SHRINKAGE AND RELATED PROPERTIES OF DOUGLAS-FIR CELL WALLS[1]

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ABSTRACT

It is often desirable in veneer or particleboard operations, or in pulping, gluing and especially permeability studies, to use nondestructive sampling techniques to estimate specific gravity or wood behavior in situ.

Two separate optometric measuring techniques are compared for measuring anatomical parameters of intact, extractive-free wood directly. Excellent estimates of wood specific gravity in the green and oven-dry condition, cell-wall area, lumen area, cell-wall thickness, and density in situ are obtained by both methods. In addition, shrinkage in cell area, cell perimeter, tangential and radial dimensional shrinkage of cells, and volumetric shrinkage are obtained from measurements taken from the water-swollen to the oven-dry condition.

Values derived by the two optometric measuring techniques were highly correlated: specific gravity with cell-wall area, basic density with cell-wall thickness.

Keywords: Specific gravity, cell-wall area, cell-wall thickness, fiber diameter, cell-wall density, lumens, cell perimeters, soft-woods.

BACKGROUND

Although much research has been done over the years, no completely adequate explanation of the anisotropic shrinkage of wood has been proposed. Numerous quantitative measurements have been associated with anisotropic shrinkage and were critically reviewed by Kelsey (1963). In a recent reexamination of the literature, Boyd (1974a) quotes the statement made by Pentoney (1953), also quoted by Kollman and Côté (1968), that "due to the complexity and diversity of structure in wood, it is believed that the mechanism of greatest influence depends upon the wood under consideration, and that this mechanism is modified by one or several of the other mechanisms."

The mechanisms affecting wood shrinkage that have been previously proposed include alternation of latewood and earlywood layers within the annual ring (Mörath 1932), effects of ray tissue (Barkas 1941; Hale 1957; McIntosh 1954, 1955, 1957; Schniewind 1959), differing fibril angle in the radial and tangential walls (Boyd 1974b; Nakato 1958a; Vintila 1939), extractives (Nearn 1955; Stamm 1964), differences in the number of transverse walls per unit of planar direction (Nakato 1958b), and the degree of lignification in the radial or tangential cell wall

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(Boyd 1974b; Kato and Nakato 1968). More recently, Barber and Meyland (1964), Barber (1968), Cave (1972, 1975, 1976), and Meyland (1972) have shown modeling to be successful as a basis for predicting shrinkage behavior, at least for the central layer of a three-layered secondary wall.

In his review (1974a), Boyd concluded that the quantitative effects associated with anisotropic shrinkage are dominated by: (1) the degree of lignification of the radial and tangential walls; (2) cell form factor (cell shape and wall thickness); (3) differences in microfibrilar angle between radial and tangential walls; and (4) the total extractive content.

The differences in shrinkage between earlywood and latewood are responsible for the buckling of veneers and shelling failures in flatsawn boards as well as for other inconveniences in the manufacture of products, and are therefore of considerable interest.

Specific gravity is a measure of the total amount of wood substance per unit of volume. However, it is the distribution of this substance in cell-wall area and also wall thickness that have a direct bearing on strength, pulping, and paper quality. Cell shape, wall thickness, relative proportions of earlywood and latewood in the annual growth rings, degree of lignification of the radial and tangential walls, and total extractive content all affect the distribution of the wood substance determining specific gravity.

The critical value for obtaining specific gravity in the oven-dry condition is that of volume. Volumes of small samples of irregular outline usually are measured by coating with paraffin (Brown et al. 1949) or celloidin (Wedel 1962) and measured by liquid displacement. Alternatively, a mercury porosimeter can be used (Winslow and Shapiro 1959; Stone 1966). Of all the techniques for deriving wood properties such as wood density that are listed by the TAPPI Forest Biology Subcommittee No. 2 (1963, 1966, 1968), all but one by Smith and Miller (1964) require measurements to be made from thin sections or by cut-out-and-weigh (from photomicrographs) and planimetric methods. The works of Boutelje (1962), Wangaard (1969), and Kellogg and Wangaard (1969) verify that microtechnical processing either through skewing or bulking of the walls results in errors for determining the proportional wall area of wood. Preliminary results of investigations conducted at FPL indicate that photographs also give erroneous values because of shrinkage differentials during drying of the photographic paper, compared to direct measurement through the microscope on the intact wood surface.

