WITHIN-STEM VARIATION IN WOOD PROPERTIES OF RED PINE (*PINUS RESINOSA* AIT.)

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Abstract. Some physical and mechanical properties, including tension parallel-to-grain, tension perpendicular-to-grain, and shear parallel-to-grain, and their variations within the tree stem of red pine (*Pinus resinosa* Ait.) were evaluated in this study. All these wood properties were obtained based on small clear specimens. Results indicate that wood properties tended to increase from pith to bark in the radial direction and decrease from bottom to top in the longitudinal direction. These variations in wood properties can be mainly attributed to the differences in wood characteristics of juvenile and mature wood. The influence of growth ring orientation was not statistically significant on shear strength parallel-to-grain and tensile strength perpendicular-to-grain. Information on variation in mechanical properties of wood across a tree stem is essential to investigate the influence of sawing pattern on mechanical properties of lumber products.

Keywords: Red pine, specific gravity, tensile strength parallel-to-grain, tensile strength perpendicular-to-grain, shear strength parallel-to-grain, within-stem variation.

INTRODUCTION

Wood properties such as specific gravity, stiffness, and strength vary among species, among trees of the same species, and within individual trees, which can be mainly attributed to genetic and environmental factors (Zobel and van Buijtenen 1989). The environmental factors can be further divided into climate (variation in climate), site quality, and stand environment (competition among individual trees) (Deresse 1998). Variation in properties may have a significant impact on the use of lumber products. Lack of uniformity in wood properties can result in undesirable forest products such as dimension lumber with low stiffness and strength (Kennedy 1995) and wood composite panels with greater thickness swell and linear expansion (Pugel et al 1989, 1990, 2004).

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Dimension lumber is one of the most important forest products in Canada. As the raw material for manufacturing of lumber shifts from old-growth forests to short-rotation plantations, wood property variation will play a more critical role in these younger trees, which will ultimately influence the quality of lumber. However, the wood properties of second-growth trees largely depend on forest management such as silvicultural practices (Zhu et al 2007; Shmulsky and Jones 2011). To study the influence of forest management and manufacturing process on quality of lumber products, it is more efficient to use integrated models that can predict properties of lumber based on the following information: 1) basic wood properties and their variations within a tree stem; and 2) location and size of growth features that influence lumber properties such as knots.

The availability of such models would allow properties of lumber to be predicted without physically processing trees and testing lumber specimens. Simulation studies using these models will allow forest managers to study the influence of forest management practices, which affect tree growth characteristics, and allow sawmill operators to study the influence of log conversion pattern on end-product properties. Development of these integrated models is one of the primary goals of a strategic research network on forest management for value-added products in Canada, known as ForValueNet. The work described in this study forms part of a project under ForValueNet to develop a finite element-based model to predict strength properties of dimension lumber. To predict lumber strength under load (eg tension or bending) using the finite element model requires the determination of a number of mechanical properties. Specifically, this study describes the first part of the project, which is the evaluation of variation in mechanical properties within a tree stem.

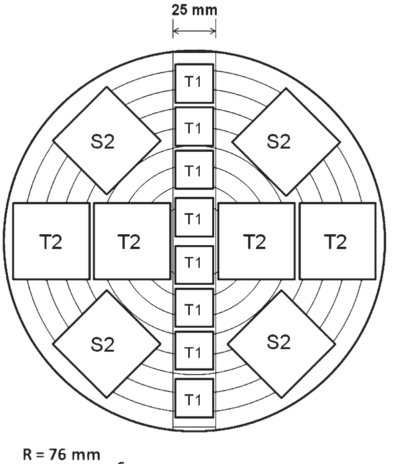
Red pine (*Pinus resinosa* Ait.) was the species used in this study. Red pine is one of the major species for plantation silviculture in the regions of north–central and northeastern US as well as southeastern Canada and is used primarily for structural lumber and pulp. Considerable research on its wood property variation has been conducted (Baker 1967; Peterson 1967; Alkan 1990; Shepard and Shottafer 1992; Kaya and Smith 1993; Deresse 1998; Shukla and Kamdem 2008). Much of the previous work was on within-stem variations of specific gravity, modulus of elasticity (MOE), and modulus of rupture (MOR). MOE is also called bending modulus, which is a measure of the resistance to bending deflection. It is usually determined from the slope of a linear load-deflection response of a bending test. To differentiate it from MOE, the slope of the stress–strain response is usually referred to as Young's modulus (E) in tensile tests (FPL 2010).

