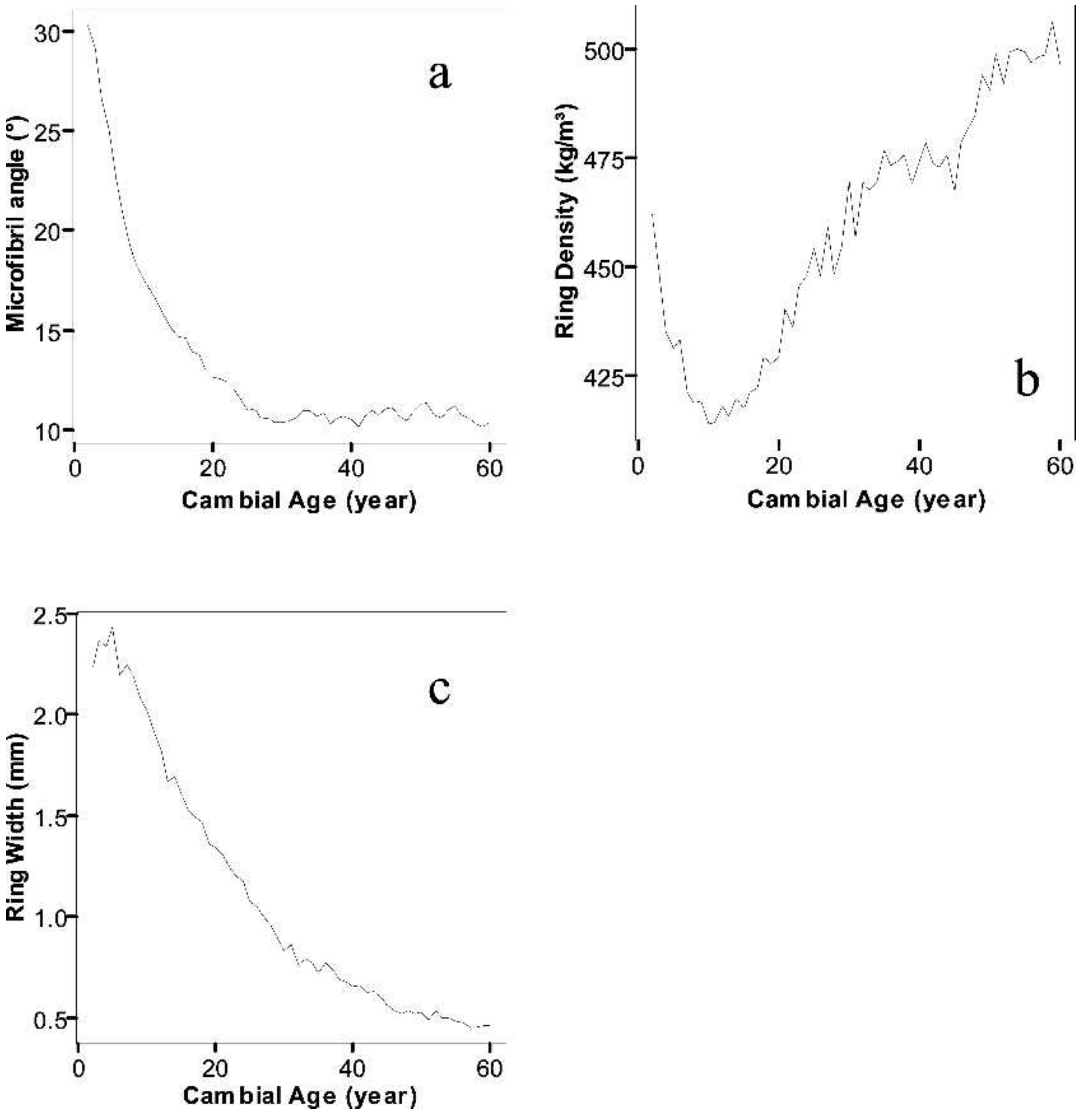

FIG. 3. Radial variation (measurement averages) of a) MFA, b) RD and c) RW as a function of cambial age.

