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Moisture Content and the Shrinkage of Lumber

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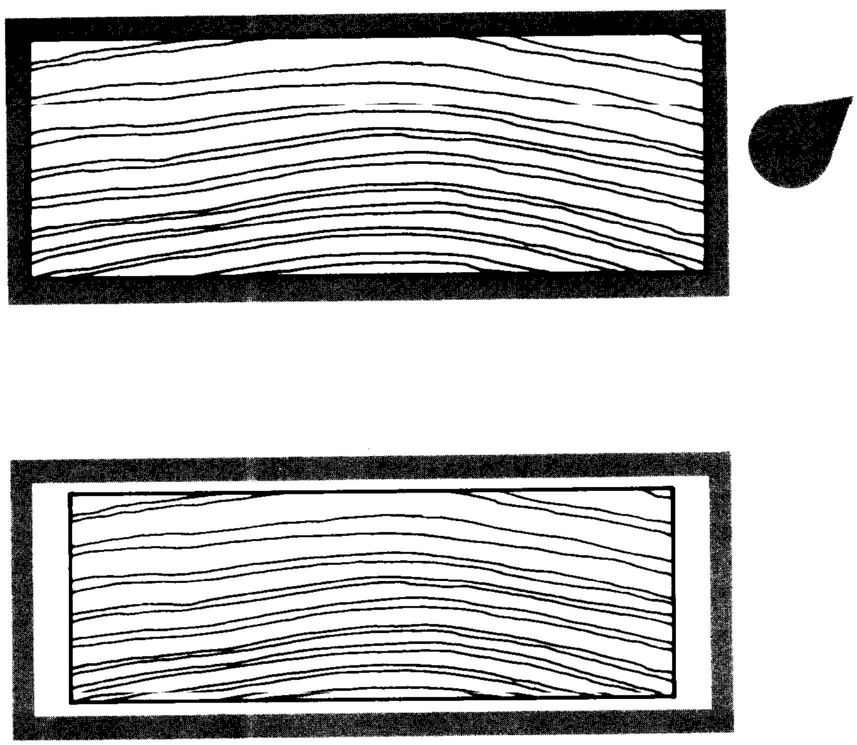

Abstract

The basis for the shrinkage factors given in the American Softwood Lumber Standard, PS 20-70, is reviewed. Using the PS 20-70 recommendations and previous work on the shrinkage of Douglas-fir and redwood 2-in dimension lumber, equations are derived for calculating the shrinkage of lumber as a function of moisture content.

Keywords: Shrinkage, moisture content, lumber, Douglas-fir, redwood.

Research Highlights

The American Softwood Lumber Standard, PS 20-70, lists specific shrinkage factors from green to 15-percent moisture content that were used historically to set green lumber dimensions for most species (2.35 percent for thickness and 2.80 percent for width). The standard does not provide a means of adjusting lumber dimensions to any other moisture content. The standard also does not provide specific shrinkage factors for species such as redwood and the cedars, which shrink less than most species. Rule-writing grading agencies need equations for adjusting lumber dimensions to any moisture content when assigning allowable properties from in-grade type data (Green 1983, Green and Evans 1987).

Using the PS 20-70 recommendations and an assumed green moisture content of 28 percent, we derive equations that can be used with most species to calculate the shrinkage of lumber as a function of percent moisture content *M*. These equations are

$$S_w = 6.031 - 0.215M$$

$$S_t = 5.062 - 0.181M$$

where *S* is the percent shrinkage from green to some percent moisture content *M* and subscripts t and w denote thickness and width of the lumber. These equations are assumed valid between 8- and 19-percent moisture content. Results predicted using these equations compare favorably with data collected in recent studies.

Using the PS 20-70 recommendations, an assumed green moisture content of 22 percent, and the historical studies used to establish those recommendations, similar equations are derived for redwood. These equations

$$S_w = 3.457 - 0.157M$$

$$S_t = 2.816 - 0.128M$$

are also assumed valid between 8- and 19-percent moisture content.

As additional data become available, we recommend that the applicability of these equations be evaluated for a variety of species.