For other wood species, in addition to MOE and MOR, extensive research has been carried out on other mechanical properties of wood and their relationships with specific gravity (Stern 1944; Doyle and Drow 1946; Kellogg and Ifju 1962; Palka 1973). However, little information is available in the literature on variations of tensile and shear properties of red pine and their relationships with specific gravity. As such, the objective of this study was to investigate variations of specific gravity and selected mechanical properties, including E, tensile strength parallel-to-grain, shear strength parallel-to-grain, and tensile strength perpendicular-to-grain within stem in both radial and longitudinal directions. As previously stated, this study was completed as part of a project to develop a model to predict strength properties of structural lumber based on basic mechanical wood properties and growth defects such as knots. Wood properties determined from this study will be used as input data to the model.

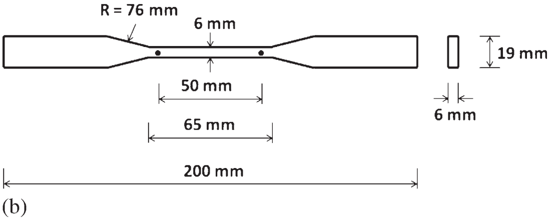
MATERIALS AND METHODS

Two red pine logs, 9.2 m long, were obtained from a local sawmill in Fredericton, New Brunswick, Canada. After the logs were marked and numbered, a 1.2-m-long bolt was cut from the top and bottom part of each log. The remainder of the logs was kept for processing into lumber that was intended for tension tests to validate model predictions. A 35-mm-thick disk was cut from both ends of each bolt, from which a 19- × 6-mm strip was cut across the entire diameter for growth ring and microscale wood density measurements. From the remaining bolt length, an approximately 25-mm-wide slab, centered on the pith, was cut. Sticks of 25 × 25 mm in cross-section were cut from this slab to produce tension parallel-to-grain test specimens, depicted by T1 in Fig 1a. The remainder of the bolt was sawn into sticks of 50- × 50-mm cross-section, depicted by T2 and S2 in Fig 1a. These sticks were used to machine tension perpendicular-to-grain and shear parallel-to-grain specimens, respectively.

The T1 sticks were machined into tension specimens for measuring E and tensile strength parallel-to-grain. Five specimens were obtained from each T1 stick. The size of the tension specimens is shown in Fig 1b, which deviated from that recommended by ASTM (2009). A modified tension parallel-to-grain test specimen was necessary to prevent failure in the grip. The T2 and S2 sticks were machined into specimens for tension perpendicular-to-grain and shear parallel-to-grain strength tests, for which the strength in both radial and tangential directions was taken into account. Each T2 and S2 stick provided 10 specimens, according to the dimension requirements in ASTM (2009). The remainder of each stick was used to determine the wood specific gravity and moisture content of the test specimen. Only clear wood specimens with straight grain and no visible defects were selected for wood material property tests. All specimens were stored in a conditioning room maintained at 20°C and 65% RH until constant weight before testing.



(a)



(b)

Figure 1. (a) Schematic of wood specimens cut from log cross-section. T1, sticks of 25- × 25-mm cross-section for tension parallel-to-grain; T2, sticks of 50- × 50-mm cross-section for tension perpendicular-to-grain; and S2, sticks of 50- × 50-mm cross-section for shear parallel-to-grain. (b) Specimen dimensions for tension parallel-to-grain test.

