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Moisture Content and the Properties of Lodgepole Pine Logs in Bending and Compression Parallel to the Grain

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Abstract

This study evaluates the effect of moisture content on the properties of 127- to 152.4-mm (5- to 6-in.-) diameter lodgepole pine (*Pinus contorta* Engelm.) logs that were tested either in bending or in compression parallel to the grain. Lodgepole pine logs were obtained from a dense stand near Seeley Lake, Montana, and sorted into four piles of 30 logs each. Two groups were tested in bending, one green and one dry, and two in compression parallel to the grain. The results of the study provide conservative procedures for estimating compression strength for green logs based on the assigned bending strength and show that modulus of elasticity determined by transverse vibration (Etv) on green logs is a conservative estimate of Etv for dry logs. Experimental problems with conditioning the logs tested in bending produced inconsistencies in some property relationships. A more comprehensive study, already in progress, should help resolve the questions raised by these inconsistencies.

Keywords: modulus of elasticity, modulus of rupture, ultimate compression stress parallel to the grain, lodgepole pine, logs, moisture content

Cover photo: Cable suspension bridge in Missoula, Montana, made of mechanically graded lodgepole pine (Green and others 2005a)

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SI conversion

Inch–pound unit	Multiply by	SI unit
inch (in.)	25.4	millimeter (mm)
foot	0.3048	meter
lb/in^2	0.45366.894	kilopascal (kPa)

$T_{°C} = (T_{°F} - 32)/1.8$

Contents

Page

Executive Summary

Background

Recent studies have developed technical procedures for mechanically grading small-diameter logs for use in engineered roundwood structures such as long-span trusses and suspension bridges. Dry logs are preferable for such structures to prevent problems in joint design and structural warping caused by twisting as the logs dry in place. In the West, the dry climate and the availability of logs from dead trees means that most structures are constructed using dry logs. There is some interest in using the mechanical grading system with green logs. Currently there are insufficient data on the effect of moisture content (MC) on log properties to make this adaptation. Before considering the need for a more extensive study of the effect of moisture content on log properties, we felt that a limited-scope study might prove useful in making conservative judgments about how property relationships used in mechanical grading are affected by moisture content.

Objectives

This study evaluates the effect of moisture content on the properties of 127- to 152.4-mm (5- to 6-in.-) diameter lodgepole pine (*Pinus contorta* Engelm.) logs that are tested either in bending or in compression parallel to the grain. The study is limited to two moisture content levels.

Procedures

We obtained 120 green lodgepole pine logs from a producer in Seeley Lake, Montana. The logs had been cut from trees growing within a few miles of the post office. The logs were debarked and sorted into four groups based on modulus of elasticity determined in transverse vibration (Etv). The logs generally averaged from about 139.7- to 165.1-mm (5.5- to 6.5-in.) diameter. Two groups of logs were shipped to the University of Idaho (UID) in Moscow, Idaho, and two to the Forest Products Laboratory (FPL) in Madison, Wisconsin. At UID, one group of 30 logs was tested green in 1/3-point bending following procedures in ASTM D 198. The other group was placed in a conditioning room at approximately 70°F and 65% relative humidity (RH). Following conditioning, the dry logs were also tested in bending. At FPL, one group of logs was tested green in short column compression by ASTM D 198 procedures and the other group conditioned at approximately 21°C (70°F) and 65% RH. The dry logs were also then tested by D 198 procedures.

Results

Bending

The average moisture content of the dry logs was 17.5%, higher than the anticipated target of 12%. The modulus of rupture (MOR) of the dry logs was only about 3% higher than that of the green logs. If projected to 12% MC, the increase in MOR would be about 6%. The modulus of elasticity in static bending (MOE) increased about 14% when tested at 17.5% MC and would be projected to increase about 28% if tested at 12% MC. The Etv of the dry logs was only about 2% higher than that of the green logs. The difference between the change in property with change in modulus for Etv compared to MOE was unexpected because we had assumed that the change would be similar for the two methods of measurement.

Compression

The average moisture content of the dry logs tested in compression was 13%. The ultimate compression stress parallel to the grain (UCS) of the dry logs was 67% higher than that of the green logs. This is consistent with other studies that indicated that compression strength is more sensitive than bending strength to change in moisture content.

Property Relationships

As expected, the slope of the MOR–MOE relationship was lower for green logs than for dry logs. We had insufficient information to draw conclusions about the effect of moisture content on the intercept of the regression equations. The ratio of UCS to MOR for green logs is relatively constant at about 0.44. That the UCS–MOR ratio is relatively constant with change in MOE for green logs is consistent with results obtained with dimension lumber. The relatively small number of compression samples detracts from the reliability of the estimates. However, the results are comparable with results obtained with a species-independent UCS–MOR relationship obtained with 186 small-diameter Douglas-fir (*Pseudostsuga menziesii* Mirb.) and ponderosa pine logs tested dry to gain confidence in obtaining a conservative estimate of the relationship.

Conclusions

Results from the large data set on small-diameter Douglas-fir and ponderosa pine logs indicate that green Etv values would provide a conservative estimate of dry Etv. Such an estimate might be very conservative for low Etv values obtained on green logs.

The increase in MOR of lodgepole pine with change in moisture content seems low when compared with historical studies. We also did not expect that the change in Etv with change in moisture content would be different than the change in static MOE. These inconsistencies may be due to the experimental problems related to the failure to achieve the target moisture content. A more comprehensive study, already in progress, will clear up these inconsistencies.

The USC–MOR relationship previously developed from data on dry Douglas-fir and ponderosa pine logs less than 127-mm (5-in.) diameter would provide a conservative estimate for 127-mm (5-in.) and larger green logs of lodgepole pine.

Moisture Content and the Properties of Lodgepole Pine Logs in Bending and Compression Parallel to the Grain

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Introduction

Recent studies have established the technical basis for the mechanical grading of round timbers from both large-diameter and small-diameter logs (Gorman and others, in progress; Green and others 2004). The log home industry and producers of engineered roundwood structures from small-diameter logs (Green and others 2005a, 2005b) are interested in using this system. For both applications, it is desirable to use dry logs to reduce shipping weight and to minimize performance problems with log twisting and fastener performance. Therefore, the proposed mechanical grading system is currently predicated on the use of dry logs.