This study evaluates the transverse shrinkage characteristics inherent in earlywood and in latewood of Douglas-fir [(*Pseudotsuga menziesii* (Mirb.) Franco], using two independent optometric techniques to measure the following characteristics of small intact specimens of all earlywood cells or of all latewood cells of Douglas-fir:

1. The specific gravity of the green and the oven-dry wood.
2. The percentage shrinkage from green to oven-dry condition for
   (a) the cross-sectional cell-wall area
   (b) the lumen area
   (c) average tracheid diameter (radial and tangential direction)
   (d) average tracheid wall thickness
   (e) ray diameter.

MATERIAL AND METHODS

Specific gravity was determined by the maximum moisture method for six specimens of earlywood cells and six specimens of latewood cells. After measurements had been completed in the green (water-swollen) condition, the specimens were oven-dried to a constant weight at 105 C in a vacuum oven (Precision Sci. Co. Model 19) at a gauge reading 50 centimeters of vacuum. With the vacuum intact and the oven turned off, the specimens were infused with immersion oil (Cargille, Type A) while in the oven until reduced to room temperature. Preliminary trials showed that the immersion oil did not cause swelling of the wood. Being infused with oil prevented the specimens from taking on moisture and therefore maintained the oven-dry state.

All cell measurements were made with a Leitz Ultrapak microscope and Xenon arc lamp to provide incident (reflected) illumination on the prepared surface of the intact wood specimen. One ocular eyepiece of the microscope was equipped with a cross hair for lineal measurements after Smith (1965), the other ocular eyepiece was equipped with the Zeiss integrating eyepiece with the dot-grid graticule (Quirk 1975). Measurements were made on both cross-sectional surfaces of each intact specimen using a 55× water immersion lens for the water-swollen condition and a 60× oil immersion ultrapak objective for the oven-dry condition.

In the tangential direction, average tangential diameter of tracheid, average diameter of rays, and number of rays per millimeter (mm) were determined along two randomly selected passes using the Dual Linear Traversing Micrometer.

In the radial direction, average radial diameter of tracheids and average tangential wall thickness were determined on ten randomly selected passes for the Dual-Linear, and ten separate randomly selected passes for the Zeiss eyepiece. In addition, for each radial pass the proportional areas of the cross section occupied by rays, tracheid walls, and lumens, were determined with the Zeiss integrating eyepiece.

Linear measurements of cell diameters and tangential wall thickness made by the Dual-Linear method can be used to estimate wood specific gravity after they are converted to area measurements on the basis of a suitable model (Smith 1965). Alternatively, direct area measurements by the dot-grid method, beside giving direct estimates of specific gravity (Quirk 1975), can be converted to estimates of cell-wall thickness (Stamm 1946, 1964, 1967; Lantican and Hughes 1973; Goggans 1962).

Calculation of percentage cell-wall area

The relationship between cell-wall area and the expected specific gravity of extractive-free wood is

$$G = DA \tag{1}$$

where D is the specific gravity of the cell wall and A is the fraction of the total area in cell wall. The percentage area of a wood cross section occupied by cell walls is estimated in two ways. The first method uses a Zeiss integrating eyepiece that superimposes a dot-grid over the surface image of the intact solid wood specimen; the proportion of dots falling on wall or lumen can then be counted. The second method uses a model of the shape of the tracheid cross section; direct measurements of cell diameter and wall thickness are made to determine the proportion of the cross section occupied by cell wall.