Moisture content was measured using an oven-dry method according to ASTM (2007a). Specific gravity was measured based on oven-dry mass and volume at test following ASTM (2007b). All specimens for specific gravity measurement were cut from the same sticks, which were used to produce tension parallel-to-grain test specimens. This made the relationship between specific gravity and tensile properties more accurate and convincing. The number of rings, average ring width, and wood density at microscale were measured on a diametral line from pith to bark by X-ray densitometry (QMS Tree Ring Scanner; Quintek Measurement Systems, Knoxville, TN). The mechanical tests were conducted using a universal testing machine following ASTM (2009). Young's modulus was measured from the tension parallel-to-grain test by using an extensometer attached to the middle of the test specimen. The gauge length used in the test was 50 mm. Nominal room condition during testing was 20°C and 65% RH. The total number of specimens tested in tension parallel-to-grain, tension perpendicular-to-grain, and shear parallel-to-grain tests was 108, 120, and 150, respectively.

RESULTS AND DISCUSSION

Wood Properties

Characteristics of the logs such as diameter, number of growth rings, and average ring width

Table 1. Characteristics of the logs based on measurements by X-ray densitometry (standard deviation in parentheses).

Specimen[a]	Diameter (mm)	Number of rings	Average ring width (mm)
L1T	214	50	2.1 (1.1)
L1B	267	74	1.8 (1.3)
L2T	204	52	1.9 (1.2)
L2B	275	74	1.8 (1.1)

[a] L1T, top section of Log 1; L1B, bottom section of Log 1; L2T, top section of Log 2; L2B, bottom section of Log 2.

as measured by X-ray densitometry are presented in Table 1. Usually, the approximate age of trees was determined by counting the annual growth rings at the base of the tree. However, the position in the trees from which these two logs were cut was uncertain. Therefore, the accurate tree ages could not be known. Based on the ring counts shown in Table 1, these trees were approximately between 70 and 80 yr old. Based on the X-ray densitometry measurements, these two logs were quite similar in diameter and number of growth rings at both top and bottom sections and may have come from the same stand of trees.

Summary statistics of specific gravity based on oven-dry mass and volume at test and tested mechanical properties are presented in Table 2. These values were obtained from specimens at an average moisture content of 12.8% with a standard deviation of 0.27%. Furthermore, values from this study were compared with those reported in the literature for red pine (FPL 2010) in Table 2. Values for tension parallel-to-grain were compared with MOE and MOR obtained from static bending tests because no corresponding results are given in FPL (2010). It was found that the average specific gravity in this study was lower than the reported value. In addition, Log 1 had an approximately 13% lower wood specific gravity than Log 2, although these two logs had similar diameters and ring numbers. As a result, Log 2 appeared to be stronger than Log 1. The factors responsible for the difference could be the age of the trees, growing conditions, and section of tree stem for testing. Also, because of the lower specific gravity of the specimens, most of the tested mechanical properties listed in Table 2 were lower than the published results.

Variation of Specific Gravity and Tension Property Parallel-to-Grain from Pith to Bark

Figure 2 shows that specific gravity measured by X-ray densitometry varied from bark to bark for both Log 1 and 2. The data were spaced at approximately 20-mm intervals to make the relationship between specific gravity and the distance from bark to bark easier to visualize. It appeared that the specific gravity at the bottom was almost identical to that at the top for Log 1, whereas for Log 2, the bottom section exhibited significantly higher specific gravity than the top. This may have been because the height growth and influence of the crown were different for

Table 2. Wood properties of red pine at 12.8% MC (standard deviation in parentheses).

