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WOOD PROPERTIES OF RED PINE (*Pinus resinosa* Ait.)

Takele Deresse
Graduate Research Assistant

and

Robert K. Shepard
Professor of Forest Resources
Department of Forest Management

College of Natural Sciences, Forestry, and Agriculture
Maine Agricultural and Forest Experiment Station
University Of Maine
Orono, Maine 04469

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INTRODUCTION

This report describes important physical and mechanical properties of red pine (*Pinus resinosa* Ait.) and the factors that influence the variation in these properties. Some results from a recently completed study on red pine in Maine (Deresse, 1998) are presented to help illustrate and explain some of the more important concepts and relationships. In addition to studies specific to red pine, important findings on other conifers are presented for comparison with red pine and to provide a more comprehensive review of conifer wood properties. The studies on the other coniferous species help to highlight the sources of wood property variation. With the current emphasis on intensive management and shortened rotations, forest managers must give increased attention to the factors that affect wood properties and ultimately the suitability of the wood for intended uses.

WOOD PROPERTY VARIATION

Wood properties in conifers vary among species, among trees of the same species, and within individual trees. The main sources of variation in wood properties are genotype, environment, and the interaction between the two. The genetic factors that influence properties of wood can be categorized as the heritability of the cambial characteristics, and the provenance.

Of the hereditary factors, the largest percentage of the total variation in tree growth characteristics and wood properties is explained by differences that exist among trees of the same stand as a result of inherited genes (Zobel and van Buijtenen, 1989). The heritability of growth rate and tree form, and specific gravity and fiber length, is very high (McKimmy, 1966; McKimmy and Nicholas, 1971; Talbert et al., 1983, Yanchuk and Kiss, 1993). In addition to these well-documented, heritable tree characteristics, the maturation of the vascular cambium is also believed to be controlled by genetic factors (Lindström, 1996).

The other major genetically controlled source of wood property variation is differences among provenances (Zobel and Van Buijtenen, 1989). Provenances are distinct populations of a species that have differentiated as a result of an environment-driven evolutionary process. Provenances through time acquire features that best suit their specific growth requirements, and they adapt to the prevailing conditions. The adaptation process may alter or modify the differentiation process of the xylary cells (woody cells) in their chemical composition or ultrastructure, hence modifying their properties. In a given species this evolutionary differentiation be-

tween populations accounts for a relatively small percentage of the total variation that occurs in wood properties (Zobel and van Buijtenen, 1989). Red pine has limited genetic diversity (Horton and Bedell, 1960; Fowler, 1965; Fowler and Morris, 1977; Mosseler et al., 1991, 1992) and, therefore, differences among trees and stands are smaller for this species than for most other species.

Among the non-hereditary factors that influence wood property variation, the environment is the most important (Zobel and Van Buijtenen, 1989). The environmental factors can be divided into climate (variation in climate), site quality, and stand environment (competition among individual trees). Coniferous tree crowns continuously change and adapt, responding to these factors. The changes in crown morphology in turn initiate changes in the activity of the vascular cambium and the derivation of xylary cells. The influence of the crown on the cambium is exerted through the distribution of photosynthates and the growth regulating hormones—auxins, gibberellins, abscisic acid, cytokinins and ethylene (Larson, 1969; Savidge and Wareing, 1984). It is now well accepted that growth hormones play an important role in determining cell size and the development of earlywood and latewood, as well as the width of the juvenile wood along the length of the bole.

Other non-hereditary factors that influence formation of wood and its variation in quality can be categorized as latent factors (Lindström, 1996). These include external factors such as gravity, wind, injuries, and growth-related stresses. The influence of gravity or wind is believed to induce reactive changes and to alter the differentiation process of the vascular cambium. In coniferous trees abnormal cells known as compression wood are formed under these modifications. The tracheids that make up compression wood are altered both chemically and ultrastructurally and become a source of variation in wood properties. Compression wood contains a larger amount of lignin and a lower percentage of cellulose than normal wood. The tracheids are shorter in length, larger in diameter, and the cross-sectional shape is rounded when compared to the typical rectangular shapes of normal tracheids (Kollmann and Côté, 1968; Haygreen and Bowyer, 1989).

Other latent factors, i.e., injuries or fungal attacks, are less significant since material with visible defects from injuries is usually not processed. However, effects of injuries and microbial attacks as a cause of variation in wood properties should be considered due to possible changes in the development of wood that is in proximity to the injured or affected tissues (Blanchette, 1992).

In addition to the sources of variation discussed above, the normal process of tree-aging is a major source of wood property variation. Under normal growth, the cambium (in coniferous species) develops from a tissue that produces juvenile wood cells into a tissue that differentiates into mature wood cells. As discussed earlier, the maturation process is closely related to the inherited characteristics of the individual tree and the relation between the cambium and the most active part of the crown. Each individual cambial derivative (whether it is a juvenile wood or a mature wood), however, passes through successive developmental stages. In each stage the xylary cell plays a different physiological role and as such has variable properties.

One of the most recognized age-related transformations of woody cells is their physiological transition from sapwood to heartwood. Depending on the property in question, heartwood (defined as the part of the stem in which all cells including the parenchyma cells are dead) can be slightly or significantly different from sapwood. In coniferous heartwood, most tracheid pits are aspirated and in some species tylosids are deposited in the lumens of the cells (Hillis, 1987). In red pine and many conifers the tracheids become impregnated by extractives, reducing the void volume. The deposition of extractives, the formation of tylosids, and the aspiration of pits consequently affect many physical properties such as color, permeability, specific gravity, and fiber saturation point, hence becoming a source of wood variation.

The remainder of this report describes important physical and mechanical wood properties and the factors that affect them. Included are specific gravity, longitudinal shrinkage, microfibril angle, modulus of rupture, and modulus of elasticity.

1. Specific Gravity

Of all indices that characterize wood properties, specific gravity is used universally to define wood quality. Specific gravity is a dimensionless number and is expressed as the oven dry weight of a sample of wood divided by its green volume divided by the density of water:

$$\text{specific gravity} = [(\text{oven dry wt})/(\text{green vol})]/(\text{density of water})$$

The strong relationship of specific gravity to mechanical properties, fiber yield, and other properties relevant to the end use of forest products, and the relative ease of its determination, make it a simple and a good descriptor.

Identifying all of the factors that influence specific gravity variation alone is impossible or at best very complex. The influence of crown and age on xylem cell differentiation rate, on tracheid size

(length, cell wall to cell lumen ratio), on the formation of latewood and earlywood, and on specific gravity are a continuum of the same process. Therefore, specific gravity may be linked directly to all previously discussed factors of variation.