found to be a significant predictor of MOR. The model shows that MOR increases by 0.18 MPa and decreases by 0.97 MPa when RD and MFA increase by one unit, respectively. The higher proportion of the variance due to trees (22%) in the MOR model compared to 7.5% in the MOE model, means that trees have a stronger effect on MOR variation than on MOE variation. This stronger effect could be a consequence of defects (most likely knots) present in the specimen. Although clear specimens were used in bending tests, some of them presented small defects that can be a factor of variation between trees. In contrast with the model of Table 1 where RD did not explain significantly the MOE variation, RD becomes significant for MOR by explaining 16% of its variation. Nevertheless MFA remains the most important factor determining the me-

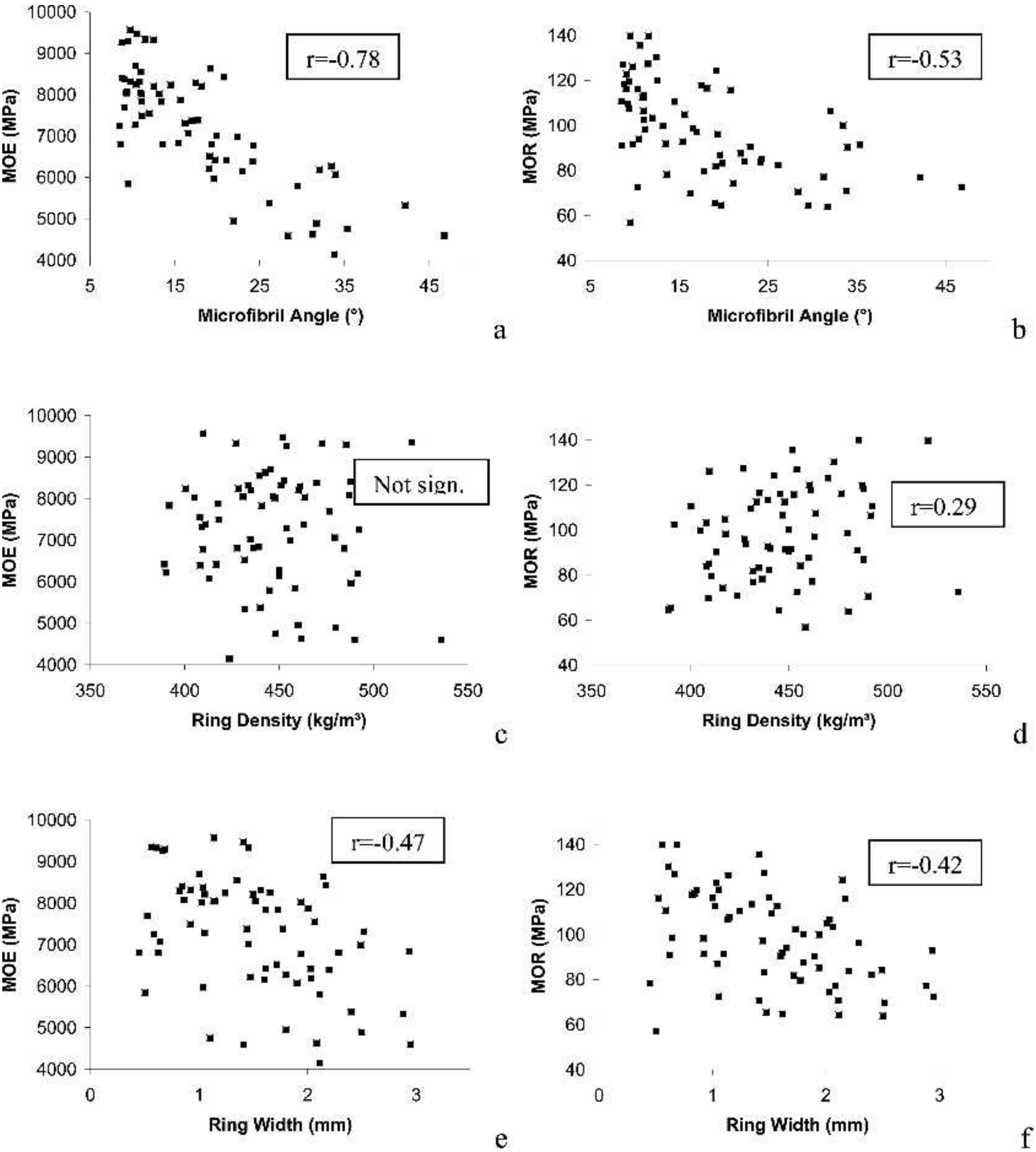

FIG. 4. Relation between a) MOE and MFA, b) MOR and MFA, c) MOE and RD, d) MOR and RD, e) MOE and RW, and f) MOR and RW.

chanical properties of wood with 50% of the variation.

DISCUSSION

While MOE seems to be dependent on MFA only, MOR seems to depend on both MFA and RD. This observation is partially consistent with the results of Yang and Evans (2003), where it was shown that MFA had a greater influence than RD on the MOE of eucalyptus and that high microfibril angle was associated to low stiffness in radiata pine (Downes et al. 2002). Booker et

TABLE 1. *Variation of MOE explained by MFA and random effect of trees.*

$$MOE = 9391.51 - 120.05 \times MFA + \gamma + \varepsilon$$

Variation due to MFA	Variation due to tree (γ)	Unexplained variation (ε)
72%	7.5%	20.5%

TABLE 2. *Variation of MOR explained by MFA and RD, and random effect of trees.*

$$MOR = 33.77 - 0.97 \times MFA + 0.18 \times RD + \gamma + \varepsilon$$

Variation due to MFA	Variation due to RD	Variation due to tree (γ)	Unexplained variation (ε)
50%	16%	22%	12%

al. (1998) also indicated in radiata pine that the relationship between modulus of elasticity and MFA is significant, while the relationship with density is not significant.

A study on radiata pine (Cown et al. 1999) showed a significant effect of both wood density and MFA on clearwood performance of the juvenile wood, while in the mature wood, density alone was important. This conclusion is contrasted by the present study, which demonstrates that RD has a low impact on the mechanical properties of black spruce as shown in Figs. 4c and 4d and in the mixed model analysis. The MOE and RD profiles shown in Figs. 2a and 3b highlight a variable effect of RD on MOE according to the position of the ring from pith to bark and probably according to the type of wood. In juvenile wood, RD has a negative effect on MOE while it has a positive effect in mature wood.