Property	Log 1	Log 2	Overall	Number of specimens	From FPL (2010) Red pine grown in Canada	US
Specific gravity[a]	0.377 (0.034)	0.429 (0.053)	0.401 (0.051)	108	—	0.46
E (GPa)	7.22 (2.27)	8.47 (3.41)	7.89 (2.98)	108	9.5[b]	11.2[b]
Tensile strength parallel-to-grain (MPa)	62.2 (12.7)	77.8 (25.4)	71.1 (22.1)	108	70[c]	76[c]
Shear strength parallel-to-grain (MPa)	6.65 (0.64)	6.74 (0.59)	6.69 (0.62)	150	7.5	8.4
Tensile strength perpendicular-to-grain (MPa)	2.59 (0.64)	3.42 (0.83)	2.98 (0.84)	120	—	3.2

[a] Based on oven-dry mass and volume at test.
[b] Values of modulus of elasticity from static bending tests.
[c] Values of modulus of rupture from static bending tests.
E, Young's modulus.

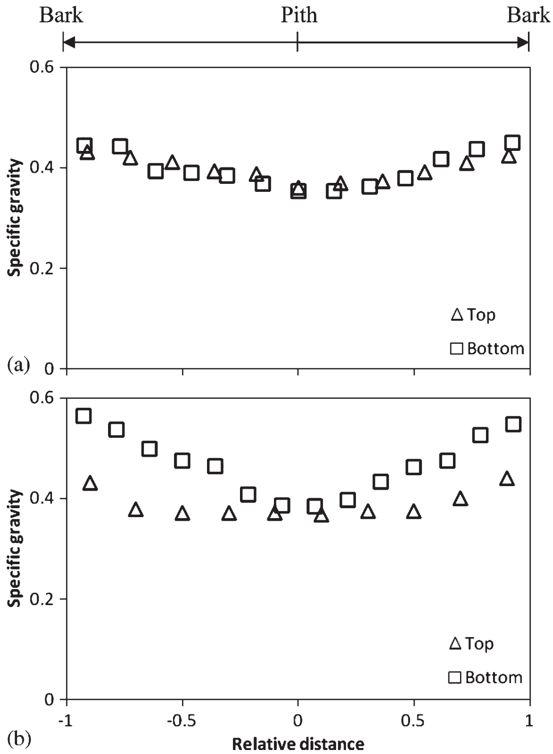


Figure 2. Variations of specific gravity measured by X-ray densitometry. (a) Log 1; (b) Log 2.

the trees (Deresse 1998; Larson et al 2001). Furthermore, Log 2 had a higher average specific gravity than Log 1, especially at the top section (Table 3), although these two logs had some similar diameter and ring count. This suggests that secondary growth rate may not be a good indicator of wood density.

Figures 3 and 4 present the radial variation in specific gravity measured by oven-dry method, E, and tensile strength parallel-to-grain in Log 1 and 2, respectively. The specific gravity variations obtained from the oven-dry method (Figs 3a and 4a) followed consistent patterns with those measured by X-ray densitometry (Fig 2a-b) for each log. In general, specific gravity and tension parallel-to-grain properties

Table 3. Young's modulus (E) and tensile strength parallel-to-grain of specimens along the tree stem (standard deviation in parentheses).

Specimen[a]	Number of specimens	Specific gravity	E (GPa)	Tension parallel-to-grain (MPa)
L1T	24	0.361 (0.017)	7.14 (0.99)	61.5 (10.3)
L1B	28	0.384 (0.045)	7.27 (2.78)	64.6 (14.5)
L2T	24	0.390 (0.046)	8.12 (2.29)	67.3 (10.8)
L2B	32	0.456 (0.047)	8.77 (4.16)	88.4 (31.2)

[a] L1T, top section of Log 1; L1B, bottom section of Log 1; L2T, top section of Log 2; L2B, bottom section of Log 2.