In a stand where growing conditions are equal or comparable, differences in mean whole-stem specific gravity among trees mostly arise due to differences in genotype. According to Zobel and Talbert (1984), 70% of the overall specific gravity variation in a species is due to these differences that occur in a given stand. The remaining 30% is accounted for by differences among provenances and sites. Compared to other conifers, provenance differences in red pine are less for the reasons that were stated earlier. Such red pine provenance uniformity in specific gravity was clearly exhibited by Peterson (1968), where among 10 provenances studied only one deviated from the rest by more than 0.02.

Within a single tree, specific gravity varies both vertically (along the length of the stem) and radially (from the pith to the bark) in distinct patterns that are characteristic to a species. In both directions the variation is influenced by age and distance from the most vigorous part of the crown. Due to better access to growth-regulating hormones and photosynthates, the portions of the cambium that are directly influenced by the crown differentiate into juvenile wood tracheids. With age and crown recession up the stem, the cambium progressively evolves into a tissue that ultimately differentiates into mature wood tracheids (Larson, 1969). One of the biggest sources of radial variation in specific gravity is due to these differences between the juvenile and mature wood.

Variation from pith to bark

At any given cross-section of a stem, specific gravity varies with age from the pith outward to the bark. According to Panshin and de Zeeuw (1980), such age-related specific gravity variation in conifers can be categorized in three general patterns (types), of which two are most prevalent in temperate conifers. The Type-I pattern is exhibited most commonly in many *Larix* and *Pinus* and occasionally in *Picea* species. In this pattern, the mean ring specific gravity increases from the pith to the bark in a linear or curvilinear trend, flattening in the mature section. This trend may exhibit a slight decrease in the outer rings of overmature trees. In the next most frequently encountered trend pattern, Type-II, the mean specific gravity of the juvenile core decreases in its early formation, and then increases until the mature period is reached. Similar to Type-I, in mature wood of Type-II species the mean ring specific gravity fluctuates around an

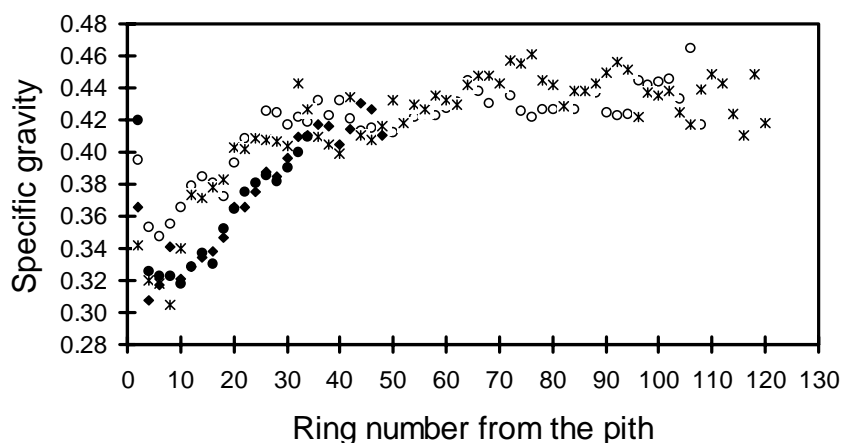


Figure 1. Specific gravity variation with age at breast height for dominant and codominant trees sampled from old red pine stands (o) and (*), and young red pine stands (•) and (◆). Each observation is the average of samples from five trees and for two consecutive rings together (From Deresse, 1998).

average maximum and may fall towards the outer rings of overmature trees.

Even though both types of patterns are encountered in red pine, it usually exhibits the Type-II pattern (Panshin and de Zeeuw, 1980). Examples of Type-II patterns were found by Peterson (1968), where 10 red pine provenances exhibited patterns in which specific gravity declined to the age of 13, after which the trend was characterized by a linear increase and then a leveling off. Similar patterns were also evident in studies of red pine in Maine where Type-II patterns occurred in both natural and plantation stands (Shepard and Shottafer, 1992; Deresse, 1998) as illustrated in Figure 1. Figure 1, based on the work of Deresse (1998), shows the change in specific gravity at breast height with age for dominant and large codominant trees from two relatively fast-growing stands and two slower growing, much older stands. The diameters at breast height of the study trees from all stands ranged from approximately 12 to 15 in.

The graph illustrates two points. First, specific gravity in the two rings closest to the pith was considerably greater than specific gravity in the third and fourth growth rings. After the ninth and tenth growth rings it began to increase, eventually leveling off at about age 30, and in one of the younger stands, at approximately age 40. This clearly indicates that red pine must be grown to an age of at least 30 years in order to begin to produce wood of maximum specific gravity. Specific gravity at the end of the juvenile period (about ring 30) was about 30% higher than in rings five and six. Growing stands to a greater age will ensure a larger volume of high specific gravity wood, which will yield a greater weight of pulp per unit volume of wood and be stronger. Growing red pine under short rotations

means that the wood will have less desirable properties for most uses than wood from older stands. It is clear, based on the trends in Figure 1, that for two trees of 12 in. DBH, one 40 years old and one 80 years old, the older tree would have a considerably higher overall specific gravity.

Second, there is a clear indication that between the ages of about 10 and 30, the specific gravity of trees from the younger, faster-growing stands was less than specific gravity of trees from the older stands, possibly because the influence of the live crown on wood development in the lower portion of the bole of the rapidly growing trees was exerted to a greater degree and for a longer time than in the older stands, where crown recession presumably began at an earlier age. This suggests the possibility of an additional reduction in wood properties of fast-growing stands, over and above the reduction due to the shorter rotations alone.

The juvenile period for specific gravity in red pine is considerably shorter than the juvenile period for red spruce, which may approach 70 years in some stands (Wolcott et al., 1987; Shepard, 1997). It is somewhat longer than for balsam fir, which ranges from 30 to 35 years (Shepard - unpublished data). In contrast, the juvenile period for loblolly pine is about 10 to 12 years (Saucier, 1989).

Specific gravity variation across the stem from pith to bark is directly related to the variation in the percentage of latewood in each growth ring. For most experimental purposes, the latewood is categorized by Mork's definition, as a region of the ring where the radial cell lumens are equal to, or smaller than, twice the thickness of radial double cell walls of adjacent tracheids (Denne, 1989). In species such as loblolly pine, an increase in specific gravity is strongly associated with an increase in the propor-

tion of latewood (Ifju and Labosky, 1972; Taylor and Burton, 1982). Kollmann and Côté (1968) illustrated this close relation between latewood percentage and specific gravity for several coniferous species, such as Scots pine, eastern white pine, and balsam fir. However, the correlation between latewood percentage and specific gravity appeared to vary among species.

