AN ABSTRACT OF THE THESIS OF

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Title: Wood Quality and Strength Relationships in Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) Wood of Different Maturity

Abstract approved: Signature redacted for privacy.

Robert L. Krahmer

The objectives of this study were to determine: 1) differences in average wood quality and strength properties of clear-wood specimens sampled from juvenile, transition, and mature wood zones in Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) trees from known forest sites; 2) relationships among wood quality properties [specific gravity (SG), rings per inch (RPI)] and strength properties [Modulus of Elasticity (MOE), Modulus of Rupture (MOR)] of small, clear-wood specimens from juvenile, transition, and mature wood; and, 3) relationships between strength properties in bending of small, clear-wood specimens and strength properties in bending and tension of the structural lumber from which the small specimens were cut. The lumber was provided by the Stand Management Cooperative from trees on 15 sites in Washington and Oregon.

Statistical analyses showed that average SG increased from juvenile to mature wood zones and was significantly different in each of the sampling zones (juvenile,

transition, and mature wood). Growth rate decreased in all stands from juvenile through mature wood as trees aged. Averages for MOR and MOE increased with maturity of wood.

Regression of SG on MOR and MOE showed low R^2 values for the juvenile wood zone which may be the result of interacting juvenile wood characteristics. Regression of RPI on SG, MOR, and MOE showed that by itself, rate of growth had very little or no effect.

Slopes for SG versus MOR and MOE for the three wood zones were similar. Intercepts were different between the juvenile-mature wood zones for MOR and between the juvenile-transition and juvenile-mature wood zones for MOE. Slopes for RPI versus SG and MOE for the three wood zones were also found to be similar. Intercepts were different between the juvenile-mature wood zones, but not different between the juvenile-transition and transition-mature wood zones. MOE regressed on MOR for the three wood zones showed no differences between any of the slopes and intercepts, although the R^2 was highest for mature wood samples. Correlations between similar properties of small, clear wood specimens and structural lumber were highest.

Wood Quality and Strength Relationships in Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) Wood of Different Maturity

by

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Typed by Keoki Apokolani Carter

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A special thanks to AbdelGadir AbdelAzim for his kindness and willingness to help me sort through statistical analysis. What a chore! And to all the other people who were involved in helping me with this project, either voluntarily or through my persistence, many thanks. You all know who you are.

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INTRODUCTION

Because of the gradual depletion of old growth Douglas-fir timber in the Pacific Northwest, quality of young growth has become an important issue. As old growth forests are harvested or set aside for other reasons, the raw material base tends to consist of fast-growth, short-rotation trees. As is expected, the quality of this fast-growth timber is like the inner most part of large old trees and this varies from most wood in old growth timber.

The changes in this raw material base present new challenges to forest managers, silviculturists, and wood products manufacturers. At this point, it is unknown whether silvicultural methods and genetic improvements will be able to produce wood that is comparable to wood that has been historically provided by the forest. Data supplied by the wood anatomist and integrated with data from forest researchers and geneticists hopefully will ensure the growth of high-quality wood that can compete in world markets for forest products.

Fast-grown, short rotation trees supply more raw materials to today's wood products industries. A large proportion of juvenile wood is consumed from these raw materials. Manufacturers and consumers of wood products are concerned because the characteristics of juvenile wood differ significantly from those of mature wood. For example, when compared to mature wood, juvenile wood in conifers is characterized by lower percentage of latewood, higher moisture content (MC), lower strength, lower specific gravity (SG), shorter tracheids, larger fibril angle, lower transverse shrinkage, higher longitudinal shrinkage, more compression wood, thinner cell walls, larger lumen diameters, and lower cellulose but higher lignin content (Meylan, 1968; Bendtsen, 1978; Senft, 1984). Many of these characteristics produce undesirable properties in wood products.

In this study properties of the small, clear wood specimens were subjected to static bending test. Data collected were analyzed and correlations between specific gravity, rings-per-inch (rate-of-growth), and the strength properties (modulus of rupture and modulus of elasticity) were concluded. Correlations between small, clear specimens and structural lumber were examined. Relationships for the overall population, as well as the juvenile, transition, and mature wood zones were also analyzed.

OBJECTIVES

The objectives of this study were to use regression analyses and analysis of variance (ANOVA) to determine:

1) differences in average wood quality and strength properties of clear-wood specimens sampled from juvenile, transition, and mature wood zones in trees from known forest sites.

2) relationships among wood quality properties (density, rings per inch) and strength properties (Modulus of elasticity, Modulus of rupture) of small clear-wood specimens from juvenile, transition, and mature wood of Douglas-fir.

3) relationships between strength properties in bending of small, clear-wood specimens and strength properties in tension of the structural lumber from which the small specimens were cut.

LITERATURE REVIEW

Juvenile Wood

Juvenile wood is a cylindrical core of approximately uniform diameter along the length of the tree stem (Krahmer, 1985), because it depends on the age of the cambium at all heights in the tree stem. For Douglas-fir, juvenile wood has been shown to occupy the first 15 to 20 growth rings adjacent to the pith (Erickson and Harrison, 1974; Senft, et al., 1985). The wood properties tend to improve with age during the early years (of the juvenile wood zone) and level off at the mature wood zone. Wangaard and Zumwalt (1949) show this trend for SG, Modulus of Rupture (MOR), and Modulus of Elasticity (MOE) in a study of second growth Douglas-fir. They also showed that their values compared favorably with that of the old growth values (Markwardt and Wilson 1935).

Specific Gravity and Strength Properties

Specific gravity (SG) and density are terms that are used interchangeably throughout the literature. Although they refer to the same wood properties, each has a different meaning. Density is defined as the mass or weight per unit volume. It is usually expressed in pounds per cubic foot or kilograms per cubic meter. It can be measured using green weight and green volume, dry weight and green volume, or weight and volume at a specified moisture content. Specific gravity is the ratio of the density of a material (wood) to the density of water at 39 degrees F. SG is based on ovendry weight and volume at a specified moisture content (Haygreen and Bowyer 1982).

There are certain wood properties that are basic quality indicators for many products. Specific gravity is one such property and can be used for estimating strength properties. Equation for specific gravity is:

$$SG = \frac{\text{oven-dry weight of given volume of wood}}{\text{weight of an equal volume of water}}$$

SG is dependent upon the anatomical characteristics of the wood. Factors such as cell dimensions and wall thickness, earlywood-latewood ratios, size and the amount of tracheid cells (fibers), and amount of ray cells are some of the factors that determine SG. Fibers of the earlywood zone are thin walled with large lumens and are low in specific gravity. As the fibers transform into latewood, their walls thicken and the lumens are smaller. The specific gravity here is higher. This is because the volume of the woody cell material is higher, (Panshin and deZeeuw, 1980; Haygreen and Bowyer, 1982; Zobel and van Buijtenen, 1989;).

Johnson (1981), in her study of correlations between specific gravity and strength values of wood samples in Douglas-fir thinnings, noted, that mature wood strength values correlated more highly than the juvenile wood strength values. She also noted that lower average strength values were found in juvenile wood and that most juvenile wood SG values were lower than mature wood SG values. McKimmy and King (1978), related their low density and strength values to the progeny that contained samples of high proportions of juvenile wood. However, it is also known that specific gravity, being an important physical characteristic of wood, is not the only causal factor of strength. Other variables may effect strength properties as well. For example, moisture content, extractives, fibril angles, number of rings from pith, etc., are some other factors that influence strength properties (Markwardt and Wilson, 1935; McKimmy, 1959; Littleford, 1961; Haygreen and Bowyer, 1982; Bendtsen and Senft, 1984).