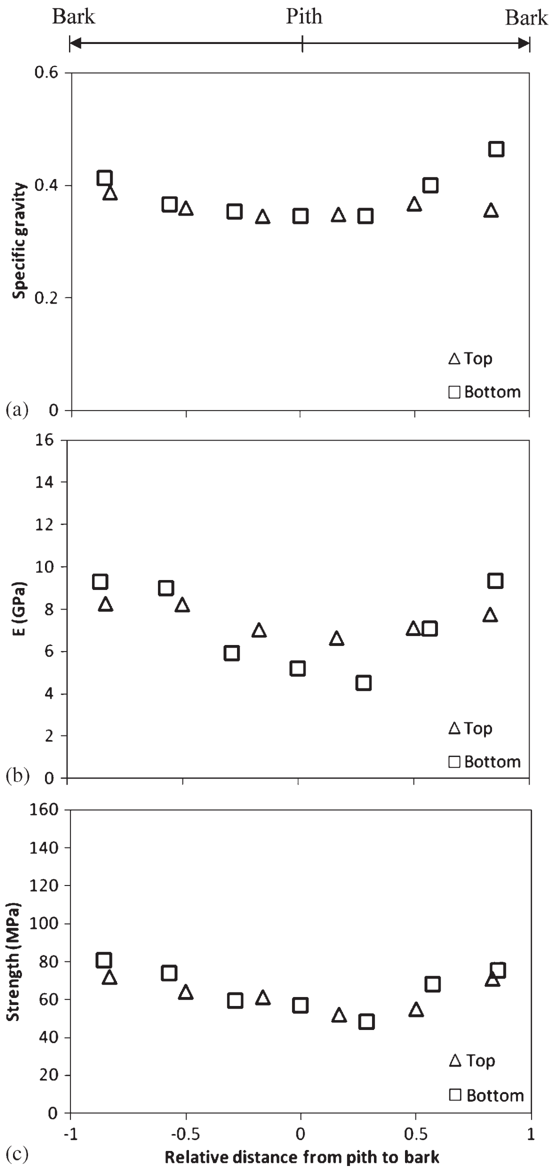


Figure 3. Variations of wood properties within Log 1. (a) Specific gravity; (b) Young's modulus E parallel-to-grain; (c) tensile strength parallel-to-grain.

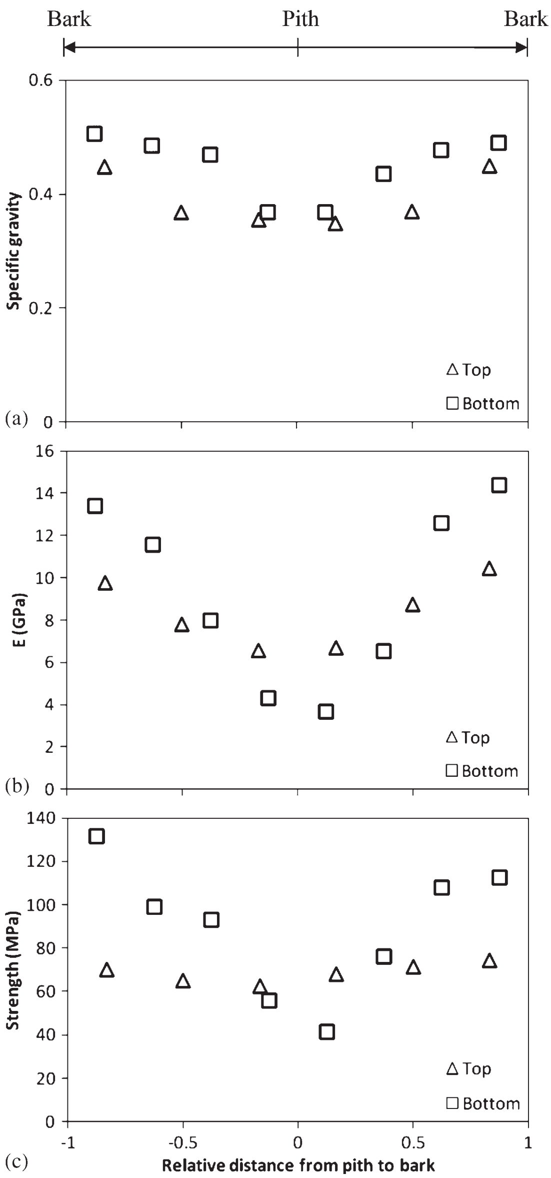


Figure 4. Variations of wood properties within Log 2. (a) Specific gravity; (b) Young's modulus E parallel-to-grain; (c) tensile strength parallel-to-grain.