For the purpose of calculating cell-wall area by direct measurement, both the tracheid and the lumen cross sections are assumed to be rectangular and the cross-sectional area of cell wall is

$$A = \frac{1}{TR}\{TR - [(T - 2w)(R - 2w)]\} \quad (2)$$

where T is the tracheid diameter in the tangential direction, and R is that in the radial direction, and average cell-wall thickness is w (Smith 1965). The cross-sectional surface of the specimen is modeled as if the area A were composed of tracheids only. Therefore, when estimating the total cross-sectional cell-wall area of the specimen, the width of the rays is included in the tangential traverse. Dividing by the number of radial rows of cells then slightly overestimates the tangential cell diameter T_1. For estimates of tracheid wall only, the cumulated width of the ray tissue is deleted and the tangential cell diameter is T.

Procedures for calculating desired wood characteristics

In all computations, the following symbols are used to indicate quantitative data for the water-swollen condition.

- G = Specific gravity of the wood determined by the maximum moisture method.
- T = Average tangential diameter of tracheid (mm).
- T_1 = Average tangential diameter of tracheid adjusted to include rays (mm).
- R = Average radial diameter of tracheid (mm).
- w = Average tracheid wall thickness (mm).
- RD = Average width of the rays (mm).
- NR = Number of rays per mm.
- N_t = Number of tracheids per mm in the tangential direction.
- N_r = Number of tracheids per mm in the radial direction.
- DL_t and Z_t = Fractional cross-sectional area of *tracheids* occupied by cell wall computed by using T in Eq. 2, and determined directly by the Zeiss integrating eyepiece.
- DL_w and Z_w = Fractional cross-sectional area of *wood* (tracheids plus rays) occupied by wall, computed by using T_1 in equation and determined directly by the Zeiss integrating eyepiece.

The same symbols accompanied by a prime (′) designate the equivalent data for the oven-dry condition. Thus G and G′ designate specific gravity of the wood for the saturated (by maximum moisture method) and oven-dry conditions, respectively.

Specific gravity of oven-dry wood

$$G' = \frac{G}{1 - S_2} \quad (3)$$

where S_2 is the coefficient of shrinkage of tracheids and rays in cross section,

TABLE 1. *Linear and multiple regression analyses of the relationship between specific gravity (Y) of Douglas-fir earlywood and latewood and the independent variables: number of cells per square millimeter (X_1) and tangential wall thickness in microns (X_2).*

Method	Condition	Wood type	Independent variable	Constant	X_1 coef	X_2 coef	R^2	$S_{y.x}$
Dual-Linear	Green	EW[1]	X_1	−0.14444	0.08075	—	0.8366	0.0251
			X_2	0.05036	—	0.07533	0.8943	0.0202
			X_1X_2	−0.08336	0.00038	0.04728	0.9923	0.0063
		LW[2]	X_1	0.86960	−0.00005	—	0.0094	0.1307 NS[3]
			X_2	0.39243	—	0.05166	0.6854	0.0736
			X_1X_2	−0.15600	0.00030	0.07230	0.9038	0.0470
		Combined	X_1	−0.03658	0.00063	—	0.7711	0.1433
			X_2	0.01653	—	0.09525	0.9249	0.0821
			X_1X_2	−0.08214	0.00027	0.06797	0.9916	0.0289
	Dry	EW	X_1	−0.15956	0.00075	—	0.8778	0.0257
			X_2	0.01257	—	0.1390	0.9042	0.0227
			X_1X_2	−0.11184	0.00039	0.08187	0.9941	0.0065
		LW	X_1	1.3253	−0.00013	—	0.0412	0.1901 NS
			X_2	0.3961	—	0.1112	0.8195	0.0825
			X_1X_2	−0.27219	0.00028	0.14014	0.9462	0.0520
		Combined	X_1	−0.04912	0.00064	—	0.8155	0.1932
			X_2	−0.03890	—	0.1761	0.9595	0.0905
			X_1X_2	−0.10927	0.00022	0.12953	0.9950	0.0336
Dot-grid	Green	EW	X_1	−0.14444	0.08075	—	0.8366	0.0251
			X_2	−0.02463	—	0.09953	0.9663	0.0114
			X_1X_2	−0.06158	0.00016	0.08197	0.9743	0.0115
		LW	X_1	0.86960	−0.00005	—	0.0094	0.1307 NS
			X_2	0.36359	—	0.05681	0.7905	0.0601
			X_1X_2	−0.08287	0.00025	0.07258	0.9632	0.0291
		Combined	X_1	−0.03658	0.00063	—	0.7711	0.1433
			X_2	−0.00084	—	0.1004	0.9383	0.0744
			X_1X_2	−0.08895	0.00025	0.07295	0.9967	0.0182
	Dry	EW	X_1	−0.15956	0.00075	—	0.8778	0.0257
			X_2	0.01450	—	0.1300	0.7322	0.0380
			X_1X_2	−0.16061	0.00053	0.06150	0.9654	0.0158
		LW	X_1	1.3253	−0.00013	—	0.0412	0.1901 NS
			X_2	0.3131	—	0.1270	0.8846	0.0659
			X_1X_2	−0.04383	0.00015	0.14067	0.9315	0.0587
		Combined	X_1	−0.04912	0.00064	—	0.8155	0.1932
			X_2	−0.09529	—	0.1894	0.9674	0.0812
			X_1X_2	−0.14065	0.00020	0.14437	0.9926	0.0409