There has been some interest in adapting the mechanical grading system developed for dry logs for use with green logs. However, the property relationships that are the basis for mechanical grading may change as a function of moisture content (Green and Kretschmann 1991). Currently there are insufficient research data on the effect of moisture content on the properties of logs to make this adaptation. The recommendations given in ASTM D 245 (ASTM 2005) for structural timbers also provide no useful guidance for adjustment of log properties for change in moisture content because they are predicated on possible exposure of structural timbers to repeated wetting and drying cycles (Green and Evans 2001). For lumber greater than 102-mm (4-in.) thick, ASTM D 245 states that ultimate compression stress (UCS) may be increased 10% for drying and modulus of elasticity (MOE) by 2%. Adjustments using the clear wood dry–green ratios of D 2555 are only required if the ratio for a given species and property are less than these increases. Before considering the need for a more comprehensive study of moisture content effects on log properties, we felt that a limited scope study might prove useful in making conservative judgments about how property relationships are affected by moisture content.

This study evaluates the effect of moisture content on the properties of 152.4 mm (6-in.-) diameter tapered lodgepole pine logs that are tested either in bending or in compression parallel to the grain. The study is limited to two moisture content levels.

Background

Traditionally, moisture content (MC) adjustment procedures adopted by engineering standards are based on data for a limited number of species, and the results are then applied to a wide range of species. The exponential formula for adjusting clearwood properties given in the *Wood Handbook* (FPL 1999) is perhaps the most extensively verified procedure. This procedure is based on data for five softwood and four hardwood species (Wilson 1932). However, this formula has never been used in ASTM D 245 as a primary basis for adjusting the strength of lumber in bending or compression parallel to the grain, or modulus of elasticity, for change in moisture content (Green and Evans 2001). The current model given in ASTM D 1990 for adjusting flexural properties of lumber for change in moisture content is based on only two species (Douglas-fir and the commercial grouping Southern Pine), and the model for compression strength parallel to the grain is based only on Douglas-fir (Green and Evans 1989). However, analysis of clear wood data suggests that the bending strength of dimension lumber of most softwood species can probably be demonstrated by one type of model (Green and others 1991), with the MOR of a few species being less sensitive than the rest to change in moisture content (Fig. 1). The general applicability of the ASTM D 1990 model for modulus of rupture (MOR) has recently been demonstrated for five additional species (Green and Evans, in progress). Thus, it seems reasonable to assume that data developed for one species may be useful in judging moisture content–property relationships for other species.

Moisture content–property adjustments procedures used to establish properties for stress-graded members used in log buildings (tables 1 and 2 of ASTM D 3957, 2005) allow a 10% increase in allowable compression strength parallel to the grain for dry logs. Timber Products Inspection, Inc. (Conyers, Georgia), developed a nationwide grading and gradestamping program for log home manufacturers and does not take any seasoning increase in deriving allowable properties. This is the same as specified in D 245 (ASTM 2005) for dry rectangular timbers. Also,

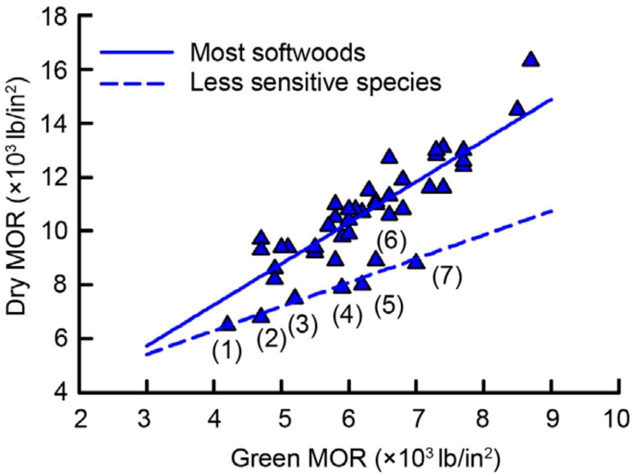

Figure 1—Relationship between modulus of rupture (MOR) for small clear specimens at 12% moisture content and green (Green and others 1991). (1) northern white cedar (*Thuja occidnetalis* L.), (2) atlantic white cedar (*Chamaecyparis nootkatensis* (D.Don.)), (3) western redcedar (*Thuja plicata* Donn. ex D.Don.), (4) redwood (*Sequoia sempervirens* (D. Don)), (5) incense cedar (*Calocedrus decurrens* (Torr.)), (6) eastern hemlock (*Tsuga canadensis*), (7) eastern redcedar (*Juniperus virginiana* L.).

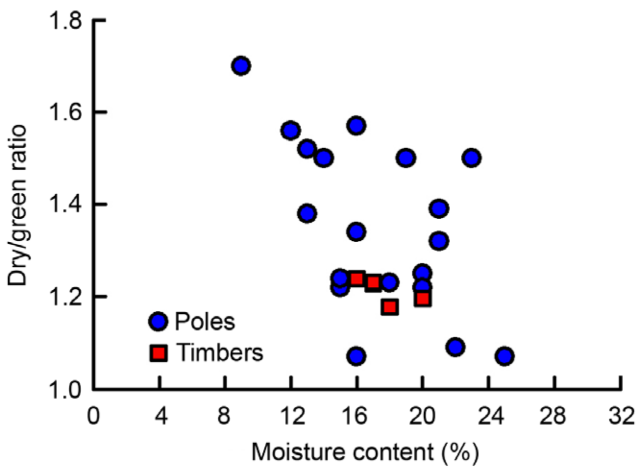

Figure 2. Effect of moisture content on the modulus of rupture of seasoned timbers and partially seasoned poles (Green and Evans 2001; Wood and Markwardt 1965; Wilson and others 1930).

as in D 245, no seasoning increase is provided for allowable bending strength. Unlike D 245, D 3957 does not provide a 2% seasoning increase for modulus of elasticity. However, from a review of the history of seasoning factors in D 245 (Green and Evans 2001), it is clear that considerations related to field exposure conditions, especially the possibility of direct and repeated exposure to rain, influenced these provisions.[1] Thus, these standards are not useful in assessing adjustments in property estimates during mechanical grading.