increased from pith to bark. The prime reason for the variations in properties was the difference between juvenile and mature wood. Juvenile wood is formed in the center portion of stem cross-section, typically the first 5 to 25 yr of growth from pith (Larson et al 2001; Shmulsky and Jones 2011). However, it is difficult to state precisely the juvenile–mature demarcation age for a species because of complicated genetic and environmental factors. For red pine, it was reported that the juvenile period ranges from 30 to 40 yr according to Shepard and Shottafer (1992) and Deresse (1998). Wood formed after this juvenile period is termed mature wood and generally has more uniform properties. Juvenile wood generally has fewer latewood cells and a higher proportion of cells with thin wall layers, which results in lower density and correspondingly lower strength compared with mature wood (Shmulsky and Jones 2011). After the juvenile period, wood cells tend to have more uniform length and structure, leading to lower property variations in the mature wood zone. Therefore, radial variation in the stem can be characterized as strongly dependent on cambial age, defined as either the number of rings from the pith or distance from the pith (Deresse 1998).

Although the wood properties in Figs 3 and 4 exhibited a general increase from pith to bark, Log 1 appeared to have relatively low property variations. In contrast, property variation for Log 2 was more drastic. However, for each property, values near the pith in Log 2 were similar to those in Log 1, but values near the bark were substantially higher than those in Log 1.

As shown in Fig 4a, the difference in specific gravity was found to be relatively small between juvenile wood and mature wood. However, more significant differences were found when E and strength of the wood close to the pith were compared with the wood close to the bark (Fig 4b-c). As a result, E and strength appeared to increase more rapidly with age than did specific gravity, which agrees with the findings of other researchers (Bendtsen and Senft 1986; McAlister and Clark 1991; Deresse 1998). These results reveal that the juvenile wood core of Log 1 was larger than that of Log 2, because the two logs had similar ring counts and diameters.

Variations of E and strength in tension parallel-to-grain tended to follow a similar pattern to that observed in specific gravity. This suggests that there may have been a strong relationship between mechanical properties and specific

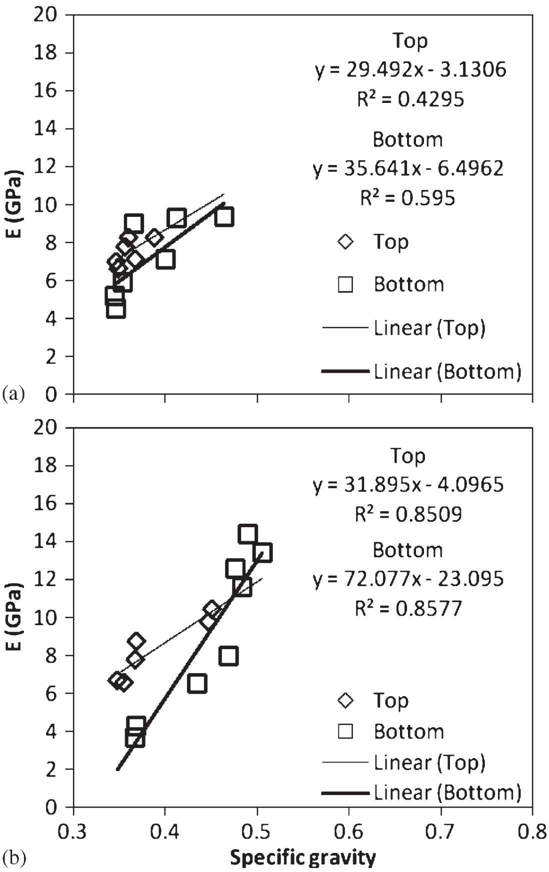


Figure 5. Relationship between specific gravity and Young's modulus E. (a) Log 1; (b) Log 2.