The similar but reverse pattern of MFA and MOE noticed earlier is confirmed by the mixed model: MFA appears to be a main predictor of stiffness. In both MOE and MOR mixed models, RW seems to have no significant effect. This conclusion is supported by the previous work of Fernandez-Golfin and Diez (1994). They showed that RW had little impact on the variation of wood density and bending strength, and therefore was of little value in predicting the mechanical properties of wood.

Models of MOE and MOR are interesting in the biological aspect because they refer to two main characteristics of wood and are built on the same design, one or two main effects and a random effect of tree. The significance of both MFA and RD in the mixed model analysis leads to focus on the cell structure and on an analogy with a spring. There is a similarity between the physical behavior of a spring and MFA in the S2 layer of the cell. Guitard and Gachet (2004) presented a micromodel in which the ultrastructure is related to the elastic anisotropy of wood to explain the variability of MOE from MFA and wood texture. In the first level of this model, the modulus of elasticity is a combination of the modulus of elasticity of the cell-wall components (isotropic properties, E^m) and the modulus of elasticity of microfibrils (E^f) taking into account the proportion of microfibrils (V) and the angle. The secondary wall named S2 is the thicker layer in the cell wall and therefore the more important. Then, according to the microfibril structure in the cell wall, a tracheid can be considered as a spring or an anisotropic solid layer reinforced by microfibril skeleton, in which the cell wall is related to the wire and the cell diameter is related to the diameter of the spring. The positive and significant impact of wood density on MOR variation as it appears in the mixed model can also be partially explained by this analogy. Indeed, the thicker wire which corresponds to a thicker cell wall, or the smaller diameter of the spring which is equivalent to a smaller lumen diameter, induces a higher stiffness of the spring or the tracheid.