For carefully seasoned timbers, mean MOE increases about 12% when dried to about 18% MC, whereas the increase is about 21% for mean MOR (Green and Evans 2001). The limited data for which non-parametric 5th percentile estimates may be made indicate that 5th percentile MOR values increases less than the mean value, with an average increase of about 12% when comparing dry to green members.

For round construction poles, ASTM D 3200 and D 2899 also make no provisions for deriving allowable properties for dry members. The history of assigning allowable properties to wooden poles has been recently documented by Wolfe and Kluge (2005). Wood and Markwardt (1965) discussed data from several historical studies on the effect of moisture content on pole properties. Their data on tamarack (*Larix laricina* K. Koch) is for poles of about 95.25-mm (3.75-in.) diameter and shortleaf pine (*P. echinata* Mill.) poles 114.3- to 177.8-mm (4.5- to 7-in.) diameter (Wilson and others 1930). The lodgepole pine poles were 228.6-mm (9-in.) butt diameter. These poles were tested in bending using 1/3-point loading and a span-to-depth ratio of approximately 19:1. Figure 2 shows data presented by Wood and Markwardt (1965) on the effect of moisture content on the MOR of partially seasoned poles. Individual data points were estimated by carefully scaling values given in plots in Wilson and others (1930) and Wood and Markwardt (1965). Wood and Markwardt recommended that green bending strength be increased by 10% when the poles are used at moisture contents of 20% or less. Given the small sample size and the large scatter (probably accentuated by the moisture gradients), this would appear to be a conservative recommendation. The dry–green ratios for the mean MOR values on slowly dried rectangular timbers given in Table 1 are also shown in Figure 2. Despite considerable scatter, there is an apparent trend of increasing strength with decreasing moisture content, and the data for the mean values for the timbers is within the range of the individual data points for partially seasoned poles.

Wilson and others (1930) also present some data on the strength of partially seasoned shortleaf pine logs in compression parallel to the grain (Fig. 3). As would be expected, compression strength is more sensitive to change in moisture content than is bending strength. At 20% MC, the predicted dry–green ratio is 1.14 and at 18% it is 1.34.

Procedures

The objective of the log sorting procedure was to obtain four groups of green logs with 30 logs per group that had about the same range in log quality. The Etv and visual assessment of growth characteristics were used as indicators of log quality. The logs used in this study were harvested in late November 2003 from a dense stand of lodgepole pine growing within about 2 miles of the west shore of Seeley Lake, Montana. Within 2 weeks of harvest, the logs were cut into 3.66 m- (12-ft-) long sections and peeled with a mechanical debarker at a local post and pole company. Some individual

[1]A discussion of the evolution of adjustment procedures for compression stress perpendicular to the grain and shear strength, as well as some sources of data, is given in Green and Evans (2001).

trees yielded more than one log, giving us a sample of 160 logs. However, it was not possible to tell the trees from which individual logs were sawn. The peeled logs were stacked and stored in an unheated building prior to our visit. Ambient day time temperatures ranged from 18° to 28°F during this period. The following week we determined the Etv (Murphy, in progress) (Fig. 4). All logs were numbered as they were nondestructively tested. Logs with defects that prevented them from meeting structural visual grading requirements were excluded from the sample (TP 1995). Following determination of Etv (E-rating), the log numbers were ranked by decreasing Etv. A few logs with exceedingly high or low MOE were also excluded from consideration, bringing the number of available logs to 120. We excluded logs with extreme MOEs to assure a more uniform distribution of MOE values between the four groups. Groups of four logs were then selected sequentially by Etv and the logs randomly assigned to one of four test groups. Two of the groups were assigned for testing in bending at the University of Idaho (UID) and two for testing in compression at Forest Products Laboratory (FPL). At each institution, one group was to be tested green and the other conditioned to a target moisture content of about 12%.

At UID, the logs were brought to room temperature and a transverse vibration determined on all logs using the Metriguard model 340 system (Metriguard, Inc., Pullman, Washington). Because the model 340 uses a load cell at only one end of the log, we recorded the vibration frequency independently for each end of the log and also weighed each log. The Etv value was calculated by procedures suggested by Murphy (2000). Static bending tests were conducted in third-point bending with a span-to-depth ratio of approximately 21:1 (ASTM D 198). The logs were loaded in 1/3-point bending with a span-to-depth ratio of approximately 21:1. The rate of cross-head movement was 25.4 mm (1 in.) per minute. Deflection at midspan was obtained using a linear variable differential transducer. Special fixtures were fabricated to cradle the ends of the logs and to impose the loads (Fig. 5). Immediately after testing to failure, a 25.4-mm (1-in.) sample was sawn from near the failure for determination of moisture content and specific gravity (ASTM D 4442 and D 2395). A disk was also cut from the middle of the log and sent to FPL to be scanned. The percentage of the disk included in the first 20 years of growth was considered the percentage of juvenile wood.

At FPL, the logs were brought to room temperature and a transverse vibration obtained with the same prototype machine used at Seeley Lake (Fig. 4). The logs to be tested dry were stickered, stacked, and conditioned for about 12 months at 68°F and 68% RH. Logs to be tested green were dead-piled outdoors, where the ambient temperature never exceeded freezing. About 24 h before testing, a log was brought into the laboratory to warm to room temperature. Tests in compression parallel to the grain followed procedures given in ASTM D 198 (ASTM 2004), with lateral supports provided at 305 mm (12 in.) from the ends of the log and at 610-mm (24-in.) spacing in the middle of the log. To facilitate handling, each full-length log was cut in half and each half tested. The average length of the logs at test was 2.5 m (98 in.). The logs were loaded at a rate of cross-head movement of approximately 2.54 mm (0.1 in.) for a time to failure of 5 to 12 min. Following testing, a 25.4-mm- (1-in.-) thick disk was cut from near failure of each log for determining oven-dry moisture content and specific gravity (ASTM D 4442 and D 2395). Disks were also scanned to determine the percentage of juvenile wood.