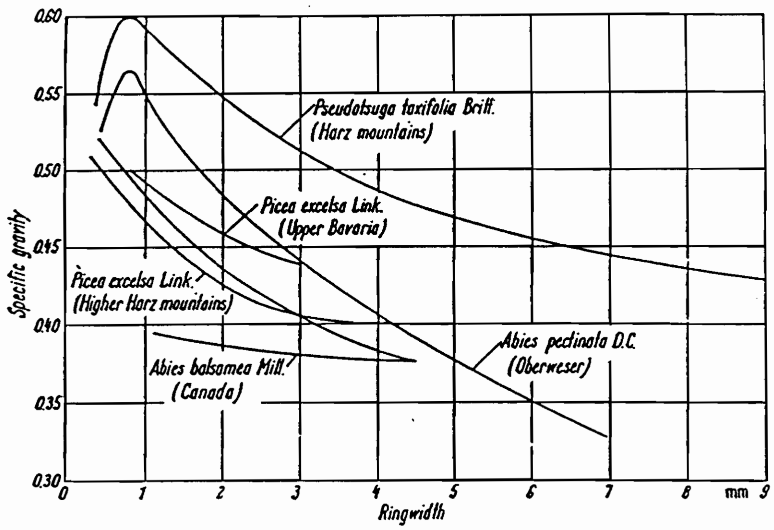
Zobel and van Buijtenen (1989) in a study on hard pines, reported the existence of a uniform pattern of low SG at the pith, increasing rapidly through the juvenile wood zone, and resumes a constant specific gravity for a series of annual rings. This seems to be normal for hard pines. Pearson and Ross (1982), found a similar trend for selected Loblolly Pine samples. It was also mentioned that overmature trees decrease in specific gravity near the bark. On the other hand, other researchers cited in Zobel and van Buijtenen (1989), such as Hughes and Mackney (1949), reported that for Pinus radiata, basic density increases linearly from the center through 22 annual rings. Others also have found that radiata pine has a continuously increasing specific gravity at least to 30 years of age (Zobel and van Buijtenen 1989). McKimmy (1966) showed that from the pith through the first decade (juvenile wood) specific gravity in Douglas-fir dropped about 5%, then increased about 9% through the next 20 years. After 40 years, SG was unstable, either increasing or decreasing.

In other conifers, a general rule for true firs, spruce, and hemlock is that SG is high near the tree center, decreases for a few rings, and levels off or increases moderately toward the bark. Krahmer (1966) found a similar pattern in Western Hemlock. He also showed that zones in which the change occurred appeared to be independent of age and included growth rings within a radius of about 2 inches of the pith. Increasing or decreasing specific gravity beyond this "juvenile wood zone" was not evident. However, the mature wood did show evidence of variations in specific gravity across its growth rings. Averages of the specific gravity of the trees were retrieved from wedges, strips, and static bending specimens. The specific gravity of the strips ranged from 0.30 to 0.47 with an average of 0.38.

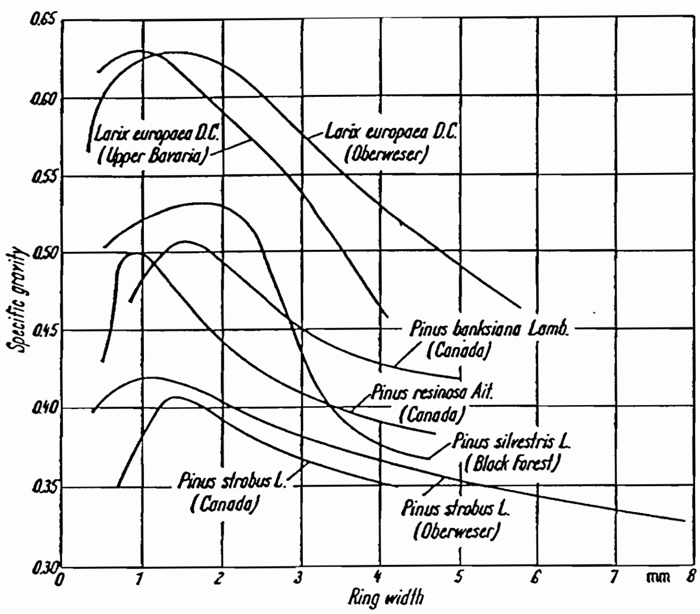
Rate of Growth - Rings Per Inch

Rate of growth, either as ring width or rings per inch has been used as a measurement of wood quality in respects to wood density (Kollmann and Côté, 1968). Within a growing season a new layer of wood (growth ring) is formed throughout the circumference of the tree stem. Wood produced early in the season is called earlywood (springwood). Wood produced later in the season is called latewood (summerwood). The former because of its thinner walls and larger lumens are of lower SG. The later has a higher SG because its cell walls are thicker with smaller lumens. Although there is a good correlation between percent summerwood and density (SG), the correlation of RPI and density is not as strong (Abdel-Gadir, 1991). Kollmann and Côté (1968) express this through several graphs, which are shown in Figures 1a and b. In Figure 1a, a comparison of the relationship between width of annual rings and SG is shown for Douglas-fir, spruce, and true firs. Here the density of spruce decreases with increasing width of annual rings, whereas in Figure 1b, the density of pines and larches increases and then decreases. The pattern of Douglas-fir lies between these two. McKimmy (1966), in a multiple regression analysis for Douglas-fir, showed that percent summerwood and tree age had an important effect on SG. Growth rate and the interaction of growth rate and tree age had no significant effect on SG.

Figure 1. Rate of growth versus specific gravity graphs derived from Kollman and Côté (1968).



a. Relationships between width of annual rings and SG for Douglas-fir, spruce, and true fir.



b. Relationships between width of annual rings and SG for different species of pine and larch.

PROCEDURES

Raw Material Preparation

Douglas-fir lumber from the Stand Management Cooperative (SMC) product recovery study (Bergstrom, 1988) was available for this study. The lumber came from trees on 15 sites in Washington and Oregon representing young-growth, coast Douglas-fir[1]. Figure 2 shows a map, locating the stands in Washington and Oregon and Table 1 gives an overall summary of the management activities, site and location, age at stump, and the donors of each stand (Fahey, et al. 1991).

Trees were felled and bucked into woods-length logs that ranged from 12-44 feet in length. The log beginning at the base of the tree was labeled Woods Log 1, the next log was labled Woods Log 2, etc. The longer woods logs were bucked into two saw logs at the saw mill and numbered 1 and 2. Each board sawn from these logs was coded to identify its site, tree number, woods log number and saw log number, respectively.

Two hundred and twenty four, four-foot long sections

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[1] Coast Douglas-fir is defined as Douglas-fir growing in the States of Oregon and Washington west of the summit of the Cascade Mountains. Interior West includes the State of California and all counties in Oregon and Washington east of but adjacent to the Cascade summit. Interior North includes the remainder of Oregon and Washington and the States of Idaho, Montana, and Wyoming. Interior South is made up of Utah, Colorado, Arizona, and New Mexico.