gravity. This is supported by the results shown in Fig 5b for Log 2. Figure 5b presents linear models for the top and bottom sections of the log and the associated values for the coefficient of determination (R^2). This result is consistent with the results reported by Shepard and Shottafer (1992) for red pine. However, a similar analysis for Log 1 did not produce a high value of coefficient of determination (Fig 5a). This means that, when the specific gravity range is narrow, the influence of this factor on E may be overshadowed by other contributing factors. These factors could be microfibril angle, fiber length, and chemical composition. In addition to low specific gravity, juvenile wood characteristically has large microfibril angle and short fiber length compared with mature wood (Loo et al 1985; Yeh et al 2006), which could also lead to low strength properties. However, specific gravity is relatively easy to measure compared with other factors, and it is probably the most reliable factor for predicting wood properties (Kellogg and Ifju 1962). Therefore, specific gravity appears to be a good indicator of E and strength properties for red pine only at the global level, in which different types of wood are included.

Variation of Specific Gravity and Tension Properties Parallel-to-Grain along the Stem

Besides the property variations across the stem from pith to bark, Figs 3 and 4 also illustrate the potential influence of height on wood properties. For Log 1, the properties measured at the top and bottom appeared similar, keeping in mind that there was a height difference of about 9 m. For Log 2, however, the specific gravity, E, and tensile strength measured at the bottom of the log tended to be higher than those at the top. In addition, the specific gravity of mature wood appeared to decrease with their positions from bottom to top although there was no clear trend for that of juvenile wood in this study. This variation can be explained by the differences in cambial age and the influence of the tree crown (Deresse 1998; Larson et al 2001).

In Figs 3 and 4, the juvenile wood close to the pith from the top has a similar specific gravity to that from the bottom. However, E and tensile strength of the corresponding juvenile wood from the top appear to be higher than those from the bottom. This could be attributed to the microfibril angle, which is higher in the juvenile wood from the bottom than from the top (Yeh et al 2006). When average specific gravity of stem cross-section was analyzed in Table 3, it showed a negative relationship between specific gravity and tree height for both Log 1 and 2, which is consistent with the results reported by Baker (1967). It was also found that average E and strength both decreased as stem height increased (Table 3). This can be mainly attributed to the decrease in specific gravity, which has a positive relationship with mechanical properties.

Also, for Log 2, at the bottom level (Fig 4a), specific gravity increased from pith to bark in a linear trend and then leveled off in the mature section. However, at the top level, specific gravity exhibited a different trend in which there was no distinct tendency to plateau in the wood zone close to the bark. This was mainly caused by the width of juvenile wood zone along the tree stem, which usually decreases upward to the tree crown (Shmulsky and Jones 2011). However, this width is species-specific, and it was reported that the diameter of the juvenile core is almost constant for red pine (Alkan 1990; Kaya and Smith 1993). Because of the tapered stem of red pine, a cylindrical juvenile core results in an increased proportion of juvenile wood as height increases in the stem. This probably accounts for the fact that there is no evidence of leveling off for wood properties in the wood zone near the bark at that level.

The decrease in wood mechanical properties from butt to top along the stem for Maritime Pine was also reported by Machado and Cruz (2005). Their results generally showed an initial increase in stiffness and strength from butt to breast height and then a decrease toward the top. In this study, there is no such trend for initial increase probably because these logs were cut from the portions above breast height in the tree stem. Therefore, based on the aforementioned results, the properties of a piece of lumber depended on its position in the stem.

Variation of Shear Strength Parallel-to-Grain and Tensile Strength Perpendicular-to-Grain along the Stem

The summary statistics for shear strength parallel-to-grain and tensile strength perpendicular-to-grain from different sections of the tree stem are presented in Tables 4 and 5, respectively. The influence of height follows a similar trend observed for tension property parallel-to-grain. Log 1 exhibits no distinct height influence, whereas for Log 2, the properties at the bottom were consistently higher than those at the top. Furthermore, to investigate the significance of variation of shear strength in different loading planes (Table 4), one-way analysis of variance (ANOVA) was performed at the 0.05 significance level. The results of ANOVA show that the p values for the top and bottom sections in both Log 1 and Log 2 are all greater than the 0.05 significance level. Therefore, there is not a statistically significant difference in shear strength obtained from the longitudinal–radial (LR) and longitudinal–tangential (LT) planes.