Most studies agree that variation in the proportion of latewood accounts for a major proportion of the ring-to-ring variation in specific gravity. However, the variation may also depend on the magnitude of the differences between mean earlywood and latewood specific gravity. Warren (1979), by isolating the weighted variance and covariance components of specific gravity (i.e., proportions of earlywood and latewood and their respective specific gravities) showed that the magnitude of earlywood to latewood differences had significant importance in accounting for the specific gravity variation. Smith (1956) reached a similar conclusion where a multiple regression model that included the specific gravities of the earlywood and latewood, as well as the proportion of the latewood, accounted for almost all of the specific gravity variation in second-growth Douglas-fir.

In red pine the influence of earlywood and latewood variation on specific gravity generally follows patterns similar to those discussed above. Results from the 10 provenances studied by Peterson (1968) showed that the juvenile wood specific gravity was mostly influenced by the change in the cross-sectional cell size (cell wall thickness and lumen width), while the mature wood specific gravity appeared to be strongly associated with the percentage of latewood. Comparable inferences were also made by Shottafer et al. (1972), who found a strong relationship between specific gravity and latewood percentage for plantation-grown red pine.

In individual growth rings of temperate region conifers, specific gravity increases from earlywood to latewood. This increase follows different patterns and appears to be species specific. The difference in specific gravity between the early- and the late-formed regions can be as much as two to four times (Kollmann and Côté, 1968). The width of earlywood or latewood or the magnitude of the differences between the two is influenced by age and growth rate. With the development of X-ray densitometry, image analysis, and other techniques for microdensitometry, work on within-ring specific gravity variation has been simplified and this variation can now be estimated in terms of its components. Estimating intra-ring variation helps in understanding the effects of growth rate or other management factors that influence growth (Liu and Tian, 1991; Walker and Dodd, 1988; Zhang et al., 1996).

Variation along the bole

Specific gravity also varies along the length of the bole within a ring (sheath) formed in one season. This variation from the base towards the apex of a tree can be explained by differences in age of the cambium and the level of direct influence of the crown. According to Simpson and Denne (1997), the specific gravity of 52-year-old Sitka spruce trees varied with tree height in patterns that varied with the position of the test samples. In samples from sheaths produced between ages 10 and 20, specific gravity decreased from the apex to the base. In contrast, the specific gravity of samples from the sheaths produced between ages 40 and 50 followed a different pattern. Specific gravity decreased from the uppermost internode downward to the eighth to twelfth internode, and then increased until it reached a maximum at about internode 20 from the top (Simpson and Denne, 1997). From a different approach, where average specific gravity of stem cross-sections was analyzed, the relationship between specific gravity and tree height was reported to be negative for jack pine (Spurr and Hsiung, 1954). Studies on native Maine conifers by Wahlgren et al. (1966) and Baker (1967) also indicated a specific gravity decline from the bottom up; however, these patterns appeared species specific and the magnitude of the decline differed greatly among the species investigated.

2. Longitudinal Shrinkage

Wood is an anisotropic (unequal physical properties along different axes) and hygroscopic (absorbs moisture from the air) material, and its physical and mechanical properties vary with the change of moisture content below the fiber saturation point (the point at which all liquid water has been removed from the cell lumen, but the cell wall is still saturated). This phenomenon of dimensional instability is exceptionally important in the use of wood as a construction material. The dimensional change with moisture is greatest in the tangential direction, generally about two times more than the radial changes. The smallest, but perhaps most important, dimensional changes occur in the longitudinal direction (along the length of the board). For most softwoods longitudinal shrinkage from the green to the oven-dry condition is estimated to be about 0.2% of the green length; however, juvenile wood may shrink four to five times more than the average value (Haygreen and Bowyer, 1989).

Longitudinal shrinkage is very important in causing twisting, warping, and other types of board deformation that occur on drying. Longitudinal shrinkage resulting from large amounts of juvenile wood in lumber is responsible for the "rising truss" phenomenon (Gorman, 1984). This problem results

from the longitudinal movement of wood in the lower chord of house trusses as moisture content changes. This movement causes the truss to rise, separating the ceiling from the room partition.

Estimation of longitudinal shrinkage is an error-sensitive procedure, even when shrinkage is relatively large, as in juvenile wood. Therefore, measurements require special attention and precision. Longitudinal shrinkage measurement can also be confounded by many of the natural and drying defects (i.e., grain deviation, warp in longer samples, and other stress-related defects). Constructing informative trends from longitudinal shrinkage data is also difficult because of large differences among specimens coming from different locations within a tree. This large variation tends to obscure the influence of other factors such as age, tree, site, and provenance.

In softwoods longitudinal shrinkage when drying is from green to oven dry follows a more or less uniform trend. The trends reported by Foulger (1966) for white pine and by Ying et al. (1994) for loblolly pine appear to be typical. In both studies longitudinal shrinkage rapidly decreased from the pith outward to rings 10 to 15 and then fluctuated around a minimum. Longitudinal shrinkage in red pine specimens from four stands also followed this general pattern when dried from green to approximately 12% MC and to 0% MC (Deresse, 1998).

Figure 2 illustrates the age-related variation in longitudinal shrinkage of wood from two red pine stands. It is apparent that a greater proportion of the wood in trees from the younger stand than from the older stand would shrink longitudinally. This is because with trees of approximately the same DBH, the first 15 growth rings would constitute a much

greater proportion of the stem cross-section in younger trees. Figure 2 also shows that longitudinal shrinkage when drying was from the green condition to 0% moisture content was approximately three times greater than when drying was to 12% moisture content.

A variety of factors influence longitudinal shrinkage, and no single factor can consistently explain the variation. Age, specific gravity, percentage of earlywood, and microfibril angle have been cited by Ying et al. (1994), and cell wall thickness and the nature of the middle lamella by Meylan (1968), as sources of variation in longitudinal shrinkage. Among these sources, microfibril angle may be the most important.

The pattern of longitudinal shrinkage reported by Ying et al. (1994) was similar to the pattern of microfibril angle (MF-angle) decline in the same study. According to the authors, 21% of the variation in longitudinal shrinkage of wood when going from the green to the oven-dry condition was explained by MF-angle, and MF-angle was a better descriptor of longitudinal shrinkage than specific gravity and proportion of earlywood. From a more theoretical approach, Cave (1968) and Meylan (1968) concluded that the relations between MF-angle of the S_2 layer and longitudinal shrinkage are similar in most conifers.