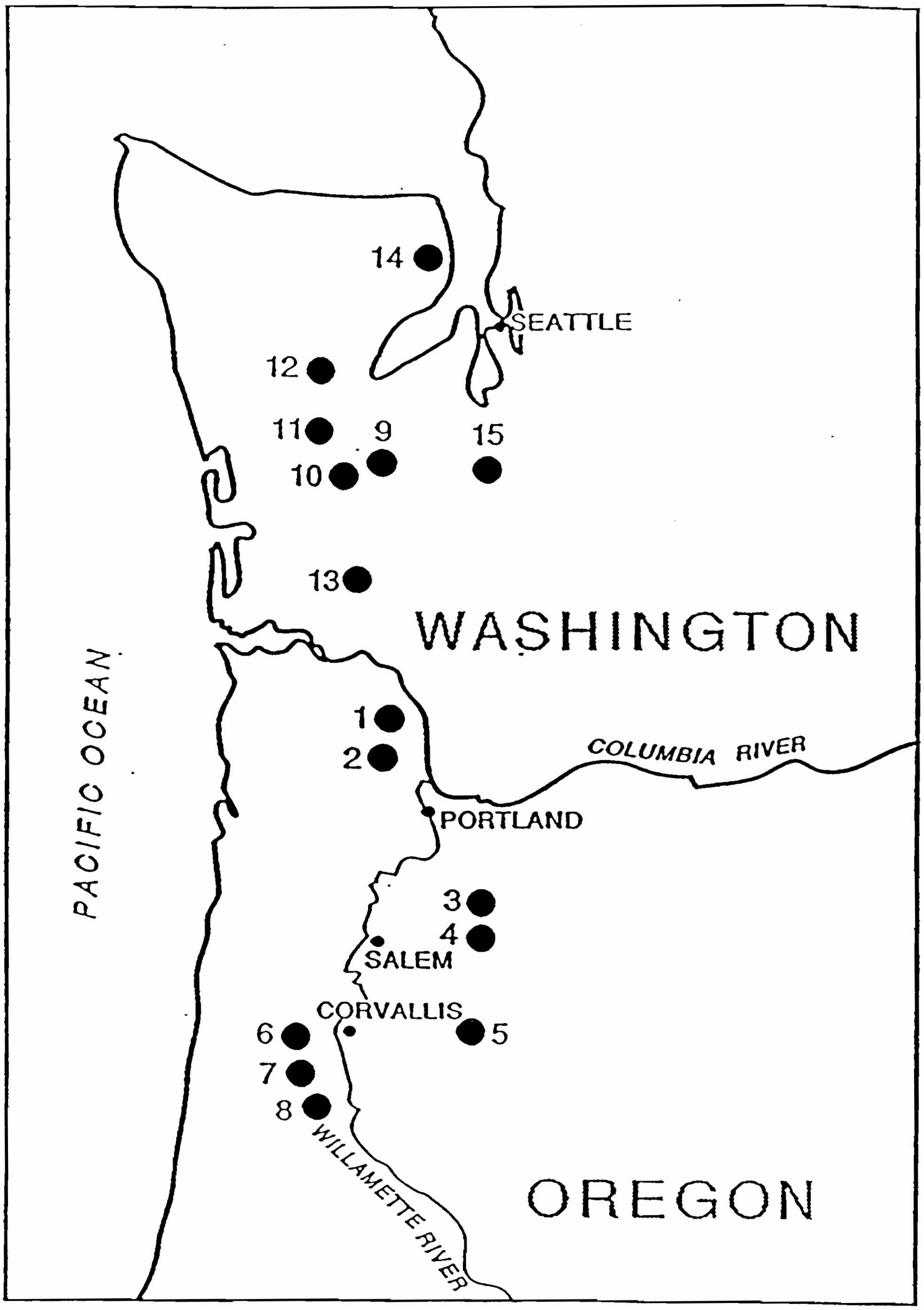


Figure 2. Map locating the stands in Washington and Oregon.

Table 1. Summary of the management activities, site and location, age at stump, and the participating donors of each stand.

Stand	Ownership	Site	Age	Location	Management activities
			Years		
1	Cavenham	128	44	T. 4 N., R. 4 W., WM, OR;	Established (EST) at less than 200 trees per acre (TPA); commercially thinned (CT) age 35
2	Bureau of Land Management	121	46	T. 4 N., R. 3 W., WM, OR;	EST at estimated 800 TPA; CT age 38
3	Longview Fibre	115	46	T. 8 S., R. 2 E., WM, OR;	EST at 250 TPA; CT ages 32 and 38; fertilized (FERT) ages 30 and 40
4	Longview Fibre	105	45/55	T. 8 S., R. 2 E., WM, OR;	EST in 2 stages; initially 100 TPA, now at 150 TPA CT ages 30 and 40; FERT ages 32 and 42
5	Willamette	115	46	T. 8S., R2 E., WM, OR;	EST at 500+ TPA; precommercially thinned (PCT) age 25, CT age 36; FERT ages 25 and 33
6	Bohemia	132	36	T. 12 S., R. 1 W., WM, OR;	EST less than 150 TPA, on a small area of poor stocking within stand; CT age 28; but no effect on sample trees
7	Weyerhaeuser	138	45	T. 13 S., R. 5 W., WM, OR;	EST at 600 TPA; PCT at age 17 to 210 trees per acre; CT ages 22, 28, 31, and 38; CT had no effect on growth
8	Weyerhaeuser	142	25	T. 14 S., R. 6 W., WM, OR;	EST by machine planting at 1200 TPA; PCT age 6 to 300 TPA; Christmas tree stand, records of weed control and FERT missing
9	Washington D.N.R.	104	56	T. 17 N., R. 3 W., WM, WA;	EST less than 100 TPA; now at 110 trees per acre; heavy brush competition first 10 years
10	Washington D.N.R.	120	61	T. 17 N., R. 3 W., WM, WA;	EST 1000+ TPA; PCT age 45 to 250 trees per acre; only dominants have responded to PCT
11	Port Blakely	125	85	T. 18 N., R. 5 W., WM, WA;	EST 350 TPA; CT age 45 and periodically for past 40 years
12	Port Blakely	130	49	T. 19 N., R. 5 W., WM, WA;	EST 600 TPA; PCT age 17; some bear damage age 20; CT age 40
13	Weyerhaeuser	130	29	T. 12 N., R. 4 W., WM, WA;	Failed plantation re-EST to 500 trees per acre with a few survivors from 4 year older planting; PCT age 20.
14	USDA Forest Service	122	55	T. 28 N., R. 2 W., WM, WA;	EST 600 trees per acre; PCT age 20 with light CT every 6 to 8 years since
15	University of Washington	98	65	T. 16 N., R. 4 E., WM, WA;	EST 800+ trees per acre; few 75-year-old trees at edge of the stand; school research stand with frequent light PCT and CT since the stand was 20 years old

were selected from approximately 348 boards (2"x6") that were obtained from Washington State University, Pullman, where the full-size lumber had been tested to failure in tension. Data available from the tests on the full size lumber included flatwise MOE, MOE in tension, tensile strength, and wood specific gravity.

The four-foot sections were first sorted to eliminate any pieces that would not provide a clear 1"x1"x16" test specimen because of knots, pitch pockets, checks, shakes, etc. The location on each remaining board (192) was marked where a defect-free test specimen would be removed. The test specimen was numbered with the original board number.

The location of test specimens with reference to juvenile and mature wood was estimated. A plastic template with concentric rings was made according to Booker (1987) to identify growth rings #10 and #20 from the pith on a board. Test specimens that were within the first ten rings from the pith were classified as juvenile wood; specimens that were beyond twenty rings from the pith were classified as mature wood; and any that fell between this range were considered transition wood. Growth rate in rings-per-inch (RPI) was determined for each static bending specimen.

Static bending specimens were then sawn from each section of lumber according to specifications in the American Society for Testing and Materials (ASTM) Standards, section D143, Small Clear Specimens of Timber, Secondary Methods (1986). Clear, flat-grained specimens were machined to 1"x1"x16" with the grain of the wood running parallel to the length of the specimen. The test specimens were conditioned in a controlled room at 70 degrees F and 70% humidity where the equilibrium moisture content of Douglas-fir was approximately 12%.

Static Bending Test

Static bending tests were conducted in accordance with ASTM, D143 (1986). In this test, deflection is increased at a constant rate until rupture occurs. During the early stage of loading, the wood is elastic and no damage occurs as a result of the loading. After the elastic limit has been reached, the additional load begins fracturing the specimen until complete rupture occurs.

The static bending test provides two properties of interest in this study. One is Modulus of Elasticity determined prior to the deflection reaching the elastic limit by the equation $MOE = PL^3/4YBD^3$. The other is Modulus of Rupture determined from the maximum load at rupture by the equation $MOR = 1.5P_{max}L/BD^2$. In both equations B is the width of the specimen (1 in.), D is the depth of the specimen (1 in.), and L is the span of the specimen (14 in.). For MOE, Y is the deflection (in.) at load P (lb.), and for MOR Pmax is the maximum load (lb.).

Static bending tests were performed on an Instron Universal Testing Machine. MOE and MOR were determined from load and deflection data obtained for each test piece using an ASYST program.

Specific Gravity Specimens

1"x1"x2" blocks were cut from the tested static bending specimens as close to the fracture as possible for specific gravity (SG) measurements. Specific gravity was based on ovendry weight and volume at 12% MC (Wood Handbook 72. Rev. 1987; Panshin and de Zeeuw, 1980).

Statistical Analyses

Statistical analysis was done using the Statistical Analysis System computing package (SAS Institute Inc., Cary, NC, USA, 1988) on a 286 IBM compatible PC. Analysis of variance (ANOVA) provided a means of partitioning the total variation into sections based on the various effects analyzed. Regression provided the concept of correlation between the response variables and the predictors.

RESULTS and DISCUSSION

General Data Description

Test samples for my study represented 12 of the 15 timber stands. Table 2 identifies some of the stem characteristics of these stands. Out of 192 test samples, only 3 samples were from Woods Log 2, Saw Log 1. The remaining 189 samples were from Woods Log 1 with 108 from Saw Log 1 and 81 from Saw Log 2.