Similarly, the data of the tensile strength perpendicular-to-grain in Table 5 were subjected to the one-way ANOVA. Results showed that all p values were greater than the 0.05 significance level, indicating that the mean value of the tensile strength perpendicular-to-grain was not significantly different between the radial (R) and tangential (T) directions. Shear strength in the

Table 4. Shear strength parallel-to-grain of specimens along the tree stem (standard deviation in parentheses).

Specimen[a]	Loading plane[b]	Number of specimens	Specific gravity	Shear parallel-to-grain (MPa)
L1T	LR	20	0.372 (0.016)	6.60 (0.56)
	LT	20		6.66 (0.58)
L1B	LR	20	0.399 (0.039)	6.55 (0.64)
	LT	20		6.78 (0.78)
L2T	LR	20	0.412 (0.024)	6.62 (0.41)
	LT	20		6.37 (0.51)
L2B	LR	15	0.484 (0.031)	6.94 (0.62)
	LT	15		7.29 (0.47)

[a] L1T, top section of Log 1; L1B, bottom section of Log 1; L2T, top section of Log 2; L2B, bottom section of Log 2.
[b] LR, longitudinal–radial plane; LT, longitudinal–tangential plane.

Table 5. Tensile strength perpendicular-to-grain of specimens along the tree stem (standard deviation in parentheses).

Specimen[a]	Loading direction[b]	Number of specimens	Specific gravity	Tension perpendicular-to-grain (MPa)
L1T	R	10	0.367 (0.017)	2.39 (0.66)
	T	10		2.43 (0.55)
L1B	R	20	0.373 (0.036)	2.66 (0.74)
	T	20		2.72 (0.56)
L2T	R	10	0.395 (0.025)	2.71 (0.60)
	T	10		2.62 (0.43)
L2B	R	20	0.482 (0.057)	3.62 (0.88)
	T	20		3.68 (0.69)

[a] L1T, top section of Log 1; L1B, bottom section of Log 1; L2T, top section of Log 2; L2B, bottom section of Log 2.
[b] R, radial; T, tangential.

LT plane was higher than that in the LR plane probably because of the existence of wood rays, which are normal to the LT plane. The arrangement of earlywood and latewood in a growth ring has a significant influence on tensile strength in the perpendicular-to-grain direction. The annual growth rings act in series in the radial direction. As a result, because of its lower density and large lumens, the earlywood zone could be the weakest link in the radial tensile strength of wood. This may account for the slightly higher tensile strength in the tangential direction in which annual growth rings act in parallel. However, because of the small sample size used in this study, further research is needed to support this finding.

CONCLUSIONS

Wood properties and their variations in red pine were investigated. Results showed that wood properties varied both radially (from pith to bark) and longitudinally (along the length of stem) within a tree stem. Average specific gravity tended to increase from juvenile wood to mature wood in the radial direction and decreased from bottom to top in the vertical direction. Specific gravity had a positive relationship with mechanical properties, especially for mature wood in red pine at the global level. As a result, E and tensile strength parallel-to-grain increased from pith to bark across the ring because of the correspondingly denser wood. For the same reason, E and tensile strength parallel-to-grain, shear strength parallel-to-grain, and tensile strength perpendicular-to-grain decreased from bottom to top in the longitudinal direction. However, for shear strength parallel-to-grain and tensile strength perpendicular-to-grain, there is evidence to show that tangential strength was slightly higher than radial strength, but these differences were not statistically significant. Although the presented test data were obtained from only two red pine logs, they could be adequate representatives of the stand sampled. Because this study was aimed at providing basic information to other researchers, more research will be conducted in the future to gain a more extensive data set of red pine wood.

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