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Moisture Content and the Shrinkage of Lumber

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Introduction

Safe structural design with wood is based on the load-carrying capacity of structural members. To calculate this capacity, a designer looks up an allowable member strength (such as the allowable modulus of rupture, R_{book}) and multiplies this by a section property calculated using assumed dimension at some reference moisture content (such as the section modulus in bending, S_{book}).[1] However, in the in-grade testing program (Green 1983, Green and Evans 1987) we are testing real lumber and measuring its actual dimensions at time of test. For the design process to work correctly, the product of assumed strength and assumed section property must equal the product of the measured values. For bending,

$$R \cdot S = R_{book} \cdot S_{book} \quad (1)$$

where R and S are measured experimentally and R_{book} and S_{book} are tabulated values given in engineering design codes.

All terms in equation (1) are usually calculated at three standard levels of moisture content: 12 percent, 15 percent, and green. Procedures are available for adjusting mechanical properties for changes in moisture content (Green and Evans 1988). The objective of this report is to establish procedures for similarly adjusting section properties.

[1]This argument holds for other material property and section property products, e.g., modulus of elasticity (MOE), moment of inertia (I), cross-sectional area (A).

Size Provisions in the American Softwood Lumber Standard

Size requirements for softwood lumber of most species produced in the United States are given in the American Softwood Lumber Standard (NBS 1986). Footnote 3 of that standard states that the "minimum green sizes are based on shrinkage factors of 2.35 percent in thickness and 2.80 percent in width from the fiber saturation point to a 19-percent maximum moisture content. . . . " No reference is given in the standard for these shrinkage factors. Smith and Wood (1964) stated that various data on shrinkage related to moisture content were studied by the American Lumber Standards Committee when establishing these shrinkage factors. They note that the factors of 2.35 and 2.80 were based on recommendations of the Forest Products Laboratory (FPL) made in April 1963. Further, they stated that these factors are based on "average shrinkage values to 15-percent average moisture content. . . . " However, they did not provide equations for calculating shrinkage at other moisture content levels and give no definition for green moisture content.

No specific shrinkage recommendations are made in the standard for redwood, western redcedar, or northern white-cedar.[2,3] However, after presenting a table of standard green sizes applicable to most species, it is noted that "somewhat smaller green sizes" would be adopted for redwood and western redcedar "in recognition of smaller shrinkage values."

[2]For the purpose of reinspection, shrinkage that may occur after dressing to standard size is recognized through a tolerance of 0.7-percent shrinkage per each 4 percentage points of moisture content for redwood and the cedars.
[3]A batch of lumber with a maximum moisture content of 19 percent is assumed to have an average moisture content of 15 percent, and a batch of lumber with a maximum moisture content of 15 percent is assumed to have an average moisture content of 12 percent (ASTM 1987).

Development of Adjustment Formulas for Calculating Lumber Shrinkage

FPL Reports for Lumber

The apparent basis for the FPL recommendation to the American Lumber Standards Committee was detailed by Comstock (1965). The study measured dimensional change for specimens having growth ring angles of 0° (flatsawn), 15°, 30°, and 45°. The 30° results were in good agreement with other studies using randomly selected lumber (Comstock 1965, p. 6). For a ring angle of 30°, shrinkage[4] values were 2.80 percent in width and 2.34 percent in thickness for coast-type Douglas-fir dried to a 15-percent moisture content (table 1). The equivalent values for redwood are 1.10 percent in width and 0.89 percent in thickness. The 30° shrinkage values for Douglas-fir are almost identical to the FPL recommendation.

Average regression equations relating percent radial shrinkage S_R and percent tangential shrinkage S_T to percent moisture content M for coast-type Douglas-fir were derived as (Comstock 1965)

$$S_R = 4.321 - 0.1470M \qquad (2)$$

$$S_T = 6.962 - 0.2622M \qquad (3)$$

For old-growth redwood, the equations are

$$S_R = 2.274 - 0.0991M \qquad (4)$$

$$S_T = 3.951 - 0.1831M \qquad (5)$$

Using equations (2) to (5) and the equations for relating shrinkage to growth ring orientation (Comstock 1965),

$$S_w = S_T \cos^2 \Theta + S_R \sin^2 \Theta \qquad (6)$$

$$S_t = S_T \sin^2 \Theta + S_R \cos^2 \Theta \qquad (7)$$

where S_w is the percent shrinkage in width, S_t the percent shrinkage in thickness, and Θ the angle between growth rings and the flat face of the board. We can derive equations for S_w and S_t at a growth ring angle of 30°. For coast-type Douglas-fir, these equations are

$$S_w = 6.302 - 0.2334M \qquad (8)$$

$$S_t = 4.981 - 0.1758M \qquad (9)$$

and for redwood,

$$S_w = 3.5318 - 0.1621M \qquad (10)$$

$$S_t = 2.6932 - 0.1201M \qquad (11)$$

The 1963 recommendations for most species can be obtained from equations (8) and (9). However, these exact formulas should not be used in the development of section property distributions for two reasons:

1. They assume a growth ring angle of 30°. In general, the growth ring angle is not known, and it is not feasible to incorporate such information into design equations. It seems more appropriate to use linear regression equations based on the 1963 recommendations but not tied specifically to the Comstock (1965) equations. Such equations should be valid for moisture content levels from about 8 to 19 percent.