The bulk of my test samples came from stands 5,9,10,11, and 15, each having a count of 34,22,21,20, and 32, respectively (Table 2). Stand #5 was the southern most site located near Corvallis, Oregon (Figure 2). The other four stands were located in southwest Washington. Stand #5 was younger than the other four stands at stump age (39 yrs.) and contained more juvenile wood (68.6% of volume). Stand #11, the oldest at stump age (85 yrs.) contained the least juvenile wood (28.3% of volume). This fit the trend that the older the stand, the smaller the amount of juvenile wood because its boundary is age related.

Wood Quality and Strength Property Averages

In Table 3, average values and number of samples are shown for the three types of wood (juvenile wood, transition wood, and mature wood) from each of the 12 timber stands. The total number of samples for each type was 54, 62, and 76, respectively.

Table 2. Stem charateristics and sample size from timber stands. Derived from Fahey, et al. (1991).

Stand	Age[1]	D.b.h. range	Juvenile wood avg.[2]	No. of test samples
			Percent	
1	44	20-26	54.7	12
3	46	14-27	53.1	19
5	39	9-24	68.6	34
6	36	11-25	62.2	9
7	45	12-25	58.3	14
8	25	9-18	94.1	4
9	56	18-28	40.8	22
10	61	10-23	40.0	21
11	85	18-26	28.3	20
13	29	10-17	91.3	3
14	56	10-24	39.0	2
15	65	10-22	34.3	32

[1] Stand age was measured at stump height.

[2] Percentage of juvenile wood is the proportion of log volume inside the first 20 growth rings.

Table 3. Average values and number of samples for wood types from timber stands.

Means of Variables by Area

Specific Gravity

Stand	Juvenile(n)	Transition(n)	Mature(n)
1	0.422 (5)	0.456 (4)	0.443 (3)
3	0.410 (5)	0.451 (10)	0.446 (4)
5	0.410 (14)	0.439 (12)	0.463 (8)
6	0.479 (5)	0.496 (4)	---- ----
7	0.394 (6)	0.419 (5)	0.476 (3)
8	0.428 (2)	0.423 (2)	---- ----
9	0.455 (6)	0.452 (8)	0.461 (8)
10	0.414 (5)	0.511 (4)	0.502 (12)
11	0.406 (3)	0.430 (4)	0.491 (13)
13	0.379 (1)	0.456 (2)	---- ----
14	---- ----	---- ----	0.561 (2)
15	0.449 (2)	0.462 (7)	0.498 (23)

Rings per inch (RPI)

Stand	Juvenile(n)	Transition(n)	Mature(n)
1	3.2 (5)	4.7 (4)	5.0 (3)
3	3.8 (5)	5.4 (10)	6.2 (4)
5	3.2 (14)	4.6 (12)	5.8 (8)
6	4.8 (5)	4.0 (4)	---- ----
7	3.6 (6)	5.8 (5)	9.0 (3)
8	2.0 (2)	3.0 (2)	---- ----
9	4.1 (6)	5.0 (8)	5.8 (8)
10	4.6 (5)	8.0 (4)	7.9 (12)
11	5.3 (3)	7.7 (4)	11.3 (13)
13	3.0 (1)	5.5 (2)	---- ----
14	---- ----	---- ----	8.5 (2)
15	9.0 (2)	6.7 (7)	8.7 (23)

(n) = Number of samples in each type of wood.

Table 3 (con't). Average values and number of samples for wood types from timber stands.

Mean of Variables by Area

MOR

Stand	Juvenile(n)		Transition(n)		Mature(n)	
	psi x 10^3		psi x 10^3		psi 10^3	
1	10.73	(5)	12.40	(4)	12.73	(3)
3	10.63	(5)	12.37	(10)	13.16	(4)
5	11.29	(14)	11.97	(12)	12.96	(8)
6	12.78	(5)	12.92	(4)	----	----
7	9.02	(6)	11.04	(5)	13.16	(3)
8	7.91	(2)	11.93	(2)	----	----
9	11.26	(6)	12.11	(8)	12.04	(8)
10	11.70	(5)	13.38	(4)	14.24	(12)
11	11.52	(3)	12.23	(4)	14.40	(13)
13	10.06	(1)	8.53	(2)	----	----
14	----	----	----	----	16.94	(2)
15	9.52	(2)	13.59	(7)	13.34	(23)

MOE

Stand	Juvenile(n)		Transition(n)		Mature(n)	
	psi x 10^6		psi x 10^6		psi x 10^6	
1	1.636	(5)	1.970	(4)	1.981	(3)
3	1.552	(5)	1.916	(10)	2.032	(4)
5	1.691	(14)	1.957	(12)	2.108	(8)
6	1.892	(5)	1.945	(4)	----	----
7	1.567	(6)	1.735	(5)	2.235	(3)
8	1.364	(2)	1.681	(2)	----	----
9	1.579	(6)	1.761	(8)	1.678	(8)
10	1.861	(5)	2.164	(4)	2.363	(12)
11	1.796	(3)	1.819	(4)	2.187	(13)
13	1.562	(1)	2.116	(2)	----	----
14	----	----	----	----	2.475	(2)
15	2.086	(2)	2.049	(7)	2.068	(23)

(n) = Number of samples in each type of wood.

Stand 13 (with one observation) had the lowest SG (0.379) in the juvenile wood zone and stand 6 had the highest (0.479). For the transition wood zone, stand 7 was the lowest (0.419) and stand 10 showed the highest (0.511). The mature wood zone showed the lowest SG (0.443) in stand 1 and highest (0.561) in stand 14.

SG for juvenile wood specimens ranged from 0.34 to 0.53 with an average of 0.42, and transition wood ranged from 0.35 to 0.53 with an average of 0.45. Mature wood ranged from 0.39 to 0.63 with an average of 0.48, which is the same as the average value in the Wood Handbook (1987) for coast Douglas-fir. These differences in SG between juvenile and mature wood are typical of that given in the literature for many softwood species (Bendtsen, 1978). ANOVA indicated that between each of the wood zones (juvenile, transition, and mature) significant differences were verified.

Rate of growth in the juvenile wood zone was the fastest (2.0 RPI) in stand 8 and the slowest (9.0 RPI) in stand 15. In the transition wood zone, stand 8 again showed the fastest (3.0 RPI) and the slowest (8.0 RPI) was in stand 10. Mature wood showed fastest (5.0 RPI) in stand 1 and slowest (11.3 RPI) in stand 11. Rate of growth decreased in all stands from juvenile into mature wood as trees aged.

Rate of growth of juvenile wood specimens ranged from

2.0 to 14.0 RPI with an average of 3.9 RPI. Transition wood ranged from 3.0 to 11.0 RPI with an average of 5.5 RPI and mature wood from 4.0 to 16.0 RPI with an average of 8.1 RPI. Significant differences between the juvenile, transition, and mature wood zones for RPI were found through the use of ANOVA.

MOR in the juvenile wood was lowest (7,910 psi) in stand 8 and highest (12,780 psi) in stand 6. Transition wood was lowest (8,530 psi) in stand 13 and highest (13,590 psi) in stand 15. Mature wood was lowest (12,040 psi) in stand 9 and highest (16,940 psi) in stand 14.

MOR for individual test specimens from juvenile wood ranged from 6,600 to 15,660 psi with an average of 10,900 psi, compared to a range of 5,060 to 16,350 psi with an average of 12,250 psi for transition wood. Mature wood ranged from 8,630 to 20,370 psi with an average of 13,540 psi. In comparing the wood zones (juvenile, transition, and mature), ANOVA showed that for MOR, significant differences among these zones were evident. Average MOR for transition and mature wood samples compared favorably with the Wood Handbook (1987) value of 12,400 psi. Juvenile wood average for MOR was low, as would be expected from previous research (Pearson and Gilmore, 1980).