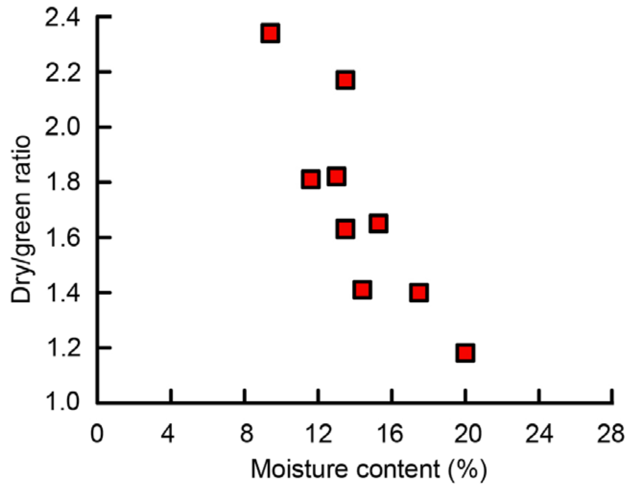

Figure 3. Effect of moisture content on the compression strength, parallel to the grain, of partially seasoned poles (adapted from Wilson and others 1930).

Figure 4. Determination of modulus of elasticity in transverse vibration of green lodgepole pine logs at Seeley Lake, Montana, using a prototype machine (photo courtesy of Karen Kovatch, the Intermountain Roundwood Association).

Results

Bending

Current Study

The green logs had an average diameter of 139.7 mm (5.5 in.) in the middle of the span, and varied from

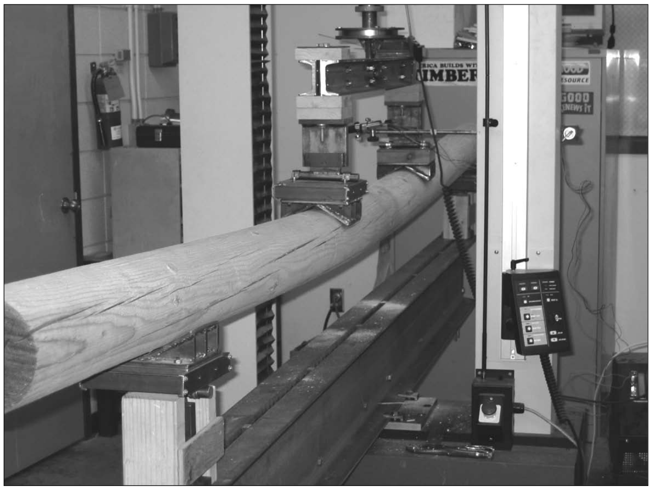

Figure 5. Flexural testing at the University of Idaho, Moscow.

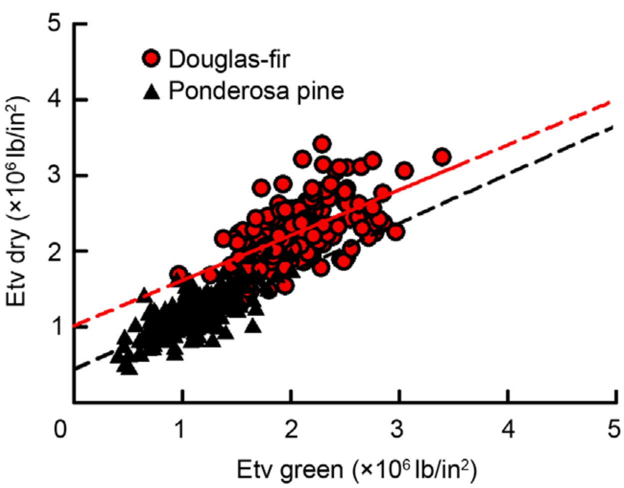

Figure 6. Modulus of elasticity by transverse vibration (Etv) for green logs with taper versus tapered logs at 14% moisture content.

123.95 to 160.78 mm (4-7/8 to 6-1/3 in.). The dry logs averaged 137.2 mm (5.4 in.) diameter, with a similar range. For all the logs sampled, the percentage of juvenile wood averaged 46%, with only two logs having more than 75% juvenile wood. Thus, most of the logs tested could be characterized as having a significant proportion of mature wood in the outer portion of the cross section.

The experimental results are summarized in Table 2. There was no indication that the green logs dried out prior to testing. The moisture content of the dry logs was 17.5%, which is considerably greater than the target of 12%. The range of the moisture content of the disks was from 16.8% to 18.4%. Thus, all logs appear to have reached nearly the same equilibrium moisture content. Unfortunately, moisture contents were not obtained for the inner and outer portions of the logs to determine if a moisture gradient existed. At present there is no clear explanation why the logs failed to achieve the target moisture content of the conditioning room.

At 17.5% MC, there is only a slight increase in MOR. The mean dry–green ratio of 1.031 would be near the bottom of the historical data for heavy timbers and poles plotted in Figure 2. The dry–green ratio for dimension lumber by ASTM D1990 would be expected to be 1.19 if dried to 17.5% MC[2]. Thus, the observed increase in MOR for lodgepole pine logs is much less than that predicted for lodgepole pine lumber.

For static MOE, the dry–green ratio based on the mean values from each data set is 1.144 (Table 2). This ratio is similar to that of historical data for round timbers (Table 1). It is also similar to the value of 1.10 predicted for lumber dried to 17.5% MC by ASTM D1990. If projected linearly to 12% MC, the MOE of our logs would have a dry–green ratio of 1.28, compared to a ratio of 1.20 predicted by D 1990 for lumber dried to 12% MC. The dry–green ratio to 12% MC is 1.24 for clear wood as given in ASTM D2555. Given that we only have 30 logs per moisture level in this study, we conclude that the increase in static MOE for lodgepole pine logs is similar to that for lumber and for clear wood.

The mean dry–green ratio to 17.5% MC for Etv is only 1.023, compared with the ratio of 1.14 for static MOE. This was an unexpected finding because we anticipated a similar dry–green ratio for both static and dynamic measurements. This will be discussed further below.