3. Microfibril Angle

The term microfibril angle (MF-angle) is used to describe the helical angles that microfibrils make in respect to the longitudinal axis of the xylary cells. Microfibrils are the smallest identifiable structural units of the cell walls and can readily be observed using an electron microscope. There is no definite

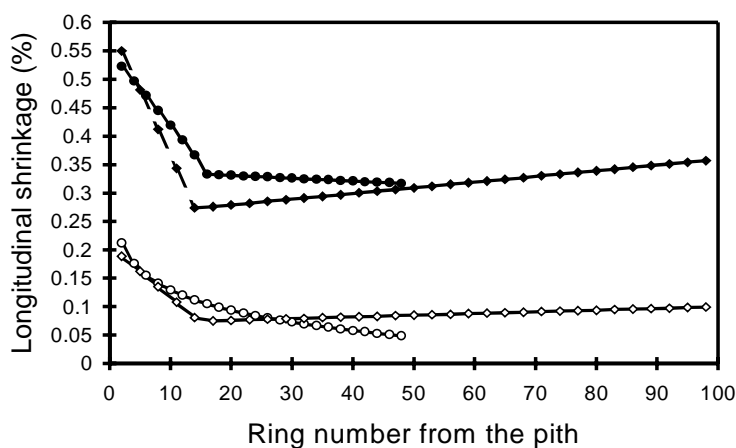


Figure 2. Best-fit curves from a regression analysis showing the relationship between age and longitudinal shrinkage at breast height in dominant and codominant trees from two red pine stands. From green to 12.4% MC -- young, fast-growing stand (o) and old, slow-growing stand (\diamond); from green to 0% MC -- young, fast-growing stand (\bullet) and old, slow-growing stand (\blacklozenge) (from Deresse, 1998).

explanation on how microfibrils are formed, but irrespective of the phases and stages through which they may pass during formation, microfibrils can be defined as aggregates of strongly bonded, cellulosic chains. In crystalline regions of microfibrils, cellulosic chains are arranged lengthwise and tend to be parallel to one other. Each crystalline region is encased in an amorphous paracrystalline sheath (Timell, 1965) and is separated by intermicrofibrillar space from an adjacent unit (Stamm, 1964).

The formation and arrangement of microfibrils differ between the cell wall layers. In the primary cell wall, the microfibrils are arranged more or less in a random fashion and are loosely packed in the matrix material (hemicellulose and lignin). In contrast, the three main layers of the secondary cell wall are made up of microfibrils that are closely packed and exhibit recognizable arrangements (Stamm, 1964; Wardrop, 1965; Kollman and Côté, 1968).

Of the three layers of the secondary cell wall, the S_2 layer is the most important in determining the properties of wood because of its thickness. Compared to the S_1 and S_3 layers, which combined have between 8 to 12 lamellae (higher aggregates of microfibrils), the S_2 layer is the thickest and has between 30 and 150 lamellae. In the tracheids of conifers the microfibrils of the S_2 layer are highly organized and run parallel to one other, mostly forming Z-helices around the cells. In normal wood

these helices make an angle with the vertical axis of the cells that is usually less than 30° (Kollman and Côté, 1968). Studies show that intermediate to strong correlation exists between the MF-angle of the S_2 layer and stiffness (Ifju and Kennedy, 1962; Tamolang et al., 1967), anisotropic elasticity (Cave, 1968), and shrinkage (Meylan, 1968; 1972)

The MF-angles of the S_2 layer are usually determined indirectly. One widely used procedure is the use of the interfibrillar spaces as reference directions for the orientation of the MF-angles. It is believed that the interfibrillar spaces can be enlarged by drying small blocks of wood at $103 \pm 2^\circ\text{C}$. The enlarged spaces appear in the form of crack-like propagations under a microscope (Stamm, 1964). The microscopic checks can further be enhanced by staining for better visualization and measurement using different techniques, as discussed in Bailey and Vestal (1937), Senft and Bendtsen (1985), and Ying et al. (1994). Figures 3 and 4 present two digitized images showing microfibril orientations in the form of short dark lines that are more or less parallel to each other and deviate from the orientation of the tracheid cell walls. These dark lines are formed by iodine precipitation in the cracks of the S_2 layer that were formed during drying. Longitudinal shrinkage of the wood in Figure 3 would be much greater than longitudinal shrinkage of the wood in Figure 4.

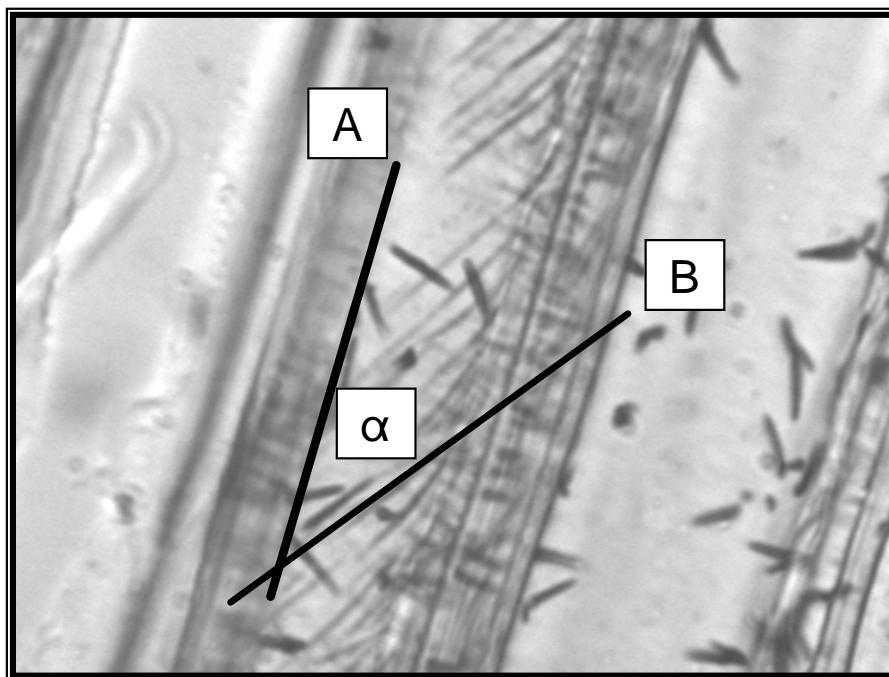


Figure 3. A digitized image showing the orientation of the cell walls (A), the orientation of the microfibrils (B), and the angle (α) included between the two. The image from a field taken in the middle of ring 2 at breast height from a fast-growing red pine tree at X1200 magnification shows relatively large microfibril angles of approximately 35° (from Deresse, 1998).