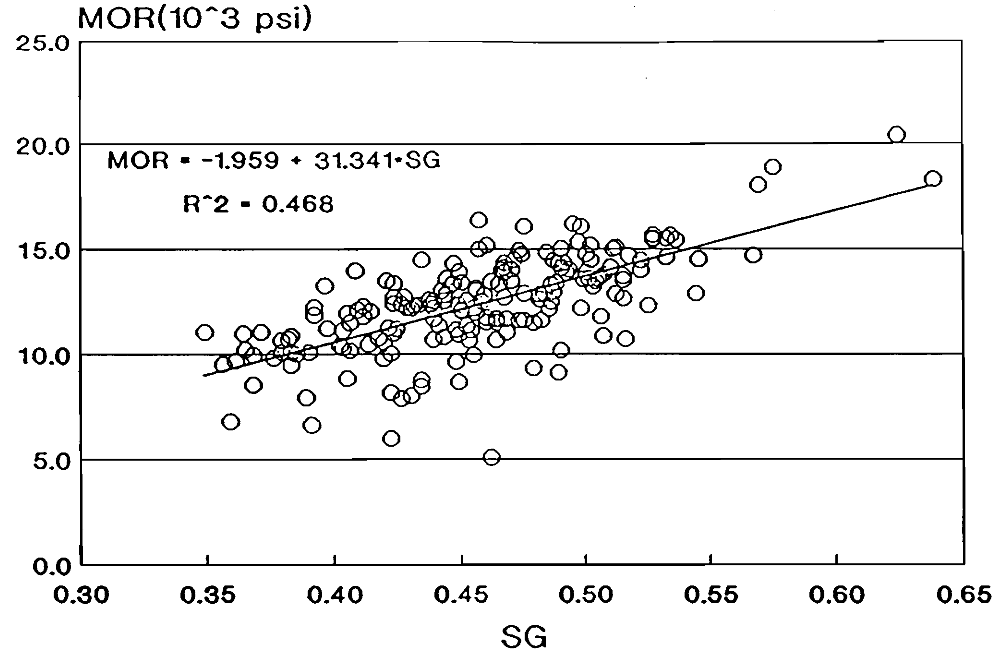
MOE in the juvenile wood zone was lowest (1,364,000 psi) in stand 8 and highest (2,086,000 psi) in stand 15. Transition wood was lowest (1,681,000 psi) in stand 8 and highest (2,164,000 psi) in stand 10. Mature wood was lowest (1,678,000 psi) in stand 9 and highest (2,475,000 psi) in stand 14.

MOE for juvenile wood specimens ranged from 1,242,000 to 2,437,000 psi with an average of 1,687,000 psi. Transition wood ranged from 798,000 to 2,502,000 psi with an average of 1,919,000 psi and mature ranged from 1,091,000 to 2,826,000 psi with an average of 2,110,000 psi. As with the other strength properties, significant differences were found between each of the wood zones (juvenile, transition, and mature) in MOE, through the use of ANOVA.

Lower MOE values for juvenile wood are usually attributed to low density and large microfibril angles (McMillin, 1973; Erickson and Arima, 1974). Averages for wood type followed the trend similar to MOR. Mature and transition wood averages compared favorably with the Wood Handbook (1987) value of 1,950,000 psi.

<u>Relationships Among Properties of Clear Wood Specimens</u>

When using the regression equation $Y = B_0 + B_1X$ on the combined data from the juvenile, transition, and mature wood zones, positive regressions of SG with MOR and MOE were observed. Figure 3 illustrates these relationships. The correlations are significant ($p = 0.0001$), and approximately 47% of the variation in MOR was explained by SG, while 42% of the variation in MOE was explained by SG.



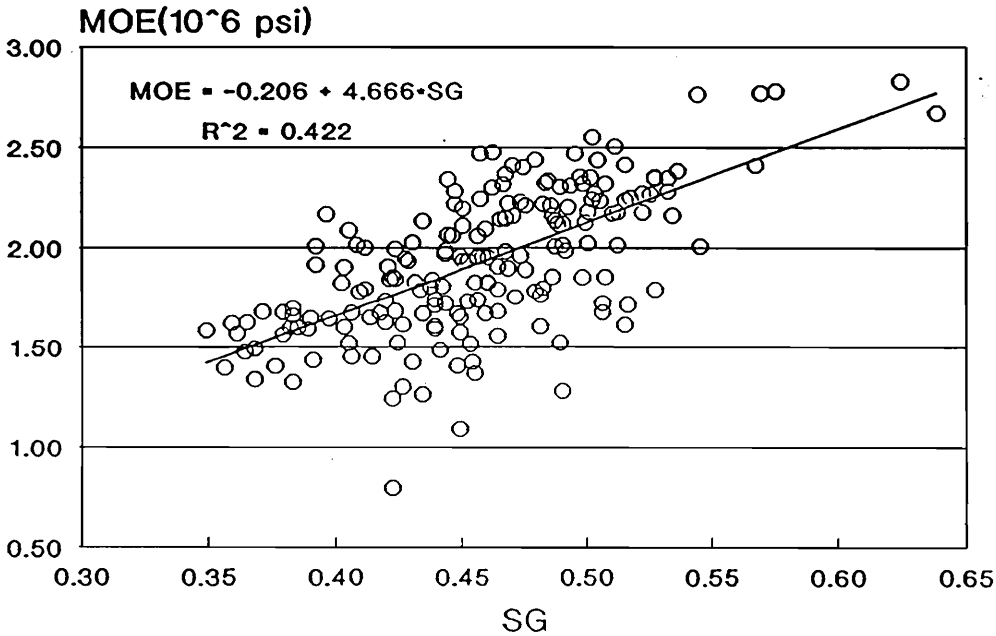


Figure 3. Regressions of specific gravity on MOR and MOE of the total population. Regression equation $Y = B_o + B_1X$ was used.

As indicated by other studies as well (Lutz, 1964; Liska, 1965; Barrett and Kellogg, 1984), strength properties increased with SG.

Figure 4 represents the regression of MOE on MOR for the total population and shows a positive correlation. A significant probability level of $p \leq 0.0001$ and a R^2 value of 0.5867 are indicated.

Figure 5 illustrates that RPI showed a weak positive correlation with SG, MOR, and MOE. All three relationships showed a similar trend; that for a designated "RPI" a wide range of values were identified. For example, where RPI = "3", MOR ranged from approximately 6,000 to 16,000 psi and for RPI = "7", MOR ranged from 4,000 to 19,000 psi.

The data points in Figure 5 tended to show a curvilinear relationship. Therefore, a log transformation for the independent variable "RPI" was performed to linearize the regression relationship. Regression model $Y = B_o + B_1 \text{ Log}_{10}X$ was employed for RPI on the properties SG, MOR, and MOE and the fitted regression lines after back transformation (antilog) are shown in Figure 6. It was confirmed by plotting the residuals against the predicted (fitted) values that the log transformation was effective in linearizing the relationship (Neter et al., 1989). Coefficient of determination (R^2) values for RPI on SG, MOR, and MOE had increased approximately 4%, 4%, and 5%, respectively, after the log transformation.