Comparison with More Recent Results

More recent studies have been conducted on the properties of small-diameter logs that could help confirm trends observed in the current study. Green and others (in preparation) obtained Etv values on 395 76.2- to 177.8-mm (3- to 7-in.-) diameter Douglas-fir and ponderosa pine logs after equilibration to a moisture content of about 14%. Etv values while still green were also obtained for these logs, so it is possible to obtain a dry–green ratio for each log. The distribution of the dry–green ratios is given in Table 3. The mean of the dry–green ratios for the ponderosa pine logs is 1.08 and for Douglas-fir logs, 1.10. A plot of dry versus green Etv values shows that the relationships for the two species is almost parallel, but with different intercepts (Fig. 6).

For Douglas-fir,

$$\text{Etv dry} = 1.017 + 0.596 \text{ Etv green}, \qquad r^2 = 0.33 \quad (1)$$

For ponderosa pine,

$$\text{Etv dry} = 0.441 + 0.643 \text{ Etv green}, \qquad r^2 = 0.51 \quad (2)$$

Both equations indicate that it would be conservative to use a green Etv measurement as an estimate of the dry value. For future reference, the relationship for the combined data set is

$$\text{Etv dry} = 0.166 + 0.965 \text{ Etv green}, \qquad r^2 = 0.80 \quad (3)$$

[2]Moisture content changes for dimension lumber for ASTM D 1990 may be estimated on line at http://www1.fpl.fs.fed.us/vicki/mcadjust.html

Table 1. Historical data on the effect of moisture content on the flexural properties of slowly dried timbers

Species, size (in.)	Condition	Sample size	Moisture content (%)	Mean MOE ($\times 10^6$ lb/in^2)	MOR ($\times 10^3$ lb/in^2) Mean	MOR ($\times 10^3$ lb/in^2) 5th
Sitka spruce 8 by 16	Green	20	34	1.243	4.326	3.48
	Dry	20	17	1.401	5.311	3.77
	Dry/Green	—	—	1.127	1.228	1.08
Western hemlock 8 by 16	Green	28	42	1.358	4.879	3.74
	Dry	29	18	1.521	5.747	4.13
	Dry/Green	—	—	1.120	1.178	1.10
Douglas-fir 8 by 16	Green	10	31	1.437	5.440	—
	Dry	10	16	1.621	6.740	—
	Dry/Green	—	—	1.128	1.239	—
Douglas-fir 6 by 12	Green	26	35	1.625	6.127	4.89
	Dry	28	17	1.767	7.542	5.75
	Dry/Green	—	—	1.087	1.231	1.76
Southern Pine 8 by 16	Green	12	51	1.450	5.620	—
	Dry	12	20	1.688	6.721	—
	Dry/Green	—	—	1.164	1.196	—

[a]Adapted from information presented in Green and Evans, 2001, Appendix B

Table 2. Properties of small-diameter lodgepole pine logs tested in bending and in compression parallel to the grain

Variable	Characteristic	Bending Green	Bending Dry	Compression Green	Compression Dry	Dry–green ratio Bending	Dry–green ratio Compression
Sample size	All logs	30	30	30	30	–	–
Moisture content (%)	Mean	95.8	17.5	54.3	13.1	–	–
Specific gravity[a]	Mean	0.40	0.44	0.40	0.43	–	–
Etv ($\times 10^6$ lb/in^2)	Mean	1.410	1.442	–	–	1.023	–
	Standard deviation	0.207	0.390	–	–	–	–
MOE ($\times 10^6$ lb/in^2)	Mean	1.392	1.593	–	–	1.144	–
	Standard deviation	0.249	0.281	–	–	–	–
Strength ($\times 10^3$ lb/in^2)	Mean	6.056	6.245	2.691	4.498	1.031	1.671
	Standard deviation	1.087	1.377	0.536	0.766	–	–
	5th	4.285	4.081	1.867	3.438	0.952	1.841
	25th	5.142	5.134	2.240	3.807	0.998	1.700
	50th	6.055	6.015	2.624	4.531	0.993	1.727
	75th	7.020	7.709	3.088	5.624	1.098	1.821
	95th	7.990	8.660	3.678	5.718	1.080	1.555

[a]Oven-dry weight and volume

Because MOE and Etv values were not taken on the same lodgepole pine logs in the current study in both the green and dry states, it is not possible to produce a similar plot for lodgepole pine. Instead dry–green ratios for MOE and Etv from the current study are plotted in Figure 7 based on mean values. For lumber, D 1990 would predict a linear relationship between green and dry MOE with decreasing moisture content. Therefore, lines are drawn between the green and dry moisture content levels to aid in visual comparisons. The trends for the dry–green ratio of Etv for the lodgepole pine logs are slightly below those for Douglas-fir and ponderosa pine. Given the much smaller sample size for the lodgepole pine in the current study and relatively higher moisture content level, the three ratios are reasonably close. However, the dry–green ratio trends for Etv are obviously lower than those we found for the static MOE of lodgepole pine (Fig. 7).

Larson and others (2004a) have reported on the effect of moisture content on static MOE as a part of a study on the properties of 101.6- to 203.2-mm (4- to 8-in.-) diameter

Table 3. Effect of moisture content on the modulus of elasticity in transverse vibration of small-diameter logs with taper

	Dry–green ratio	
Characteristic	Ponderosa pine	Douglas-fir
Sample size	202	193
Moisture content (%)	13.7	13.6
Distribution of ratio		
Mean	1.080	1.100
5th	0.755	0.804
10th	0.813	0.873
25th	0.926	0.986
50th	1.042	1.093
75th	1.207	1.185
90th	1.382	1.324
95th	1.496	1.449