2. The two formulas lead to different implied green moisture content levels M_g (i.e., 27.0 percent for width and 28.0 percent for thickness for Douglas-fir and 21.8 and 22.4, respectively, for redwood). Again, it is not feasible to use more than one M_g value for general design use.

Note that the M_g values used here are defined as the value of M that gives zero shrinkage in the linear regression evaluations.[5] Because significant nonlinearity in the moisture content and shrinkage relationship may occur near the true fiber saturation point, this value may not be identical to the true fiber saturation point. Available data suggest that the M_g value is higher than the intersection moisture content obtained by applying a similar assumption of linearity to mechanical properties data (Wilson 1932).

The results obtained by Wood and Soltis (1964) using Douglas-fir, western hemlock, and Southern Pine are comparable to the Comstock (1965) results. Wood and Soltis fit regression equations to their individual species data assuming M_g = 28 percent. Using the 1963 FPL recommendations of 2.35-percent shrinkage in thickness and 2.80-percent shrinkage in width and assuming M_g = 28 percent, simultaneous linear regression

[4]Shrinkage = 100 x (dimension green - dimension dry) ÷ dimension green

[5]Note that M_g defined here is in fact a function of Θ for equations derived in this manner.

equations of the form $S = a + bM$ may be solved to obtain for coast-type Douglas-fir

$$S_w = 6.031 - 0.215M \quad (12)$$

$$S_t = 5.062 - 0.181M \quad (13)$$

Development of Adjustment Formulas for Redwood

Because the American Softwood Lumber Standard does not list specific shrinkage factors for width and thickness of redwood, we had to develop factors compatible with the 1963 FPL recommendations. Using equations (8) to (11), developed from equations presented by Comstock (1965), we may compare the shrinkage from green to 15-percent moisture content for Douglas-fir and redwood lumber (table 2). Applying the ratios from table 2 to the shrinkage factors recommended in 1963 for most species when dried to 15-percent moisture content,

$$S_w = 2.8 \times 0.393 = 1.100$$

$$S_t = 2.35 \times 0.381 = 0.895$$

Equations (10) and (11) assume $M_g = 22$ percent. Using this value of M_g, $S_w = 1.100$, and $S_t = 0.895$, a general shrinkage equation for redwood may be derived in a manner similar to that described for equations (12) and (13):

$$S_w = 3.454 - 0.157M \quad (14)$$

$$S_t = 2.816 - 0.128M \quad (15)$$

In the absence of other information, these equations would seem more appropriate than equations (12) and (13) for calculating the shrinkage of redwood, western redcedar, and northern whitecedar.

Additional Shrinkage Information

Forintek study–Barrett and Foschi (1981) presented equations for adjusting cross-sectional area A, moment of inertia I, and section modulus S for changes in moisture content:

$$A = A_g[1 - 0.005544(M_g - M)] \quad (16)$$

$$I = I_g[1 - 0.10674(M_g - M)] \quad (17)$$

$$S = S_g[1 - 0.008156(M_g - M)] \quad (18)$$

where the subscript g denotes green.

Barrett and Foschi felt that their data were insufficient to experimentally establish M_g. They assumed $M_g = 25$ based on shrinkage and moisture content data presented by Madsen et al. (1980), stating their assumption was consistent with previous work for Douglas-fir (table 3).

Stamm (1964, figs. 13-1 and 13-2) investigated volumetric shrinkage and moisture content relationships using 2- by 2- by 6-in specimens. For 52 softwoods, the average green moisture content was 26 percent, while that for 107 hardwoods was 27 percent. Reanalysis of the softwood data used by Stamm (table 4) indicates that a value of $M_g = 28$ or 29 might be more applicable to species currently included in the U.S. in-grade testing program (table 5). Because Barrett and Foschi (1981) did not give regression equations for shrinkage in width and thickness, comparison of the results obtained in various studies must be made on some other basis. On the basis of cross-sectional area (fig. 1), the slope of the moisture content and dimension relationship proposed by Barrett and Foschi is slightly steeper than those of Wood and Soltis (1964) and Comstock (1965). The $M_g = 25$ value assumed by Barrett and Foschi is lower than those used by Soltis and Comstock and lower than those measured by Stamm. Reanalysis of their data using a higher M_g value would probably bring their results more in line with the information on which the 1963 FPL recommendations were based.