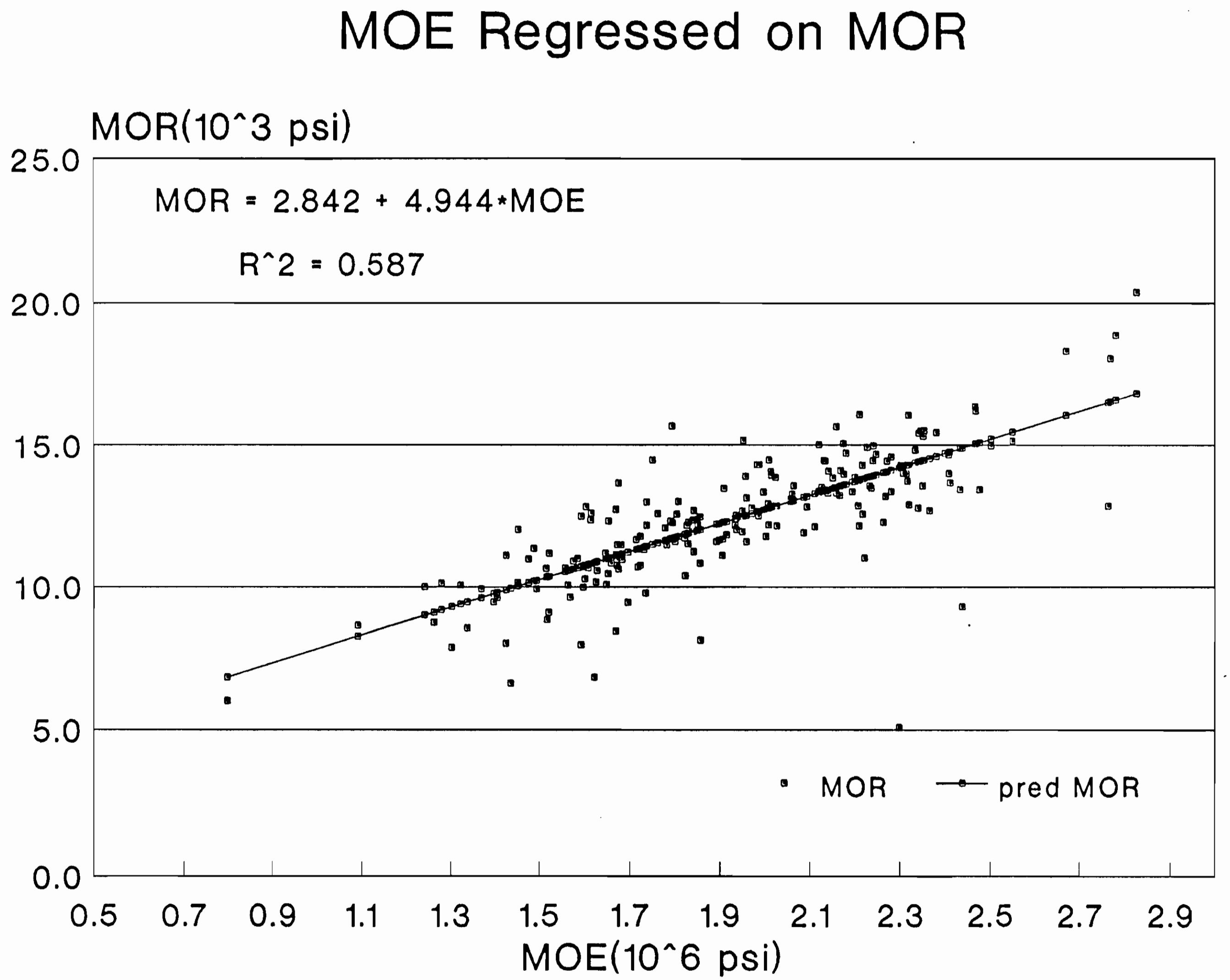


Figure 4. Relationship between MOE and MOR of the total population. Simple linear regression model $Y = B_o + B_1X$ was used.

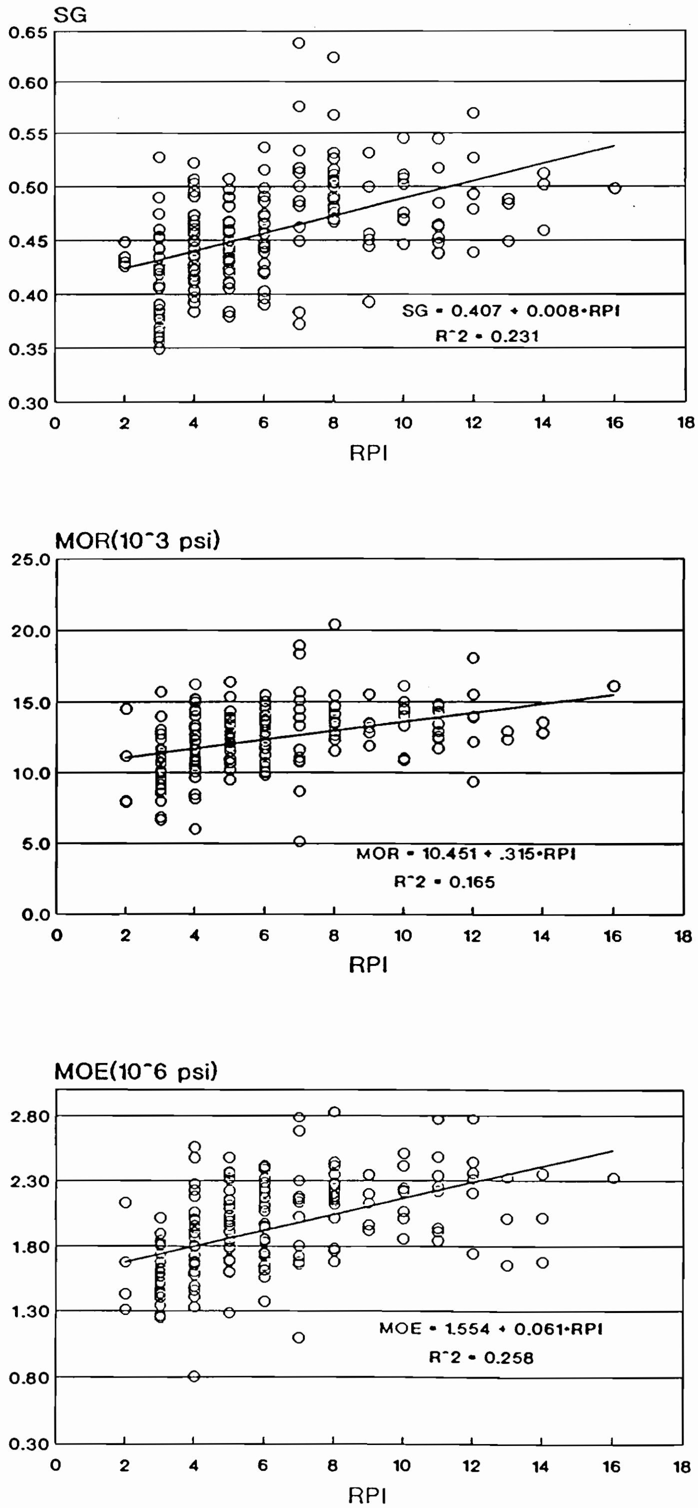


Figure 5. Linear regression function of RPI on SG, MOR, and MOE for the total population.

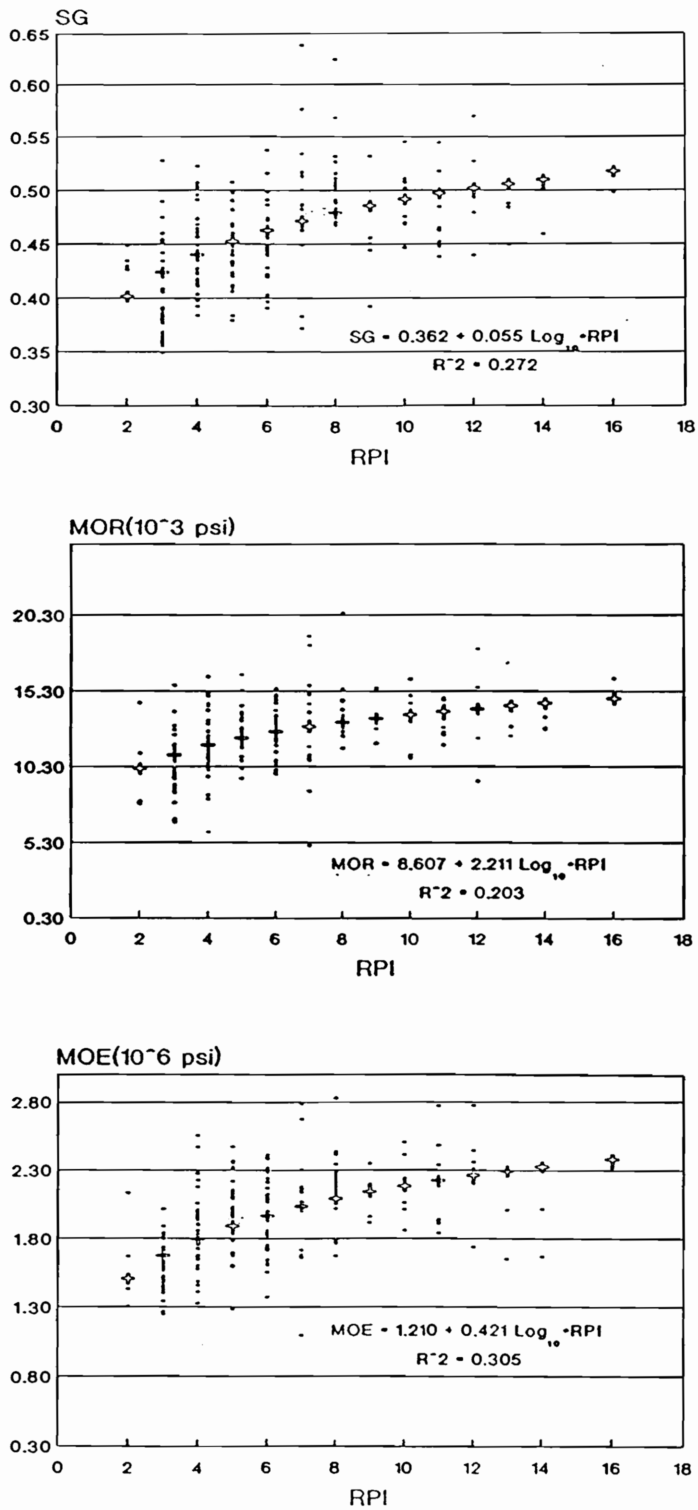


Figure 6. Linear regression function of RPI on SG, MOR, and MOE after log transformation (antilog) for the total population.