The relationships between wood characteristics remain numerous and complex, in that one response factor must be explained by more than one independent variable. In the present study, many variables have not been explored, i.e., earlywood density, earlywood width, earlywood proportion, and especially variables concerning tracheid structure (diameter, length, cell-wall thickness).

Finally, at least three hierarchical levels of factors could affect the relationships between MOE and MFA: within tree (radial variation from pith to bark, and longitudinal variation along the stem), tree (tree height, tree diameter), and stand (stand density, site fertility). In this study, only the within-tree level represented by the radial axis, and tree levels were jointly considered with a mixed model.

CONCLUSIONS

Microfibril angle, ring density, and ring width present a specific radial variation with respect to cambial age from pith to bark. The mechanical properties also present a specific radial variation from pith to bark. A visual examination can highlight a complex relationship between these traits, but only the relation between the modulus of elasticity and microfibril angle is clear. The mixed model was then used to analyze these relationships. This work led to the following conclusions: Microfibril angle and MOE presented a strong negative correlation; microfibril angle alone is a good predictor of MOE, while ring density and microfibril angle are a good predictor of MOR. Ring density is a better predictor of strength than stiffness. Ring width has no significant impact on MOE and MOR.

In both MOE and MOR mixed models, the tree random effect is important. This means that, regardless of MFA and RD, the MOE and MOR mean values depend on tree characteristics. However, the tree variance is less than the error variance indicating that other factors of variation exist within trees. The absence of a significant random effect on the coefficient of the independent variables in MOE and MOR models indicates that the effect of MFA on MOE and the effect of RD and MFA on MOR are constant from one tree to another.

ACKNOWLEDGMENTS

We would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) for funding under strategic grant no. 234774.

REFERENCES

ALTEYRAC, J., S. Y. ZHANG, A. CLOUTIER, AND J. C. RUEL. 2005. Influence of stand density on ring width and wood density at different sampling heights in black spruce (*Picea mariana* (Mill.) B.S.P). Wood Fiber Sci. 37(1): 83–94.

BAMBER, R. K., AND J. BURLEY. 1983. The wood properties of radiata pine. Commonwealth Agricultural Bureaux, Slough, UK. 1983, 84 pp.

BARNETT, J. R., AND V. A. BONHAM. 2004. Cellulose microfibril angle in the cell wall of wood fibres. Biological-Reviews. 79(2):461–472.

BENDTSEN, B. A., AND J. F. SENFT. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. Wood Fiber Sci. 18(1):23–38.

BOOKER, R. E., J. HARRINGTON, AND T. SHIOKURA. 1998. Variation of Young's modulus with microfibril angle, density and spiral grain. Pages 296–311 *in* Proc. IAWA/IUFRO International Workshop on the Significance of Microfibril Angle, University of Canterbury, Christchurch, NZ.

BUTTERFIELD, B., AND V. PAL. 1998. Relating microfibril angle to wood quality in clonal seedlings of radiata pine. Pages 337–347 *in* Proc. IAWA/IUFRO International Workshop on the Significance of Microfibril Angle, University of Canterbury, Christchurch, NZ.

CAVE, I. D. 1968. The anisotropic elasticity of the plant cell wall. Wood Sci. Technol. 2(4):268–278.