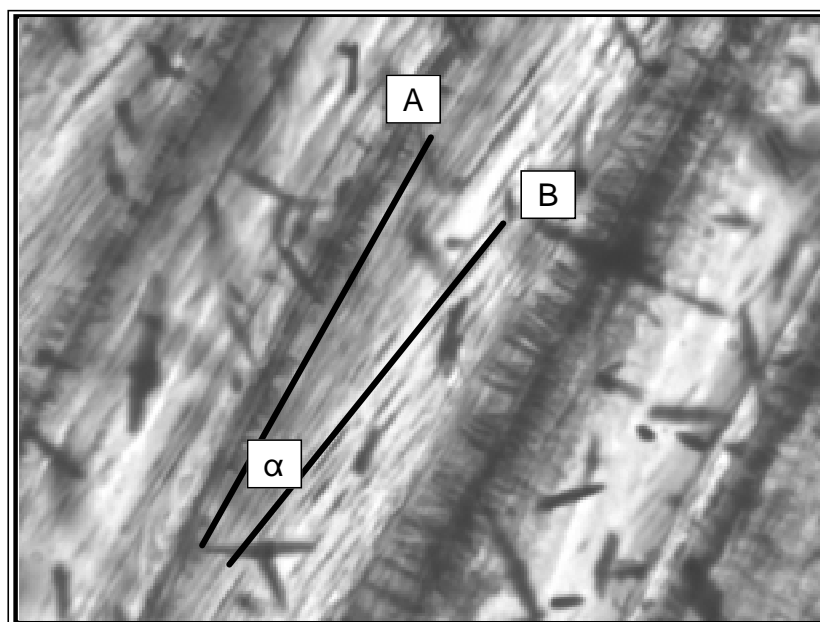


Figure 4. A digitized image showing the orientation of the cell walls (**A**), the orientation of the microfibrils (**B**), and the angle (α) included between the two. The image from a field taken in the middle of ring 30 at breast height from a fast-growing red pine tree at X1200 magnification shows microfibril angles of approximately 9° (from Deresse, 1998).

In contrast to specific gravity and mechanical properties, less work has been done on MF-angle because of the tedious nature of the methods available. To date all known procedures of MF-angle measurement require considerable time in measurement or specimen preparation, and the indirect X-ray diffraction method requires a more expensive technology.

Published results indicate that variation exists in MF-angle among species, among trees of the same species, and within a single tree. Depending on the methodology, techniques, and level of sampling, these variations can be very large. Having this in mind, Megraw (1985) cautions that inferences that can be made from MF-angle measurements are limited.

The mean MF-angle in the S_2 layer varies with age and exhibits trends that probably indicate genotypic characteristics of the species. The MF-angle declines (the angle between the microfibril and the vertical axis gets smaller) with age from the pith outward to the bark. Work by Erickson and Arima (1974) on 28-year-old Douglas-fir, Wang and Chiu (1988) on 34-year-old Japanese cedar, and Ying et al. (1994) on 25-year-old loblolly pine illustrate this trend. In these studies larger angles were clearly associated with juvenile wood, and the mean ring MF-angle was found to be large in the first few rings near the pith and was followed by a steep decline in approaching the 'mature' region. In all three studies the rate of MF-angle decline was significantly re-

duced after 10 years and leveled off in the outer rings. According to Wang and Chiu (1988), this pattern of MF-angle decrease with age was observed at all heights of the tree stems of Japanese cedar; however, the rate of decrease at the base of the stems was slower compared to higher positions.

MF-angle decreases from earlywood to latewood. The mean earlywood MF-angle may be two to three times larger than the mean latewood MF-angle. For mature Douglas-fir wood (age 36 to 45 years), Ifju and Kennedy (1962) reported an average ratio of 0.33 between the latewood and the earlywood MF-angles. Analyzing the trend of earlywood and latewood MF-angles in Japanese cedar, Wang and Chiu (1988) found that the latewood MF-angles leveled off at about 10° , and the earlywood MF-angles at 15° to 25° .

In red pine mean ring MF-angles surveyed in two young stands showed a decline with age (Deresse, 1998). The results from this study also revealed that within individual rings the largest and the smallest MF-angles were primarily associated with the tracheids formed at the beginning and at the end of the growing season, respectively. In one of the stands, for which every second ring from the pith was surveyed to ring 40, the MF-angles in the early formed tracheids averaged 2.5 times larger than the MF-angles in the tracheids formed in the latter part of the growing season. Figure 5 illustrates the variation of MF-angles (from one of the stands) with age and for six equally spaced positions within each

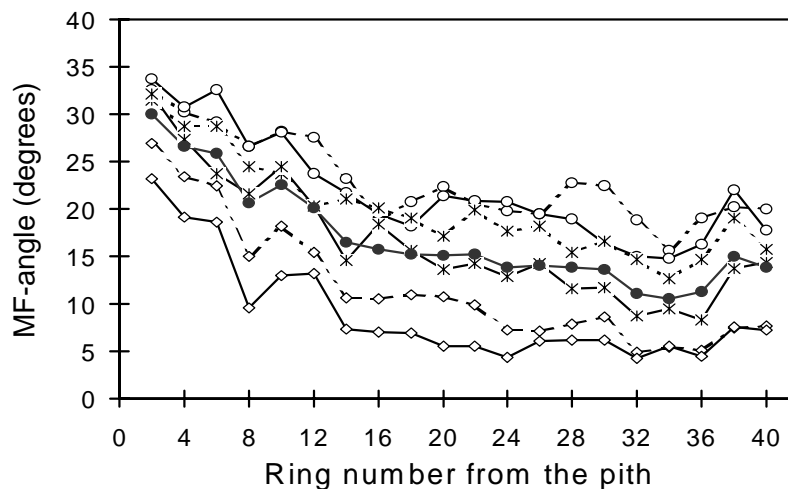


Figure 5. MF-angle variation with age at breast height for dominant and codominant trees in a young red pine stand. Averages for ten samples at each of six within-ring positions (P) equally spaced from each other when going from earlywood to latewood; P-1 (-o-), P-2 (-○-), P-3 (-*-), P-4 (-*-), P-5 (-◇-), P-6 (-◇-) and ring mean MF-angle(-●-). Positions were 15%, 30%, 45%, 60%, 75%, and 90% of the distance across the ring (from Deresse, 1998).

ring. The positions were at 15%, 30%, 45%, 60%, 75%, and 90% of the distance across the ring. It is clear that MF-angle decreased until about the 15th growth ring, after which it changed very little.

MF-angle exerts some control over longitudinal shrinkage, with shrinkage generally increasing as MF-angle increases (Megraw et al. 1998). It is evident from Figures 2 and 5, that the trend in longitudinal shrinkage closely follows the trend in MF-angle, with both decreasing until about the 15th growth ring from the pith and changing relatively little after that. A relationship exists between MF-angle and longitudinal shrinkage, because when the orientation of the microfibrils in the S_2 layer of the cell is at a significant angle from the cell axis, the cell becomes shorter as the wood dries, and consequently, longitudinal shrinkage occurs (Haygreen and Bowyer, 1989).