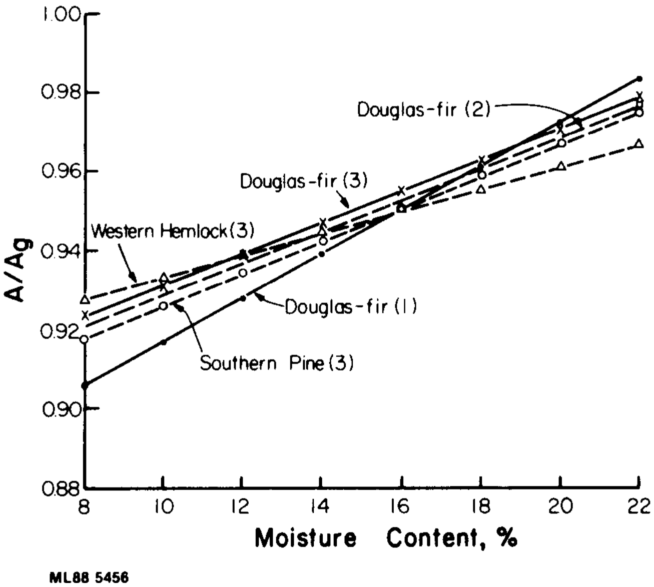

Figure 1–Predicted ratio of cross-sectional area at the indicated moisture content A to that when green, A_g. Data from (1) Barrett and Foschi (1981), (2) Comstock (1965), and (3) Wood and Soltis (1964). (ML88 5456)

Douglas-fir moisture content study- The cooperative study between FPL and Forintek[6] on the influence of moisture content on the flexural properties of Douglas-fir dimension lumber (Aplin et al. 1985) provides additional data with which to judge the adequacy of the 1963 FPL recommendations. We conducted preliminary analysis of these data using the dimensions from the matched samples[7] (table 6). Plots of the dimensions predicted using equation (12) as functions of the measured dimensions are shown in figure 2. In general, the equations appear to adequately predict the experimental results. The results indicate that a slightly lower M_g value might bring the 2-by-8 values closer to the 1 to 1 line (fig. 2c). However, data for other species are needed to justify such changes.