———. 1969. The longitudinal Young's modulus of *Pinus radiata*. Wood Sci. Technol. 3(1):40–48.

———, and J. C. F. WALKER. 1994. Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. Forest Prod. J. 44:(5):43–48.

COWN, D. J., J. HEBERT, AND R. BALL. 1999. Modelling *Pinus radiata* lumber characteristics. Part 1: Mechanical properties of small clears. NZ. J. For. Sci. 29(2):203–213.

COWDREY, D. R., AND R. D. PRESTON. 1966. Elasticity and microfibrillar angle in the wood of Sitka spruce. Proc. Roy. Soc. Lond. 166B(1004):245–272.

DONALDSON, L. A. 1992. Within- and between-tree variation in microfibril angle in *Pinus radiata*. NZ. J. For. Sci. 22(1):77–86.

DOWNES, G. M., J. G. NYAKUENGAMA, R. EVANS, R. NORTHWAY, P. BLAKEMORE, R. L. DICKSON, AND M. LAUSBERG. 2002. Relationship between wood density, microfibril angle and stiffness in thinned and fertilized *Pinus radiata*. IAWA-J. 23(3):253–265.

FERNANDEZ-GOLFIN, J. I., AND M. R. DIEZ. 1994. Influence of ring width on the density and other physical and mechanical properties of structural timber of various species. Investigacion-Agraria-Sistemas-y-Recursos-Forestales. 3(2):211–219.

GUILLEY, E., AND G. NEPVEU. 2003. Interprétation anatomique des composantes d'un modèle mixte de densité du bois chez le Chêne sessile (*Quercus petraea* Liebl.): Âge du cerne compté depuis la moelle, largeur de cerne, arbre, variabilité interannuelle et duraminisation. Ann. For. Sci. 60:331–346.

GUITARD, D., AND C. GACHET. 2004. Paramètres structuraux et/ou ultrastructuraux facteurs de la variabilité intra-arbre de l'anisotropie élastique du bois. Ann. For. Sci. 61:129–139.

Harris, J. M., and B. A. Meylan. 1965. The influence of microfibril angle on longitudinal and tangential shrinkage in *Pinus radiata*. Holzforschung 19(5):144–153.

Lindstrom, H., P. Harris, and R. Nakada. 2002. Methods for measuring stiffness of young trees. Holz Roh-Werkst. 60(3):165–174.

Panshin, A. J., and C. de Zeeuw. 1980. Textbook of wood technology. McGraw-Hill Book Co., New York, NY, 772 pp.

Singer, J. D. 1998. Using SAS PROC MIXED to fit multilevel models, hierarchical models, and individual growth models. J Educational and Behavioral Statistic. 24(4):323–355.

Walker, J. C. F., and B. G. Butterfield. 1996. The importance of microfibril angle to the processing industries. NZ Forestry 4(4):34–40.

———, and R. C. Woollons. 1998. Cell wall organisation and the properties of xylem–a speculative review. Pages 323–326 *in* B. G. Butterfield, ed. Proc. IAWA/IUFRO International Workshop on the Microfibril Angle in Wood, University of Canterbury, Christchurch, NZ.

———, B. G. Butterfield, T. A. G. Langrish, J. M. Harris, and J. M. Uprichard. 1993. Primary wood processing: principles and practice. Chapman and Hall, Ltd, London, UK, 595 pp.

Wardrop, A. B. 1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. Aust. J. Sci. Res. 4B(4):391–414.

Yang, J. L., and R. Evans. 2003. Prediction of MOE of eucalypt wood from microfibril angle and density. Holz Roh-Werkst. 61(6):449–452.

Zhang, S. Y., and Y. Zhong. 1992. Structure-property relationship of wood in East-Liaoning oak. Wood Sci. Technol. 26(2):139–149.

Zobel, B. J., and J. P. van Buijtenen. 1989. Wood variation, its causes and control. Springer-Verlag, Berlin, Germany, 363 pp.