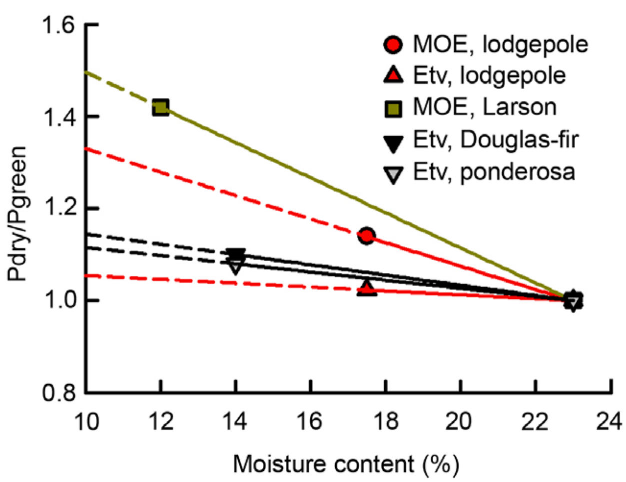

Figure 7. Dry–green ratio of modulus of elasticity (MOE) values for tapered small-diameter logs. pgreen, properties of green wood; pdry, properties of dry wood. (Larsen and others, 2004a)

ponderosa pine logs tested in bending. In the moisture content–property phase of their study, they first obtained a static MOE on 31 tapered logs that were simply supported with a span to depth ratio of at least 28:1. For each log, they placed three successively higher dead loads in the center of the span. Three green MOE values were calculated for each log and the values averaged. The logs were then air-dried to a target moisture content of 12% and tested as simply supported beams with a center-span load using a portable testing machine. The moisture content of the logs was reported to be generally less than 12%, and the dry MOEs were therefore adjusted to 12% MC using an equation given in ASTM D 2915-98 for dimension lumber. The moisture content adjustment procedure used by Larson and others (2004a) has subsequently been deleted from ASTM D 2915 (Green and Evans 2001). However, the equation would have produced adjustments in MOE very similar to those currently given in ASTM D 1990 for lumber. The dry–green ratio reported by Larson and others was also plotted in Figure 7. Although the ratio is higher than that we found for static MOE of lodgepole pine, both static estimates are much higher than those for Etv. Thus, we are led to the tentative conclusion that static MOE of small-diameter logs is more sensitive to change in moisture content than is Etv.

Ranta-Maunus and others (1998) report the results of a large European project to evaluate the use of small-diameter 76.2- to 152.4-mm (3- to 6-in.) logs in construction. Based on results for a data set that combined spruce (*Picea* spp.) and fir (*Abies* spp.) logs from Finland and logs from the United Kingdom, they concluded that MOE and MOR were not dependent upon moisture content. However, from the final project report (Ranta-Maunus 1999), it would appear that the ranges of log quality and moisture content between the logs from the two sources may have been significantly different. Boren (2000) conducted a similar analysis on the spruce and pine data for the logs only from Finland and concluded that there was a significant interaction between age and moisture content on both MOR and MOE. While tabulated data was not presented, plots of MOE versus moisture content indicate that MOE would increase at least 30% in drying from about 20% to 12% MC. This increase is similar to that we projected for the MOE of lodgepole pine and larger than that we found for Etv.

As was done in Figure 7, we can project the change in MOR for our lodgepole pine logs that might have occurred if the logs had been dried to 12% MC. The projected dry–green ratio would be 10.062 (Fig. 8). This is much less that the ratio of 1.34 that we would project from Boren's plots. It is also less than the dry–green ratio of 1.70 given for clear ponderosa pine in ASTM D 2555 for drying to 12% MC. Larsen and others (2004a) did not break green logs in bending, so it is not possible to make comparisons with that study.

Ultimate Compression Stress Parallel to the Grain (UCS)

Table 2 presents a summary of the results for the tapered logs tested in compression parallel to the grain. The log sizes are very similar to those discussed above for bending. The average moisture content of these logs was 13.1%, a value close to the target moisture content of 12%. As with the logs tested in bending, most of the logs contained a predominance of mature wood. Although failures in the compression tests sometimes occurred near the end of the specimens, the predominance of the failures was not at the ends. Likewise, the failure location could often be associated with a knot, but there was not usually a clear indication that the failure initiated at the knot. With our limited sample sizes, it is not possible to make sweeping conclusions about the effect of defects on compression strength. This will be addressed in a future paper that involved more extensive sample sizes (Green and others, in progress).

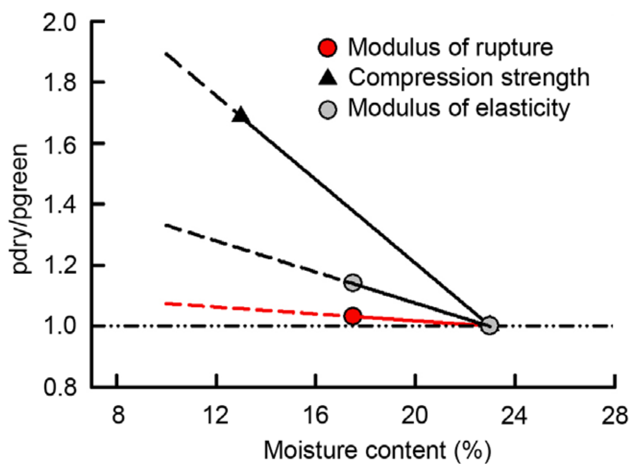

Figure 8. Prediction of dry–green ratio for small-diameter lodgepole pine (*Pinus contorta*) logs. pgreen, properties of green wood; pdry, properties of dry wood.

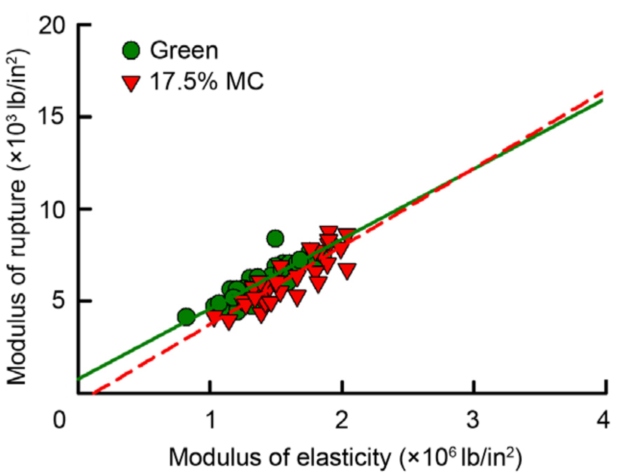

Figure 9. Relationship between modulus of rupture and modulus of elasticity for small-diameter lodgepole pine (*Pinus contorta*) logs at two moisture content levels.