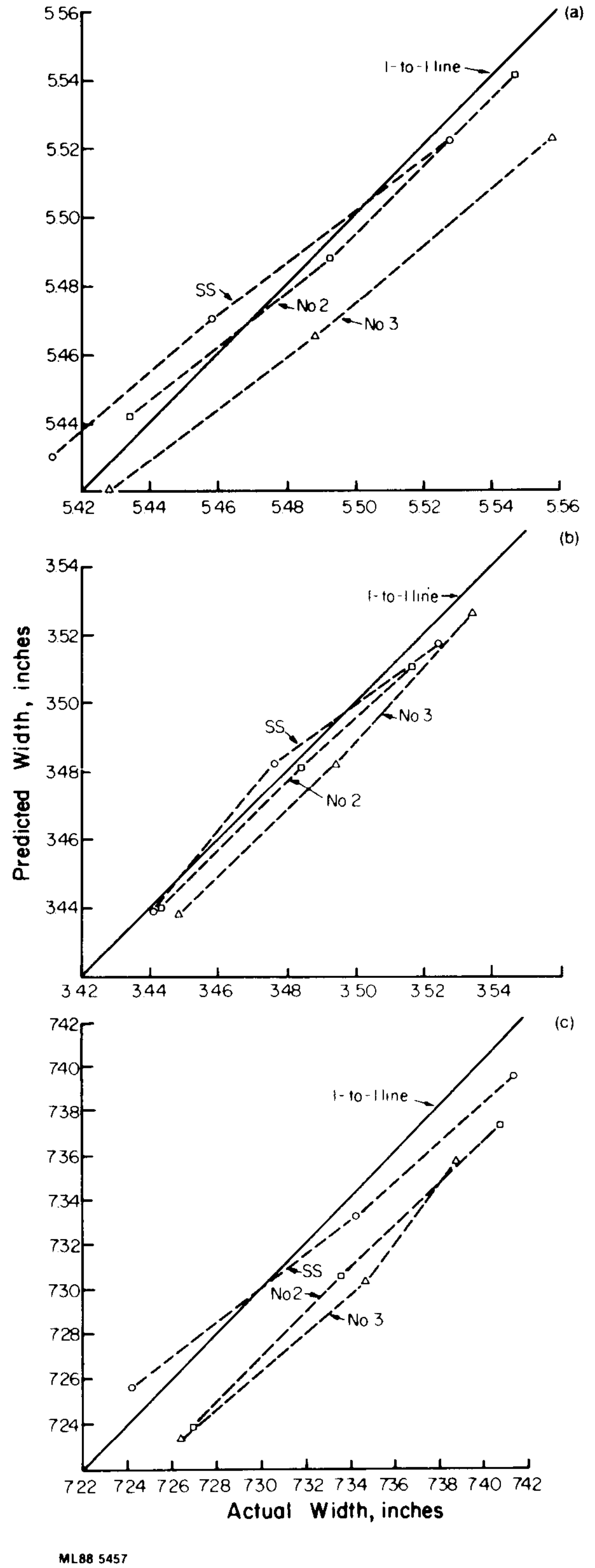

Figure 2–Comparison of actual and predicted widths for Douglas-fir lumber, predicted from equation (12) using data from Aplin et al. (1985). (a) 2 by 4, (b) 2 by 6, and (c) 2 by 8. (ML88 5457)

[6]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[7]In this analysis, only the average values of the matched sample dimensions were used. A more complete analysis could be obtained using the dimensions for the same pieces at two moisture content levels.

Princes Risborough studies – Covington and Fewell (1975) measured shrinkage between green and 15-percent moisture content for 2,008 joists of European redwood and whitewood,[8] Canadian western hemlock, and western white spruce. Sizes ranged from 44 by 100 mm (1.7 by 3.9 in) to 44 by 300 mm (1.7 by 11.8 in). Equations of the form

$$d_1 = d_2[1 - C(M_2 - M_1)] \qquad (19)$$

were fit to the data, where d is a geometrical property, C a shrinkage coefficient, and the subscripts 1 and 2 denote a lower and a higher moisture content value, respectively; M_g = 28 percent was assumed. Table 7 lists average shrinkage coefficients for all sizes.

Dry-green ratios at 15 and 28 percent predicted by equations (12) and (13) agree very well with those predicted by equation (19) (table 8). Differences are less than 1 percent.

Wood and Soltis study – As previously mentioned, Wood and Soltis (1964) obtained shrinkage data on lumber having a random growth ring orientation. The study used a total of 360 pieces of three species (Douglas-fir, western hemlock, and southern pine), three grades (Construction, Standard, and Utility), and two sizes (2 by 6 and 2 by 10) of lumber. The average shrinkage to 15-percent moisture content compares favorably with the 2.8-percent shrinkage in width and 2.35-percent shrinkage in thickness obtained from equations (12) and (13) (table 9).

[8]Names used here are in accordance with established European custom. Redwood refers to *Pinus sylvestris,* also called Scots pine. Whitewood refers to *Picea alba,* or white spruce.

Conclusions and Recommendations

From the available data, the recommendations on moisture and shrinkage relationships made by the FPL in 1963 appear to provide an adequate basis for adjusting test dimensions in the in-grade testing program to design moisture content levels. Equations (12) and (13) with an assumed green moisture content of 28 percent are recommended for most species. Equations (14) and (15) with an assumed green moisture content of 22 percent are recommended for redwood, western redcedar, and northern whitecedar. We believe the equations are valid for predicting average trends in the moisture content and dimension relationship between 8- and 19-percent moisture content.

As the data become available, we recommend that the applicability of these equations to species other than Douglas-fir and redwood be evaluated.