The poor correlation of RPI on SG and strength properties may have been influenced by combining all of the test data from the three wood zones. Therefore, analyses were made on data from each wood zone. Tables 4, 5, and 6 illustrate the various trends of SG and RPI regressed on the strength properties (MOR and MOE), and MOE on MOR.

SG showed a significant ($p = 0.0001$) positive correlation with MOR and MOE in all three wood zones (juvenile, transition, and mature); coefficients of determination ranged from 0.278 to 0.434 for SG versus MOR and from 0.245 to 0.310 for SG versus MOE (Table 4). For SG versus MOR and MOE, the juvenile wood zone had the lowest R^2 values. As previously mentioned, this may be the result of an added effect of large microfibril angles that are commonly found in juvenile wood (Erickson and Arima, 1978). The number of microfibrils present (i.e. cell wall thickness) and their orientation have a pronounced effect on the elastic properties of wood and have a direct effect on SG and strength properties (Dinwoodie, 1981 and Megraw, 1985). R^2 values for mature wood were higher, possibly showing that SG was having a much greater effect on MOR and MOE than the small fibril angle associated with mature wood fibers.

The relationships of RPI with strength properties were positive, but much lower than with SG (Table 5). For the most part RPI regressed on SG, MOR, and MOE did not show

Table 4. Relationship between specific gravity and strength properties by wood zones. Simple linear regression model $Y = B_o + B_1X$ was used.

Response Variable	Wood* Zone	B_o	B_1	P-value	R^2
MOR					
	JV	-0.034	25.85	0.0001	0.278
	TR	-0.218	27.52	0.0001	0.294
	MA	-0.293	28.46	0.0001	0.434
MOE					
	JV	0.322	3.227	0.0001	0.245
	TR	0.018	4.195	0.0001	0.310
	MA	0.080	4.175	0.0001	0.309

* In the wood zones; JV=juvenile wood, TR=transition wood, and MA=mature wood.

Table 5. Relationship between rings per inch and strength properties by wood zones. Simple linear regression model $Y = B_o + B_1X$ was used.

Response Variable	Wood* Zone	B_o	B_1	P-value	R^2
SG					
	JV	0.395	0.006	0.007	0.127
	TR	0.422	0.005	0.056	0.059
	MA	0.460	0.003	0.086	0.039
MOR					
	JV	10.06	0.209	0.108	0.048
	TR	11.33	0.166	0.258	0.021
	MA	12.56	0.119	0.123	0.031
MOE					
	JV	1.386	0.075	0.0001	0.358
	TR	1.682	0.042	0.0466	0.064
	MA	1.892	0.026	0.0475	0.052

* In the wood zones; JV=juvenile wood, TR=transition wood, and MA=mature wood.

Table 6. Relationship between Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) by wood zones. Simple linear regression model $Y = B_o + B_1X$ was used.

Response Variable	Wood* Zone	B_o	B_1	P-value	R^2
MOR					
	JV	2.570	4.937	0.0001	0.431
	TR	3.564	4.527	0.0001	0.451
	MA	4.406	4.330	0.0001	0.566

* In the wood zones; JV=juvenile wood, TR=transition wood, and MA=mature wood.

significance at the 0.05 probability level.

In Table 5 RPI versus SG showed a weak positive relationship only in the juvenile wood zone. Approximately 13% of the variation could be explained by RPI. The transition and mature wood zones showed no relationship. Apparently rate of growth has little or no effect on SG in these zones.

For RPI versus MOR no relationship was found in any of the three wood zones. Rate of growth alone seems to have had no effect on MOR.

RPI versus MOE showed a moderate (R^2 = 0.358) relationship in the juvenile wood zone, whereas, the transition and mature wood zones showed very weak relationships.

Rate of growth (RPI) versus SG and the strength properties (MOR and MOE) in each of the wood zones showed that by itself, it had very little or no effect on these properties. Other studies where test samples were not separated by individual wood zones showed similar results (McKimmy, 1966; Saucier and Ike, 1972; Bendsten, 1978; Barrett and Kellogg, 1984). This suggests that some trees may be rapidly grown without losing the characteristic qualities that are desirable by the wood product industry.

Table 6 shows the regression analysis for the relationship between MOE and MOR by wood zones. The coefficient of determination (R^2) was lowest (0.431) in the juvenile wood zone and highest (0.566) in the mature zone. The correlations for all the wood zones were significant at the 0.0001 probability level.

Further analysis was done to compare the slopes and intercepts of the regression lines for SG versus MOR and MOE, RPI versus SG and MOE, and MOE versus MOR in the juvenile (JV), transition (TR), and mature (MA) wood zones (Neter et al., 1989). The slopes and intercepts for RPI versus MOR were not analyzed because the P-value for the relationship (Table 5) showed that the slope was not significantly different from zero. In other words, the regression line was nearly horizontal.

In this analysis, 4 models were considered to represent the full and/or the reduced models. They were:

(1) $Y_i = B_{11}X_{11} + B_{12}X_{12} + B_{21}X_{21} + B_{22}X_{22} + B_{31}X_{31} + B_{32}X_{32} + \epsilon_i$

(2) $Y_i = B_{11}X_{11} + B_{21}X_{21} + B_{31}X_{31} + B^*_2X^*_2 + \epsilon_i$

(3) $Y_i = B^*_1X^*_1 + B_{12}X_{12} + B_{22}X_{22} + B_{32}X_{32} + \epsilon_i$

(4) $Y_i = B^*_1X^*_1 + B^*_2X^*_2 + \epsilon_i$

where:

X_{11} = "1" if wood zone is JV or "0" otherwise
X_{12} = "X" if wood zone is JV or "0" otherwise
X_{21} = "1" if wood zone is TR or "0" otherwise
X_{22} = "X" if wood zone is TR or "0" otherwise
X_{31} = "1" if wood zone is MA or "0" otherwise
X_{32} = "X" if wood zone is MA or "0" otherwise

X^*_1 = "1" for all wood zones
X^*_2 = "X" for all wood zones

These models were fitted by the method of least squares. The regression sum of squares and the error sum of squares were obtained. Models (1) and (2) were first used to test for common slopes (parallelism). Model (1) was regarded as the full model and model (2) as the reduced model. The following test statistic was used:

$$F^{*}=\frac{SSR_1-SSR_2}{p-m}\div\frac{SSE_1}{n-p}$$

where:

SSR_1 = regression sum of squares for full model
SSR_2 = regression sum of squares for reduced model
SSE_1 = error sum of squares for full model
p = number of independent variables in full model
m = number of independent variables in reduced model
n = number of data points in all observations

If the results from this test statistic showed that the slopes were not statistically different, model (2) would be used as the full model and model (4) as the reduced to test for common intercepts. Otherwise, model (1) would be used as the full model and model (3) as the reduced model.

In testing for parallelism of the slopes for SG versus MOR in the three wood zones (JV, TR, and MA), it was found that at the 0.05 probability level there were no differences. Also, it was found that when tested for common intercepts at the 0.05 probability level for the three wood zones, a difference was found between the juvenile and mature wood zone but no differences were found between the juvenile and transition or the transition and mature wood zones.

The results for SG versus MOE for common slopes and intercepts of the three wood zones were similar. At the 0.05 probability level the slopes were found to be no different between the three wood zones, but the intercepts showed differences between juvenile and transition as well as juvenile and mature wood zones. No difference was found between the transition and mature wood zones.

In testing for parallelism of the slopes and for common intercepts for RPI versus SG and MOE in all three of the wood zones (JV, TR, and MA), it was found that at the 0.05 probability level the slopes of the three regression lines for each property showed no difference, while intercepts were significantly different between the juvenile and the mature wood zones. However, there were no significant differences between the juvenile and transition wood zones, as well as between the transition and mature wood zones. This suggests that transition wood as defined in this study (rings 11-20) possesses characteristics of both juvenile and mature wood. Bendsten and Senft (1986) alluded to this type of scenario in a study of cottonwood and loblolly pine. They found that definite boundaries between the juvenile-mature wood zones were inconsistent from tree to tree. AbdelGadir and Krahmer (1992), also showed considerable variation in age boundaries for juvenile-mature wood zones in Douglas-fir.