In contrast to the trends summarized above and the trends illustrated in Ying et al. (1994), McMillin (1973), using the polarized light technique, did not find differences in MF-angles between the core, middle, or outerwood samples of loblolly pine. Investigating differences in MF-angle of earlywood and latewood, the study also found no pattern that may indicate the effect of age on the MF-angle.

In most of the above studies the relation between MF-angle and age is evident. The variation in MF-angle can also be correlated with tracheid length, tracheid cross-sectional size, and other physical and mechanical properties (Megraw, 1985). Strong correlations were found with tracheid length in Douglas-fir ($r=-0.94$; Erickson and Arima, 1974), with

tensile strength in Douglas-fir ($r=-0.88$; Ifju and Kennedy, 1962), and with modulus of rupture ($r=-0.54$) and modulus of elasticity ($r=-0.68$) of the early juvenile wood of red pine (Deresse, 1998).

4. Modulus of Rupture and Modulus of Elasticity

Modulus of rupture (MOR) and modulus of elasticity (MOE) are important properties for the use of wood as a structural material. MOR is an indication of the bending strength of a board or structural member, and MOE is an indication of the stiffness. The correlation of MOR and MOE with specific gravity is typically very strong, as reported by Shottafer et al. (1972) and Shepard and Shottafer (1992) for red pine, Wolcott (1985) for red spruce, and Han (1995) for red maple. However, in some coniferous species, such as *Abies fabri*, *Picea asperata*, and *Pinus massoniana*, the relationship of MOE to specific gravity is weaker than the relationship between MOR and specific gravity (Zhang, 1997), and this was also found to be true in fast-growing red pine (Deresse, 1998). It has been reported that wood samples having similar specific gravity can also exhibit significantly different strength values due to factors that may be associated to other factors to which specific gravity is less sensitive (Perem, 1958; Zhang, 1995; Deresse, 1998). The determination of MOR and MOE together with specific gravity, therefore, is important to better understand these relationships.

When analyzed among trees and within a tree, mechanical property variation tends to follow similar patterns to those observed in specific gravity. The largest variation in mechanical properties of

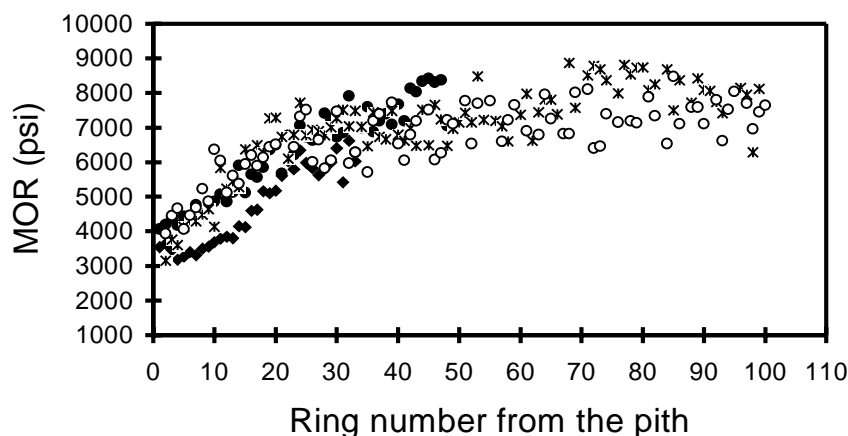


Figure 6. Modulus of rupture (MOR) variation with age at breast height for dominant and codominant trees sampled from old red pine stands (o) and (*) and young red pine stands (•) and (◆). Each observation is the average of samples from five trees (from Deresse, 1998).

wood is found between trees of the same stand, and the remaining variation can be explained in a similar way to the variation in specific gravity. The radial variation in a single tree of a coniferous species can be characterized as strongly and positively dependent on cambial age (number of rings from the pith). Work by Wolcott (1985) on red spruce and Shepard and Shottafer (1992) on red pine showed a rapid increase in MOR and MOE from the pith to the boundary of the juvenile core and a tendency to plateau in the mature wood, as shown in Figure 6 for MOR of red pine (Deresse, 1998). These variation trends in many instances are distinct to each species, and they may also reflect the environment under which the trees develop.

Figure 6 shows the same general relationship between MOR and age as between specific gravity and age in Figure 1. (The relationship between MOE and age was much like the relationship between MOR and age.) In three of the four stands MOR leveled off at about age 30 (or continued to increase very slightly after that age). However, in one of the young stands, MOR continued to increase until at least age 40. MOR in the other young stand was considerably lower. The difference between the two stands is attributed largely to measured differences in MF-angle, with angles in the stand having the lower MOR being greater than those in the stand having the higher MOR (Deresse, 1998). The same was true of MOE. A major difference in the relationship between MOR (and MOE) and age and the relationship between specific gravity and age is in the relative increase in the two properties that occurred during the juvenile period. Specific gravity increased by about one-third during the juvenile period. In contrast, MOR approximately doubled

during the juvenile period, and MOE was approximately three times greater at the end of the juvenile period (Deresse, 1998). Thus, strength and stiffness increase relatively much more with age than specific gravity does. The same is true for other species.

The juvenile periods for MOR and MOE in red pine are shorter than in red spruce, where they range from 40 to 60 years (Wolcott et al., 1987; Shepard, 1997). They are about equal to those for balsam fir (Shepard, unpublished data). By contrast, the juvenile period for both MOR and MOE in loblolly pine is reported to be about 13 years (Bendtsen and Senft, 1986).

Compared to the physical properties such as specific gravity and shrinkage, there are more concerns about the decline in the quality of wood that comes from intensively managed stands in terms of mechanical properties. Many studies support the opinion of Bendtsen (1978) and Senft et al. (1985), who feel that the decline in mechanical properties is attributable to the accelerated growth that leads to an early harvest of trees containing a larger proportion of juvenile wood. Therefore, the differences in quality are attributable largely to the differences in juvenile and mature wood.

A study by Pearson and Ross (1984) that covered three sources of loblolly pine (a 41-year-old naturally regenerated stand, a 25-year-old plantation, and a 15-year-old plantation of genetically selected stock, with all trees of comparable dbh) supports the above discussion. The results from that study showed that in all stands MOR and MOE increased as sample distance from the pith increased. The magnitude of this increase, however, differed markedly among the three sources. These differences were particularly large in wood from

near the pith. Overall, the samples from the natural stand exhibited the highest values and the genetically selected trees the lowest. According to the authors these differences were attributable to the age difference of the three sources.