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Table 1 – Shrinkage from green to 15-percent moisture content for various ring angles (Comstock 1965)

Species	Shrinkage (percent) for various ring angles			
	0°	15°	30°	45°
Douglas-fir				
Width	3.03	2.97	2.80	2.57
Thickness	2.12	2.18	2.34	2.57
Redwood				
Width	1.20	1.18	1.10	1.00
Thickness	0.79	0.82	0.89	1.00

Table 2 – Shrinkage from green to 15-percent moisture content

Dimension	Shrinkage (percent)		Ratio (Redwood/ Douglas-fir)
	Douglas-fir	Redwood	
Width	2.801	1.100	0.393
Thickness	2.344	0.892	0.381

Table 3 – Estimates of the fiber saturation point and intersection point for Douglas-fir defect-free specimens (Barrett and Foschi 1981)

Property	Method	Moisture content (percent)	Reference
Intersection point (M_p)	Mechanical test	24	Wilson (1932)
	Shrinkage test	25.8	Wilson (1932)
Fiber saturation point	Electrical conductivity	30.5	Wilson (1932)
	Equilibrium moisture content as a function of relative humidity	28	Stamm (1964)

Table 4 – Green moisture content estimates (Stamm 1964)

Species	External volumetric shrinkage[1] (percent)	Specific gravity[2]	Green moisture content[3] (percent)
Douglas-fir			
Coast	11.8	0.45	26.2
Intermediate	11.2	0.41	27.3
Rocky Mountain	10.6	0.40	26.5
Western larch	13.2	0.48	27.5
			Mean 26.9
Southern Pine			
Loblolly	12.3	0.47	26.2
Longleaf	12.2	0.54	22.6
Shortleaf	12.3	0.46	26.7
Slash	12.2	0.56	21.8
			Mean 24.3
Hem-Fir			
Western hemlock	11.9	0.38	31.3
California red fir	11.8	0.37	31.9
Grand fir	–	–	–
Noble fir	12.5	0.35	35.7
Pacific silver fir	14.1	0.35	40.3
White fir	9.4	0.35	26.9
			Mean 33.2
Spruce-Pine-Fir			
Alpine fir	9.0	0.31	29.0
Balsam fir	10.8	0.34	31.8
Black spruce	11.3	0.38	29.7
Englemann spruce	10.4	0.31	33.5
Jack pine	10.4	0.39	26.1
Lodgepole pine	11.5	0.38	30.3
Red spruce	11.8	0.38	31.1
White spruce	13.7	0.37	37.0
			Mean 31.1
Mixed species			
Eastern hemlock	9.7	0.38	25.5
Tamarack	13.6	0.49	27.8
Sitka spruce	11.5	0.37	31.1
Red pine	11.5	0.44	26.1
Eastern white pine	8.2	0.34	24.1
Western white pine	11.8	0.36	32.8
Ponderosa pine	9.6	0.38	25.3
Sugar pine	7.9	0.35	22.6
			Mean 26.9
Hardwoods			
Aspen, trembling	11.5	0.35	32.9
Aspen, bigtooth	11.8	0.35	33.1
Cottonwood	14.1	0.37	38.1
Red alder	12.6	0.37	34.1
Yellow-poplar	12.3	0.38	32.4
			Mean 34.2
Cedars			
Northern white	7.0	0.29	24.1
Alaskan	9.2	0.42	21.9
Incense	7.6	0.35	21.7
Port-Orford	10.1	0.40	25.3
Western red	7.7	0.31	24.8
			Mean 23.6
Other species			
Eastern redcedar	7.8	0.44	17.7
Southern redcedar	7.0	0.42	16.7
Southern white cedar	8.4	0.31	27.1
Southern cypress	10.5	0.42	25.0
Cookbark fir	9.0	0.28	32.1
Lowland white fir	10.6	0.37	28.6
Mountain hemlock	11.4	0.43	26.5
Alligator juniper	7.8	0.48	16.3
Jeffrey pine	9.9	0.37	26.8
Limber pine	8.2	0.37	22.2
Mountain pine	10.9	0.49	22.2
Pitch pine	10.9	0.45	24.2
Pond pine	11.2	0.50	22.4
Sand pine	10.0	0.45	22.2
Pinyon pine	9.9	0.50	19.8
Redwood			
Virgin	6.8	0.38	17.9
2nd, open	6.3	0.28	22.5
2nd, close	7.4	0.32	23.1
Pacific yew	9.7	0.60	16.2
			Mean 22.6

[1]Green volume, ovendry weight basis.
[2]Green basis.
[3]Volumetric shrinkage divided by specific gravity.