[1] EW—Earlywood.
[2] LW—Latewood.
[3] NS—Not significant at 95%.

assuming longitudinal shrinkage is zero. S_t is the coefficient of shrinkage of tracheids only in cross section.

Considering the tracheids only,

$$S_t = (N_t \times T)(N_r \times R) - (N_t \times T')(N_r \times R')$$

$$\text{but } N_t \times T = 1 \text{ and } N_r \times R = 1 \text{ or} \qquad (4)$$

$$S_t = 1 - (N_t \times T')(N_r \times R')$$

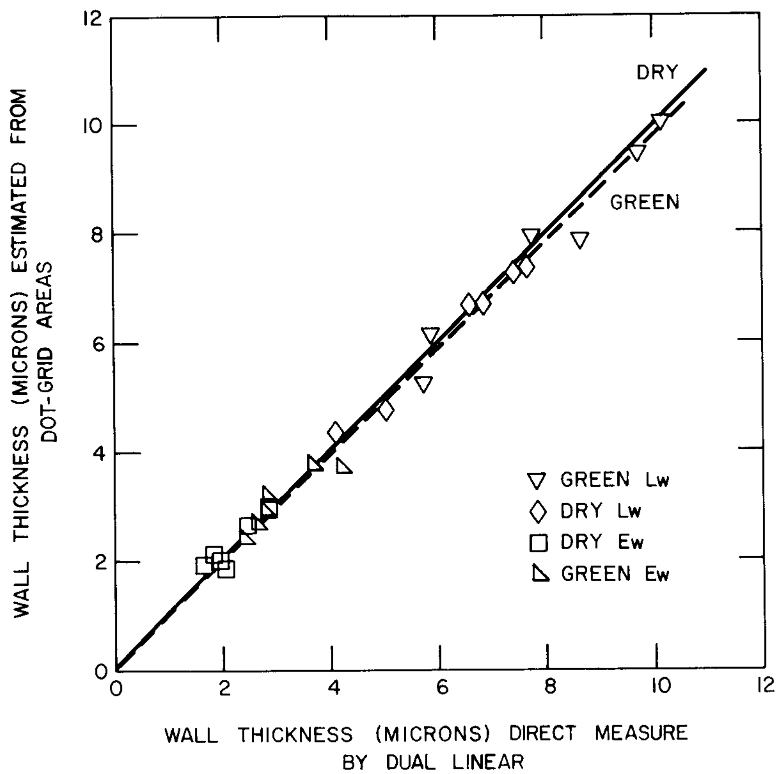

FIG. 1. Comparison of wall thickness determined by direct measure and by indirect measure from modeling.