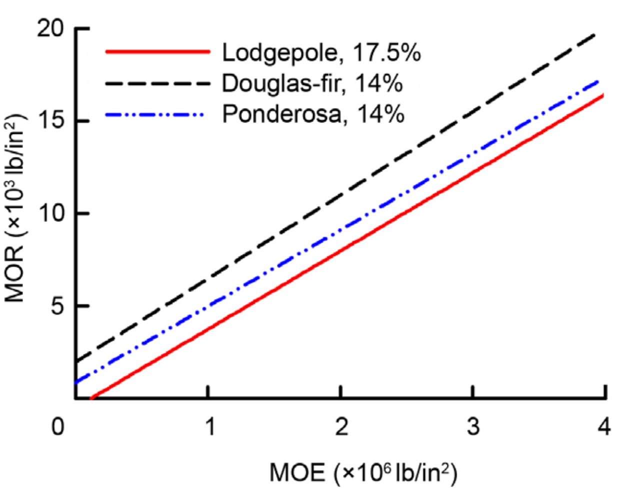

Figure 10. Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for small-diameter logs (Table 4).

The mean UCS value is 67% higher at 13% MC than that measured green and the median value 73% higher. These results are similar to that reported by Wilson and others (1930) for partially seasoned poles, Figure 3. They are also similar to the 90% increases we would project from the plots of Boren (2000) for the compression strength of small diameter pine and spruce thinnings. The increase we found is greater than the 44% increase predicted for the UCS of lumber by D 1990 but less than the 2.06 dry–green for small clear specimens of lodgepole pine given in ASTM D 2555.

Larson and others (2004b) also report some information on moisture content effects on UCS for small-diameter ponderosa pine logs. Their logs were tested in short-column compression and were cut from the ends of the same logs as those reported in Larson and others (2004a). Sixty nine specimens were cut from tapered logs tested green, and a similar number of logs dowelled to a constant diameter and tested dry. They had already concluded that there was no significant difference between the UCS of tapered logs compared with those of logs machined to a constant diameter. Based on this conclusion, a dry–green ratio for UCS of 1.95 was reported. This is higher than the dry–green ratio of 1.67 we found for lodgepole pine. Part of this difference could be due to species differences (The clear-wood ratio for the UCS of ponderosa pine is 2.17 and that for lodgepole is 2.06) and part could be because the old D 2915 MC adjustment procedure for lumber was also used to adjust the ponderosa pine UCS values to 12%. The difference between the UCS–MC adjustment in D 2915-98 and that of D 1990, now referenced in D 2915, is shown in figure 12, page 51, of Green and Evans (1989). However both studies confirm that moisture content has a much bigger effect on the UCS than it does on MOR.

Property Relationships

Regression Relationships

Table 4 shows the relationships between MOE, Etv, and MOR found for lodgepole pine, as well as similar relationships for dry Douglas-fir and ponderosa pine obtained in a separate study (Green and others, in progress). As expected, the relationships between MOE and Etv and between MOR and MOE and MOR and Etv are good for both the green and dry lodgepole pine. The r^2 value of 0.92 for the MOE–Etv relationship is probably spuriously high, as can happen with small data sets. Also as expected, the slope of the MOR–MOE relationship for the green lodgepole pine is less than that for the dry logs. These relationships, along with the green and dry data points, are shown in Figure 9. With such a small data set, it would be risky to speculate about trends in the intercept with change in moisture content. For dry logs, the slopes for the three species are similar (Table 4), and the regression lines appear virtually parallel (Fig. 10).

Compression Strength–Bending Strength Relationships

This study also affords an opportunity to evaluate the effect of moisture content on the relationship between UCS and

Table 4. Regression relationships for flexural properties of small-diameter logs

Species	Moisture content (%)	N	Y	X	$Y = A + B \times X$			Reference[a]
					A	B	r^2	
Lodgepole pine	96	30	MOE[b]	Etv[b]	– 0.233	1.152	0.92	1
	96	30	MOR[b]	MOE	0.754	3.810	0.76	1
	96	30	MOR[b]	Etv	– 0.338	4.534	0.55	1
	17	30	MOE	Etv	0.775	0.567	0.61	1
	17	30	MOR	MOE	– 0.497	4.232	0.75	1
	17	30	MOR	Etv	2.550	2.562	0.51	1
Douglas-fir	14	93	MOE	Etv	0.770	0.722	0.54	2
	14	92	MOR	MOE	1.961	4.513	0.58	2
	14	95	MOR	Etv	3.502	4.099	0.38	2
Ponderosa pine	14	97	MOE	Etv	0.135	0.877	0.66	2
	14	97	MOR	MOE	0.853	4.125	0.54	2
	14	98	MOR	Etv	1.159	3.838	0.41	2
Lodgepole pine	13	30	UCS	Etv	0.182	2.439	0.35	1

[a]1, current study; 2, Green and others (in progress)
[b]MOR has units of 10^3 lb/in^2 and MOE and Etv 10^6 lb/in^2

Table 5. Relationship between ultimate compression stress parallel to the grain (UCS) and modulus of rupture (MOR) for green lodgepole pine logs

Position in distribution	Green		Dry[a]	
	MOR[2]	UCS/MOR	MOR	UCS/MOR
Mean	6.056	0.444	6.245	0.720
5th	4.285	0.436	4.081	0.842
25th	5.142	0.436	5.134	0.742
50th	6.055	0.433	6.015	0.752
75th	7.020	0.440	7.709	0.730
95th	7.990	0.460	8.660	0.660

[a]The average moisture content of the dry MOR samples was 17.5%. The UCS samples averaged 13.1%.

MOR for green logs. Table 5 gives the UCS–MOR ratio for equivalent percentile levels of the MOR and UCS distribution (Table 2). The UCS–MOR ratio is seen to be reasonably constant for green logs, especially given the small sample sizes used in the current study.