Table 5 – Summary of green moisture contents based on data of Stamm (1964)

Type	Number of species	M_g (percent)			
		Average	Standard deviation	Minimum	Maximum
All softwoods	54	26.1	5.1	16.2	40.3
All in-grade softwoods except cedar[1]	29	28.8	4.3	21.8	40.3
All in-grade softwoods	34	28.0	4.4	21.7	40.3
All in-grade woods (including hardwoods)	39	28.8	4.7	21.7	40.3

[1]Green (1983).

Table 6 – Predicted (eqs. (12) and (13)) and actual dimensions for Douglas Fir lumber based on average values from Aplin et al. (1985)

Nominal size (in)	Grade	Moisture content (percent)	Measured value (M, in)		Predicted (P, in)		Error ($\frac{P-M}{M}$ x 100, percent)	
			Thickness	Width	Thickness	Width	Thickness	Width
2 by 4	Select Structural	67.0	1.576	3.576	–	–	–	–
		20.4	1.558	3.524	1.546	3.517	-0.8	-0.2
		15.8	1.540	3.476	1.532	3.482	-0.5	0.2
		10.2	1.527	3.441	1.517	3.439	-0.7	-0.1
	No. 2	69.9	1.598	3.577	–	–	–	–
		19.3	1.554	3.516	1.553	3.510	-0.1	-0.2
		15.6	1.540	3.484	1.543	3.481	0.2	-0.1
		10.2	1.531	3.443	1.527	3.440	-0.3	-0.1
	No. 3	80.1	1.575	3.575	–	–	–	–
		21.7	1.565	3.534	1.557	3.526	-0.5	-0.2
		15.9	1.550	3.494	1.541	3.482	-0.6	-0.3
		10.2	1.535	3.448	1.524	3.438	-0.7	-0.3
2 by 6	Select Structural	66.0	1.562	5.636	–	–	–	–
		18.6	1.544	5.528	1.535	5.522	-0.6	-0.1
		14.3	1.527	5.458	1.523	5.470	-0.3	-0.2
		11.0	1.517	5.412	1.514	5.430	0.2	0.3
	No. 2	76.1	1.571	5.651	–	–	–	–
		19.0	1.553	5.547	1.545	5.541	-0.5	-0.1
		14.6	1.533	5.493	1.533	5.488	0	-0.1
		10.8	1.528	5.434	1.522	5.442	-0.4	0.1
	No. 3	76.2	1.569	5.630	–	–	–	–
		19.1	1.554	5.558	1.544	5.522	-0.6	-0.6
		14.4	1.537	5.488	1.530	5.465	-0.5	-0.4
		10.7	1.520	5.428	1.520	5.420	0	-0.1
2 by 8	Select Structural	56.4	1.580	7.545	–	–	–	–
		18.7	1.557	7.415	1.553	7.394	-0.3	-0.3
		14.9	1.545	7.343	1.543	7.332	-0.1	-0.1
		10.2	1.529	7.242	1.529	7.256	0	0.2
	No. 2	62.4	1.579	7.524	–	–	–	–
		18.6	1.552	7.409	1.552	7.372	0	-0.5
		14.5	1.547	7.336	1.540	7.305	-0.5	-0.4
		10.2	1.530	7.269	1.528	7.236	-0.1	-0.5
	No. 3	69.0	1.574	7.521	–	–	–	–
		17.8	1.552	7.389	1.545	7.356	-0.5	-0.4
		14.5	1.546	7.347	1.536	7.302	-0.6	-0.6
		10.3	1.529	7.264	1.524	7.234	-0.3	-0.4

Table 7 – Shrinkage coefficients from Covington and Fewell (1975)

Species	Average shrinkage coefficient *C*	
	Thickness	Width
Redwood-whitewood	0.00257	0.00196
Western hemlock	0.00207	0.00214
Western white spruce	0.00220	0.00164

Table 8 – Comparison of dry-green ratios predicted by this study and those determined by Covington and Fewell (1975)

Species	Dry-green ratio (15 and 28 percent)			
	Thickness		Width	
	Equation (13)	Equation (19)	Equation (12)	Equation (19)
European redwood-whitewood	0.9765	0.9666	0.9719	0.9745
Canadian hemlock	0.9765	0.9731	0.9719	0.9722
Canadian white spruce	0.9765	0.9714	0.9719	0.9787

Table 9 – Average shrinkage to 15-percent moisture content (Wood and Soltis 1964)

Species	Shrinkage in width (percent)	Shrinkage in thickness (percent)
Douglas-fir	2.7	2.2
Western hemlock	3.1	2.3
Southern Pine	2.5	2.9
Average	2.8	2.5