Considering the whole wood (tracheids plus rays), the number of tracheids per mm of water-swollen wood, measured in the tangential direction is

$$N_t = \frac{1 - (NR \times RD)}{T}$$

Therefore,

$$S_2 = 1 - \left[\frac{1 - (NR \times RD)}{T} \times T' + (NR \times RD')\right]\left[N_r \times R'\right] \quad (5)$$

or

$$S_2 = 1 - [(N_t \times T') + (NR \times RD')][(N_r \times R')]$$

Percentage of shrinkage from green to oven-dry condition

Percentage shrinkage in cross-sectional tracheid wall area = S_w

$$S_w = \left[1 - \left(\frac{Zt'}{Zt}\right)(1 - S_1)\right] \times 100 \quad (6)$$

for whole wood wall area use Z_w and S_2 values.

Percentage shrinkage in cross-sectional lumen area = S_L

TABLE 2a. *Average measurement data for earlywood and latewood of Douglas-fir: tracheids.*

Specimen	Specific gravity		Number of tracheids per mm²		Average tracheid diameter				Proportional tracheid wall area				Coefficient of tracheid shrinkage, S_t
					Tangential		Radial		Dual-Linear		Zeiss dot-grid		
	Green	Dry	Green (NG)	Dry (ND)	Green	Dry	Green	Dry	Green (D_t)	Dry (D'_t)	Green (Z_t)	Dry (Z'_t)	
					μm				*mm²*				%
					Earlywood								
1	0.349	0.393	628.2	703.7	34.6	31.8	46.0	44.6	0.3828	0.2853	0.3466	0.2937	10.73
2	0.349	0.375	710.6	757.1	36.2	33.8	38.9	39.1	0.3542	0.2541	0.3623	0.2699	6.14
3	0.280	0.301	600.4	649.4	33.7	31.5	49.4	48.9	0.2666	0.1972	0.2943	0.1918	7.54
4	0.276	0.302	627.3	685.7	32.6	30.0	48.9	48.6	0.2688	0.1995	0.2736	0.2050	8.53
5	0.232	0.241	524.0	541.8	36.8	34.7	51.8	53.3	0.2301	0.1669	0.2328	0.1913	3.28
6	0.220	0.235	521.9	558.6	35.6	33.9	53.8	52.8	0.2124	0.1558	0.2139	0.1785	6.58
Average	0.284	0.308	602.1	649.4	34.9	32.6	48.2	47.9	0.2858	0.2098	0.2873	0.2217	7.13
					Latewood								
1	0.954	1.329	1,301.1	1,819.7	32.3	27.9	23.8	19.7	0.9447	0.8836	0.9410	0.8742	28.50
2	0.905	1.181	1,633.7	2,136.4	30.9	27.3	19.8	17.2	0.8934	0.8890	0.9025	0.8866	23.53
3	0.827	1.178	1,023.4	1,465.6	33.4	28.1	29.3	24.2	0.8609	0.8338	0.8440	0.8108	30.17
4	0.798	1.087	1,189.7	1,643.0	32.7	27.1	25.7	22.5	0.8452	0.8073	0.7974	0.7937	27.59
5	0.695	0.912	1,338.4	1,752.5	31.9	27.4	23.4	20.9	0.6854	0.6718	0.7056	0.6408	23.63
6	0.650	0.875	1,559.6	2,101.1	28.6	24.6	22.4	19.3	0.7067	0.6161	0.6645	0.6439	25.77
Average	0.805	1.094	1,341.0	1,819.7	31.6	27.1	24.1	20.6	0.8227	0.7836	0.8092	0.7750	26.53

TABLE 2b. *Average measurement data for earlywood and latewood of Douglas-fir: rays, whole wood.*