Testing for parallelism and/or commonality of the slopes and intercepts for the regression of MOE on MOR for all wood zones (JV, TR, and MA) showed that the slopes in the three wood zones were not significantly different from each other. This suggested parallelism of these wood zones and that for every unit increase of MOE there existed an equal increase of MOR. Figure 7 shows the relationships of MOE and MOR for the three wood zones. Although the intercepts also showed no significant differences between each of wood zones, the juvenile and mature wood zones showed the closest possibility of any difference ($F^* = 2.84 < F[0.05, 1, 127] = 3.84$). Because it was found that there were no significant differences between any of the three wood zones for MOE regressed on MOR, it can be concluded that the same regression line may be used as a representative for each of these individual wood zones.

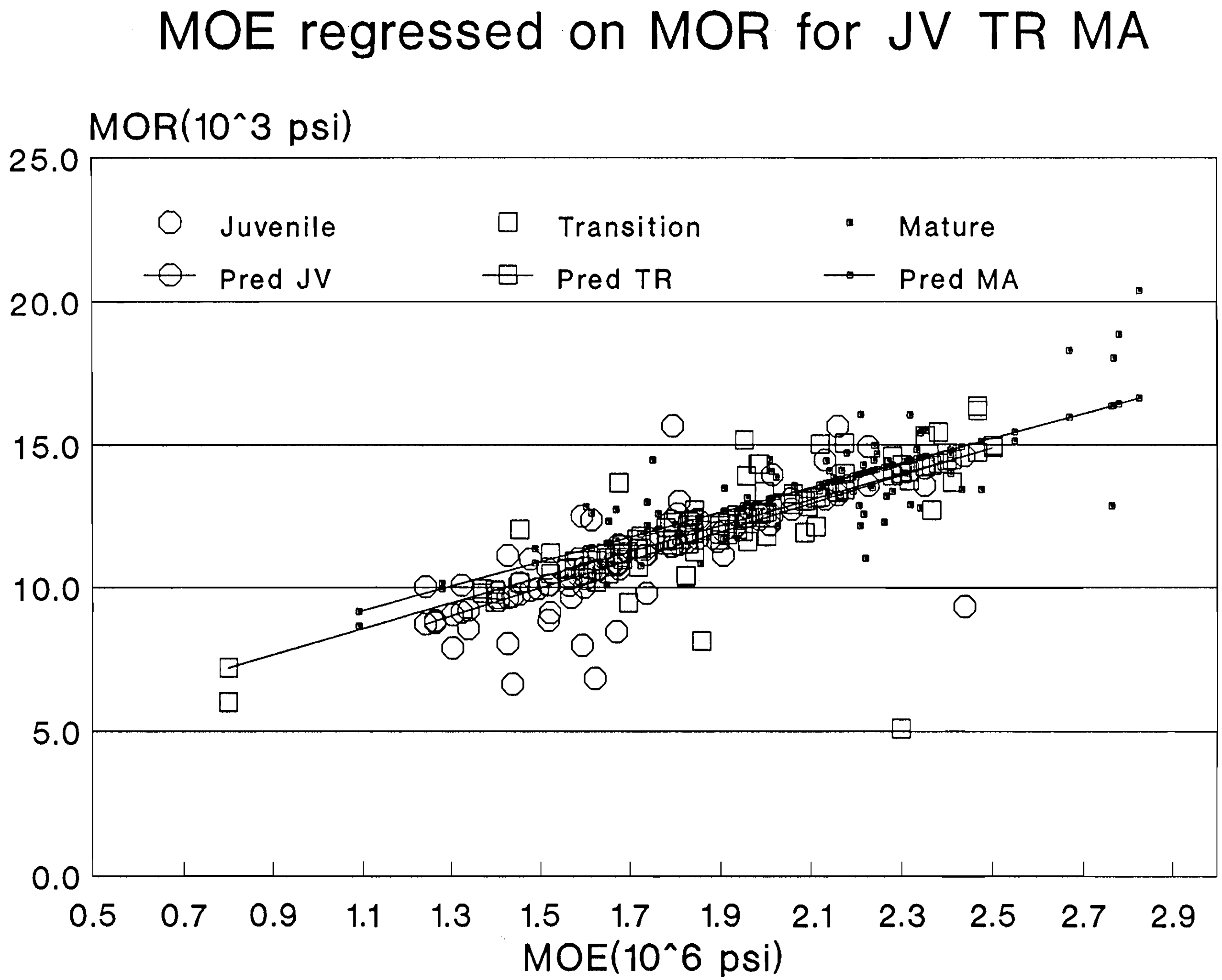


Figure 7. Relationship between MOE and MOR for juvenile, transition, and mature wood zones.

Relationship Between Small, Clear Specimens and Structural Lumber

A matrix was developed to analyze for correlations between strength property data measured on small, clear specimens at OSU and those measured on the structural lumber at WSU. Table 7 shows that properties did correlate. All of the correlations were significant at the 0.0001 probability level.

In general, the SG of the small, clear specimens correlated the highest with SG of the structural lumber (0.725) and lowest with TS (0.303). The relationship of RPI of the small, clear specimens was the best with MOEF (0.337) and poorest with TS (0.161) of the structural lumber. MOR of the small, clear specimens correlated the highest with MOEF (0.367) and lowest with TS (0.278) of the structural lumber, while MOE correlated the best with MOEF (0.607) and poorest with SG (0.317) of the structural lumber.

The best relationships were found to be between similar properties of the small, clear specimens and the structural lumber. For example, the specific gravities had the highest R^2 value (0.725). SG is measured on smaller, clear wood specimens cut from the test samples and therefore, specific gravities would be expected to be similar. The next highest R^2 value was for MOE of clear wood versus MOEF of the lumber. MOE measured in the flat-

Table 7. Coefficients of determination (R^2) for correlation of wood properties of small, clear wood specimens and structural lumber (determined by simple linear regression).

Clear wood Properties (OSU)	Properties of Lumber (WSU)			
	SG[1]	TS[2]	MOET[3]	MOEF[4]
SG	0.725	0.303	0.348	0.376
RPI	0.185	0.161	0.325	0.337
MOR	0.353	0.278	0.366	0.367
MOE	0.317	0.357	0.559	0.607

[1] SG = specific gravity
[2] TS = tensile strength
[3] MOET = modulus of elasticity in tension
[4] MOEF = modulus of elasticity in bending in flat-wise direction

wise direction on the structural lumber is a similar test to MOE measured in static bending on the clear wood specimens. Among strength property relationships, MOR of clear wood specimens had the lowest R^2 value when correlated with TS of the lumber. Although both test the wood to failure, the tests are different and the influence of knots in the structural lumber would be expected to greatly influence the relationship. RPI was consistent in being the weakest representative of a clear wood property related to a property of the structural lumber.

CONCLUSION

In this study the goal was to examine averages and correlations of wood quality and strength properties from juvenile, transition, and mature wood zones in Douglas-fir. Conclusions that can be drawn from this study are as follows:

* Average SG increased from juvenile to mature wood zones and was significantly different in each of the sampling zones (juvenile, transition, and mature wood).
* Growth rate decreased in all stands from juvenile through mature wood as trees aged.
* Averages for MOR and MOE increased with maturity of wood.
* Regression of SG on MOR and MOE showed low R^2 values for the juvenile wood zone which may be the result of interacting juvenile wood characteristics.
* Regression of RPI on SG, MOR, and MOE showed that by itself, rate of growth had very little or no effect.
* Slopes for SG versus MOR and MOE for the three wood zones were similar. Intercepts were different between the juvenile-mature wood zones for MOR and between the juvenile-transition and juvenile-mature wood zones for MOE.
* Slopes for RPI versus SG and MOE for the three wood zones were also found to be similar. Intercepts were different between the juvenile-mature wood zones, but not different between the juvenile-transition and transition-mature wood

zones.

* MOE regressed on MOR for the three wood zones showed no differences between any of the slopes and intercepts, although the R^2 was highest for mature wood samples.

* Correlations between the small, clear wood specimens and structural lumber were highest when similar properties were related.

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