In contrast to the approach taken by Pearson and Ross (1984), where comparisons were made primarily on the basis of the physical position of the specimens, the use of microbending test specimens (Bendtsen and Senft, 1986) enables the separation of the age effect in quantifying differences that exist between materials of different sources. The application of microbending tests has been demonstrated in Wolcott (1985), Shepard and Shottafer (1992), and Han (1995), where the methodology was used to determine the transition periods from juvenile to mature wood. In Deresse (1998), results from microbending tests were used to statistically separate the effects of age, stand, and ring width on the variation of MOR and MOE in two red pine stands. Results from this study indicated that the variation observed in the data, and the mechanical property differences between the two stands, could not be fully explained by age only, as had been reported by Pearson and Ross (1984) for loblolly pine. Multiple regression analysis showed that ring width (average ring width in samples containing more than one ring) was a highly significant source of variation, and a large proportion of the differences between the two stands could be explained by the differences in growth rate. Ring width was negatively correlated to both MOR and MOE; however, the impact of changes in ring width was stronger on MOE than MOR (Deresse, 1998).

EFFECT OF GROWTH STIMULATING FACTORS AND VIGOR ON PROPERTIES OF WOOD

Growth rate, defined as the number of woody cells that are derived from the vascular cambium per unit time, is primarily a product of the influence of genetics and environment. Therefore, one can consider growth as a permanent trace of the effect of all factors. It is also understood that the rate of growth is variable, and that at any given height in a tree stem it declines with age as a result of a decline in the influence of the crown. Because there are differences in growth between parts of the bole strongly influenced by the crown and those less influenced by the crown, it is important to recognize this when growth rate is discussed in relation to wood properties.

Growth rate can be partially controlled through the manipulation of the stand environment. Stand manipulation in the form of initial spacing, thin-

ning, or fertilization intrinsically affects wood properties through changes in crown morphology. However, the magnitude of the changes on properties of wood differ from species to species.

In discussing the influence of fast growth on wood properties, it is most appropriate to clearly identify the periods of fast growth in question or the stage in tree development at which this stimulated growth has occurred. The effect of fast growth at early stages of tree development should not be expected to have the same effect as increased growth in a later stage of development. For example, increased initial growth rate favors formation of a large juvenile core. This means that DBH alone is not necessarily a good indicator of wood properties; age must also be considered, as was illustrated previously. It is also important to understand that differences exist in the way different species respond to factors that stimulate or retard growth. In some species (i.e., red pine) the early growth environment (competition) (White and Elliot, 1992; Puettmann and Reich, 1995) was reported to induce lasting crown adaptation, and by inference a lasting effect on wood properties.

Spacing is one of the best tools to control stand development, and increased spacing has a positive effect on growth rate. Comparing initial spacing to growth and specific gravity, Baker and Shottafer (1970) and Larocque and Marshall (1995) found that increased spacing favored radial growth in red pine and that specific gravity appeared to decline. In the latter study the mean earlywood and latewood densities also declined with an increase in spacing. Similar observations on the relationship between spacing and specific gravity were also made for Norway spruce by Lindström (1996) and for Sitka spruce by Petty et al. (1990).

In contrast to the findings discussed above, an earlier report by Baker (1969) for 16-year-old red pine trees planted at three spacings found no clear decline in average tree specific gravity as spacing increased. Similarly, Jayne (1958) did not find any significant differences for red pine that was planted at three different spacings and on two different sites.

The duration of the initial-spacing effect on growth and wood properties depends upon the overall development of the stand. Discussing this short-term and long-term influence on growth and specific gravity of unthinned Sitka spruce stands, Simpson and Denne (1997) reported that initial spacing had the expected effects on radial growth in the first 15–20 years of growth, where wider rings were strongly and positively correlated with the wider spacings. However, in later years (25–40 years of growth) this correlation was reversed and became negative. In contrast to ring width, the

correlation between specific gravity and initial spacing became increasingly positive with age.

The effect of thinning and fertilization on specific gravity is well reviewed in Zobel and van Buijtenen (1989). In contrast to initial spacing, the influence of these practices appears to depend upon conditions under which specific applications are made. The direct influence of thinning may be short-lived and may cause a radial growth increase while specific gravity and fiber length may decline (Erickson and Harrison, 1974; Megraw, 1985).

The effect of fertilization also depends on the objectives of its application. If fertilizers are applied to remedy a soil deficiency that is a source of extreme growth retardation, the results could be an improvement in certain aspects of wood quality. Otherwise, as Larson (1969) explained, fertilization may have an adverse effect by reducing the rate of crown recession and prolonging the juvenile period. The effect of fertilization on red pine properties, discussed in Gray and Kyanka (1974), illustrates the variable effects, with radial growth and MOE improving and all other physical and mechanical properties showing a slight or significant decline.

The effect of fast growth (radial growth rate) on wood properties has been much debated. Wood property variation that appears to be related to growth rate may be the result of the differences between juvenile and mature wood. Illustrative results of such differences are discussed in Pearson and Gilmore (1971, 1980) and Pearson and Ross (1984). The three studies were based on loblolly pine logs of comparable size that were sawn and tested under similar techniques. Samples that originated from stands of different age groups exhibited property variations that were largely explained by the age differences. Pearson and Gilmore (1971), by analyzing the results from MOR and MOE tests, also concluded that if age was statistically removed by using specific gravity as its descriptor all samples would belong to the same population, irrespective of the ring width.

In many conifers, and especially the hard pines, growth rate seems to have little effect on most properties of wood (Taylor and Burton, 1982; Zhang, 1995). Zobel and van Buijtenen (1989) list studies that comprehensively cover different aspects of this topic. However, it is also important to point out findings on loblolly pine that indicate specific gravity decreased as growth rate increased (Yao, 1970). This relation between specific gravity and growth rate for samples taken at breast height of loblolly pine trees was also found by Pearson and Gilmore (1971).

In contrast to species that are characterized by an abrupt transition from earlywood to latewood, there is some question as to the relationship be-

tween wood properties and growth rate for those species that have gradual transition, such as white pine, and red, black, and white spruce. Brazier (1977), reviewing wood property variation in species characterized by a gradual earlywood to latewood transition and a narrow latewood band, pointed out the negative influence of growth rate on specific gravity. In several coniferous species (*Abies fabri*, *Abies nephrolepis*, *Picea asperata*, and *Picea koraiensis*) characterized by gradual transition from earlywood to latewood, similar observations were also made by Zhang (1995), and the effect of growth rate was more pronounced on mechanical properties than on specific gravity. The influence of growth rate on the properties of red pine wood was also found to vary. The results in Deresse (1998) show that no specific gravity difference was exhibited between two young, fast-growing stands as a result of their difference in growth rate. In contrast, significant differences existed between the two stands in MOR and MOE, as discussed earlier.