Specimen	Rays: Diameter		Rays: Number per millimeter		Wall thickness: Dual-Linear		Wall thickness: Zeiss dot-grid[1]		Proportional wood wall area: Dual-Linear		Proportional wood wall area: Zeiss dot-grid		Number of cells per unit area, whole wood (tracheids and rays)		Volumetric shrinkage of whole wood, S_2
	Green	Dry	Green	Dry	Green	Dry	Green	Dry	Green (D_w)	Dry (D'_w)	Green (Z_w)	Dry (Z'_w)	Green (NG)	Dry (ND)	
	μm				μm				mm²						%
Earlywood															
1	12.0	9.8	3.6	3.9	4.22	2.87	3.77	2.96	0.3742	0.2794	0.3459	0.2929	601.2	677.0	11.20
2	10.6	8.4	4.7	4.9	3.68	2.47	3.78	2.64	0.3460	0.2488	0.3614	0.2690	675.3	725.9	6.97
3	12.4	10.9	4.9	5.2	2.87	1.99	3.19	1.93	0.2574	0.1906	0.2933	0.1908	563.9	612.4	7.91
4	12.8	11.4	4.6	5.1	2.83	1.95	2.88	2.00	0.2598	0.1925	0.2728	0.2041	590.5	645.7	8.55
5	12.8	11.9	3.5	3.4	2.63	1.83	2.67	2.11	0.2243	0.1628	0.2323	0.1907	500.4	519.6	3.70
6	13.6	11.2	3.7	4.4	2.40	1.67	2.42	1.93	0.2062	0.1513	0.2134	0.1780	495.9	531.2	6.64
Average	12.3	10.6	4.2	4.5	3.11	2.13	3.11	2.26	0.2780	0.2042	0.2865	0.2209	571.2	618.6	7.50
Latewood															
1	10.1	9.4	3.9	4.2	10.13	7.41	10.04	7.26	0.9411	0.8785	0.9392	0.8724	1,251.1	1,743.4	28.24
2	12.4	11.5	4.1	4.2	7.78	6.59	7.92	6.68	0.8879	0.8833	0.8998	0.8839	1,551.0	2,022.7	23.32
3	12.0	11.9	4.8	5.5	9.74	7.68	9.40	7.33	0.8498	0.8204	0.8414	0.8082	961.0	1,369.9	29.85
4	14.1	13.1	4.7	5.9	8.63	6.85	7.85	6.67	0.8338	0.7922	0.7945	0.7908	1,112.3	1,516.2	26.63
5	11.1	10.7	4.9	5.5	5.88	5.02	6.12	4.71	0.6755	0.6607	0.7032	0.6384	1,256.8	1,650.2	23.84
6	10.0	8.7	4.5	5.2	5.73	4.10	5.26	4.35	0.6978	0.6074	0.6480	0.6274	1,488.7	2,005.5	25.77
Average	11.6	10.9	4.5	5.1	7.98	6.28	7.77	6.17	0.8143	0.7738	0.8043	0.7702	1,270.2	1,718.0	26.28

[1] Wall thickness estimated from $W = \frac{T + R}{4}\left[1 - \sqrt{1 - \frac{4TR}{(T + R)^2} \times Z_t}\right]$