Because the moisture content of the logs tested in compression is much lower than those tested in bending, the UCS–MOR ratio for the dry logs is not directly comparable to those for the green logs. However, the ratio for the green lodgepole pine logs can be compared with the relationship between UCS–MOR previously developed for small-diameter Douglas-fir and ponderosa pine logs tested at about 14% MC (Green and others, in progress). This latter data set involved the testing of 186 logs, and the UCS–MOR relationship was relatively independent of species. The ratios for green lodgepole pine are seen to be lower than the average trend for 127- to 152.4-mm (5- and 6-in.) diameter Douglas-fir and ponderosa pine logs (Fig. 11) but above those for logs 76.2- to 127-mm (3- to 5-in.) diameter. The trend for the UCS–MOR relationship to be flatter for green logs than for dry is consistent with that found when comparing green versus dry dimension lumber (Green and Kretschmann 1991). Although not shown in Figure 11, the UCS/MOR ratios for dry lodgepole pine logs given in Table 4 would be above those for the 127- to 152.4-mm (5- and 6-in.) Douglas-fir and ponderosa pine. Until better data are available for lodgepole pine tested in bending, it would appear conservative to use the Douglas-fir and ponderosa pine relationship for the smaller 76.2- to 127-mm (3- to 5-in.-) diameter logs for 127- to 152.4-mm (5- to 6-in-) diameter (or larger) green lodgepole pine logs. The relationship for the 76.2- to 127-mm (3- to 5-in.) Douglas-fir and ponderosa pine logs (Green and others, in progress) is

$$\text{UCS/MOR} = 0.00704(\text{MOR})^2 - 0.1130(\text{MOR}) + 0.750 \quad \text{for MOR} \leq 8.018 \times 10^3 \text{ lb/in}^2, \tag{4}$$

and

$$\text{UCS/MOR} = 0.30 \quad \text{for MOR} > 8.018 \times 10^3 \text{ lb/in}^2.$$

This relationship has been shown to produce conservative estimates when compared with 9-in.-diameter logs of the

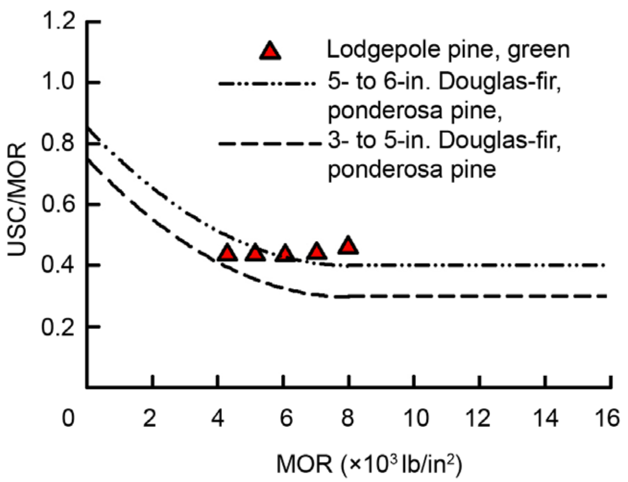

Figure 11. Effect of moisture content on the relationship between ultimate compression stress parallel to the grain (UCS) and modulus of rupture. (Douglas-fir and ponderosa pine relationships of 14% MC from Green and others, in progress.)

Englemann spruce– (*Picea engelmanni*–) alpine fir– *(Abies lasioca*–) lodgepole pine species grouping (Green and others, in progress). It has also been shown with dimension lumber that the UCS–MOR ratio decreases with decreasing lumber width (Green and Kretschmann 1991). Thus, Equation (4) would be expected to produce conservative estimates of UCS for lodgepole pine logs of larger diameters.

Conclusions

From our limited-scope study of the effect of moisture content on the properties of small-diameter lodgepole pine tested in bending and in compression parallel to the grain, we conclude the following:

1. Modulus of elasticity by static test (MOE) increased about 14% when dried to 17.5% MC. This increase is consistent with that found in historical studies for rectangular timbers. If projected to 12% MC, the increase would be about 28%.
2. Modulus of elasticity by transverse vibration (Etv) increased only about 2% when dried to 17.5% MC, and if projected to 12% MC would only increase about 4%. More extensive studies with Douglas-fir and ponderosa pine indicate that Etv would increase 10% to 12% in drying to 12% MC. The inconsistency between the change in Etv with decreasing moisture content and that for static MOE was unexpected and warrants further investigation.
3. Modulus of rupture is not very sensitive to change in moisture content. The increase in MOR from green to 17.5% MC is only about 3%, and if projected to 12% MC would increase only about 6%. This is less than found in historical studies for round or rectangular timbers.
4. Strength in compression parallel to the grain increased 67% in drying to 13% MC. This is consistent with historical studies that show a much larger dry–green ratio for UCS compared to that for MOR.
5. As expected, the slope of the MOR–MOE relationship for green logs is less than that for dry logs.
6. The relationship between ultimate compression stress parallel to the grain and modulus of rupture for green logs is relatively constant, produces a low UCS for a given MOR value, and changes less with change in moisture content than found in more extensive studies with small-diameter logs that were tested dry. This shift in the UCS–MOR relationship for green versus dry logs is consistent with trends observed with dimension lumber.

Results from the large data set on small-diameter Douglas-fir and ponderosa pine logs indicate that green Etv values would provide a conservative estimate of dry Etv. Such an estimate might be very conservative for low Etv values obtained on green logs.

The increase in MOR of lodgepole pine with change in moisture content seems low when compared with historical studies. Also, it was unexpected that the change in Etv with change in moisture content was different than the change in static MOE. These inconsistencies may be due to the failure to experimental problems with achieving the target moisture content. We hope our more comprehensive study, already in progress, will clear up the inconsistencies.

The USC–MOR relationship previously developed for dry Douglas-fir and ponderosa pine logs less than 127 mm (5-in.) diameter would provide a conservative estimate for 127- to 152.4-mm (5- to 6-in.) and larger green logs of lodgepole pine.

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D 2395-02	Standard test methods for specific gravity of wood and wood-based materials
D 2899-03	Standard practice for establishing allowable stresses for round timber piles

D 3200-74	Standard specification and test method for establishing recommended design stresses for round timber construction poles
D 3957-03	Standard practice for establishing stress grades for structural members used in log homes
D 4442-92	Standard test methods for direct moisture content measurement of wood and wood-based materials
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