In other coniferous species, such as Sitka spruce, a statistically significant negative relationship between ring width and specific gravity was found by Brazier (1970). Simpson and Denne (1997) found the same relationship in Sitka spruce after taking the effect of age into consideration. In the latter study the relation between ring width and specific gravity, however, appeared to differ when analyzed by age and tree height.

Compared to the findings discussed in the two studies above, a stronger negative correlation between ring width and specific gravity was reported for Norway spruce. Investigating trees from a fertilization experiment, Lindström (1996) found a strong relation between the logarithmic value of ring width and ring specific gravity. A non-linear regression was also found to best model the relation between the two variables, indicating the varying effect of ring width on the measured specific gravity values.

In Norway spruce the ring width effect on specific gravity appeared to vary depending upon the width of the rings. For example, ring width changes in narrow rings (ranging between 0.04 in. and 0.12 in.) had a larger relative impact on specific gravity than changes in wider rings. With an increase in ring width, the magnitude of the specific gravity change as a result of a change in ring width became more variable, and the relation between the two diminished. This type of variability was also observed for samples taken from the inner core of the stem in Sitka spruce (Simpson and Denne, 1997).

Deresse (1998) found a similar relationship in red pine, where specific gravity was negatively related to ring width (Figure 7) and positively related to age. Over the range in ring width from

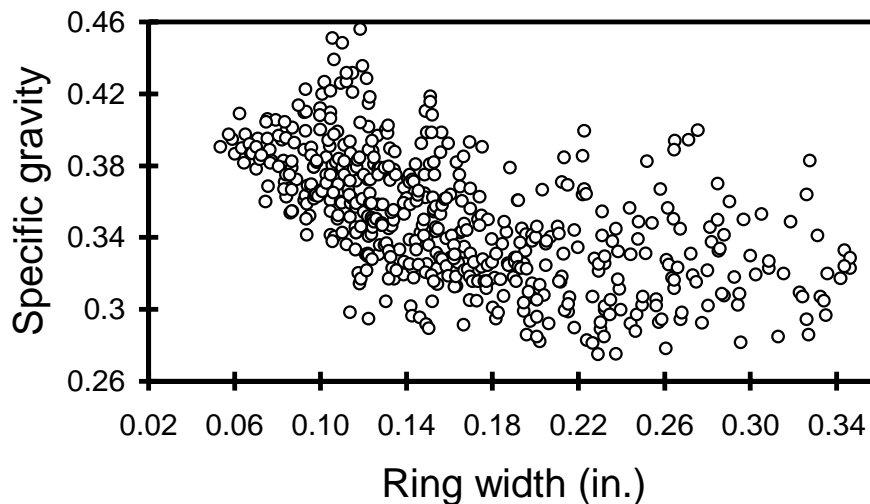


Figure 7. Specific gravity variation with ring width at breast height through age 30 in dominant and codominant trees from two young, fast-growing red pine stands (from Deresse, 1998).

approximately 0.18 in. to 0.35 in., there was no relationship between specific gravity and ring width in red pine. Specific gravity did not increase as ring width decreased until ring width decreased below 0.18 in. It should be emphasized that the higher specific gravities at the narrow ring widths are partly related to the fact that specific gravity increases with age, and as age increases, ring width decreases. The source of variability in the wider rings could be a result of other factors, such as reaction wood that can be present in the juvenile wood (Simpson and Denne, 1997).

Work by Petty et al. (1990) supports the results from the above studies. The results for the outermost five rings at breast height from 48-year-old trees of Norway and Sitka spruce exhibited an inverse linear relation between ring width and specific gravity. The relations were strong in Sitka spruce ($r = -0.85$), which had predominantly narrower rings. In contrast, in the Norway spruce specimens that contained rings 0.12 in. and more wide, the correlation between the two variables was lower ($r = -0.44$). A similar relationship was also evident in western hemlock (DeBell et al., 1994), but the "average drop" in specific gravity was extremely large. Samples containing rings 20-24 from the pith showed an average decrease in specific gravity from 0.47 to 0.37 for an average ring width increase from 0.08 in. to 0.32 in.

These growth-rate-related property variations (in specific gravity and some mechanical properties), encountered in species like the spruces with gradual transition from earlywood to latewood or other species that lack a clear abrupt transition (i.e., red pine), are mostly attributed to the nature of the transition wood that develops under a variable growth rate. It has been discussed that specific

gravity of those species, and by inference many mechanical properties, is closely related to the variability and width of the earlywood and latewood. It is believed that in these species the relative width of the latewood, meaning its proportion, is more affected by ring width than in species that have an abrupt transition from earlywood to latewood. According to Taylor and Burton (1982), there is a negative correlation between ring width and latewood proportion in loblolly pine, especially in rings formed in the early stages of tree development. In Brazier (1977) the same phenomenon was also reviewed based on the results of Larson (1969). These researchers attributed the variation to the changing nature of the "intermediate-wood". The point is that the intermediate-wood, found between the true early-wood and true latewood, in slow growth qualifies more as latewood while in vigorous growth it tends to be more like earlywood.

In recent reports, DeBell et al. (1994) on western hemlock and Zhang et al. (1996) on black spruce, documented a strong positive correlation between earlywood width and overall ring width, meaning a strong negative relation between ring width and the percentage of latewood. The increase in ring width and consequently the increase in the earlywood proportion also had an adverse effect on mean earlywood specific gravity, and a slight decline in the earlywood specific gravity was evident in both spruces.

Compared to its effect on specific gravity and mechanical properties, the effect of growth rate on fiber length appears to be similar in most coniferous species. This influence on softwood tracheid length is particularly visible in the early stages of tree development. The relation between growth rate and tracheid length in most studies was found to be

negative and the magnitude of fiber length decrease was reported to be significant when growth rates exceed 0.04 in. (Bisset et al., 1951; Bannan, 1967(a) (b); Taylor and Burton, 1982).

It is clear that many factors affect wood properties. Of those factors, the forest manager has the greatest control over two of the most important, tree age and growth rate (ring width). This applies to red pine as well as to other conifers. Therefore, it is essential that the forest manager be aware of the effect that these two factors may have on a variety of wood properties and the possible implications of intensive management for the properties of the future wood supply.

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Wood Properties Of Red Pine (*Pinus resinosa* Ait.)

Takele Deresse
Graduate Research Assistant

and
Robert K. Shepard
Professor of Forest Resources

Department of Forest Management
College of Natural Sciences, Forestry, and Agriculture
University of Maine
Orono, Maine 04469

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