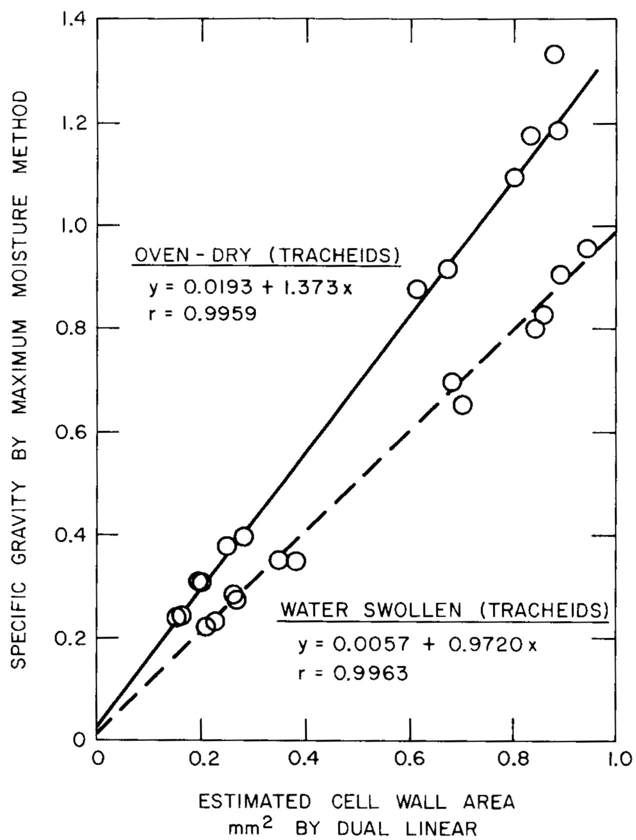

FIG. 2. Specific gravity estimates from cell-wall area determined by Dual-Linear method for both earlywood and latewood in the green and oven-dry condition.

$$S_L = \left[1 - \frac{(1 - Zt')}{(1 - Zt)}(1 - S_t)\right] \times 100 \tag{7}$$

Shrinkage in wall area as percent of cell area

$$S_w = Z_t - Z_t'\left(\frac{(N_r \times N_t)}{(N_r' \times N_t')}\right) \times 100 \tag{8}$$

Shrinkage in lumen area as percent of cell area

$$S_L = (1 - Z_t) - (1 - Z_t')\frac{(N_r \times N_t)}{(N_r' \times N_t')} \times 100 \tag{9}$$

Shrinkage in tracheid diameter

Tangential, $$ST = \frac{(T - T')}{T} \times 100 \tag{10}$$

Radial, $$SR = \frac{(R - R')}{R} \times 100 \tag{11}$$

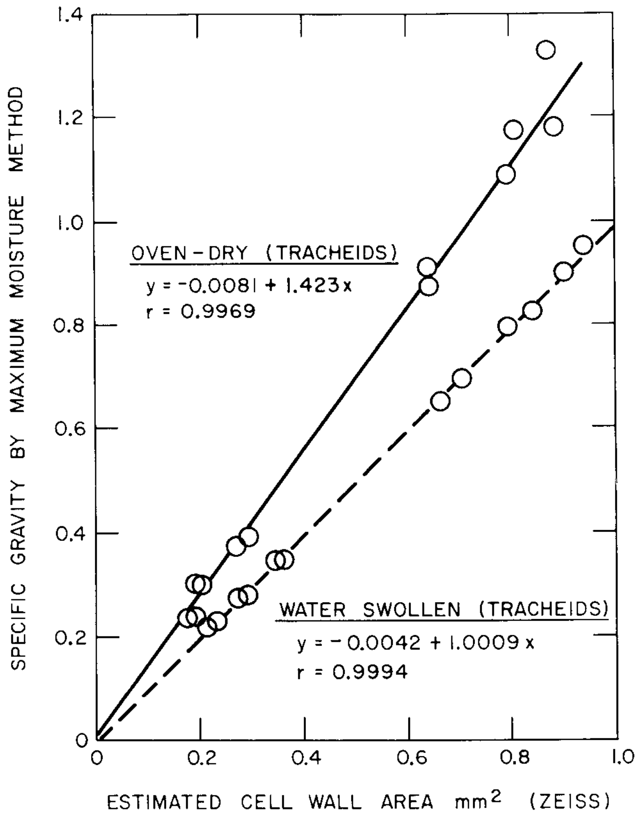

FIG. 3. Specific gravity estimates from cell-wall area determined by the Zeiss dot-grid method for both earlywood and latewood in the green and oven-dry condition.

Shrinkage in cell-wall thickness

$$SW = \frac{(w - w')}{W} \times 100 \tag{12}$$

Shrinkage in diameter of rays

$$SRD = \frac{(RD - RD')}{RD} \times 100 \tag{13}$$

Estimated wall thickness from dot-grid area measurements with the Zeiss eyepiece

$$w = \frac{(T + R)}{4}\left[1 - \sqrt{1 - \frac{4TR}{(T + R)^2} \times Z_t}\right] \tag{14}$$

where

T = tangential cell diameter
R = radial cell diameter
Z_t = proportional area in tracheid wall.

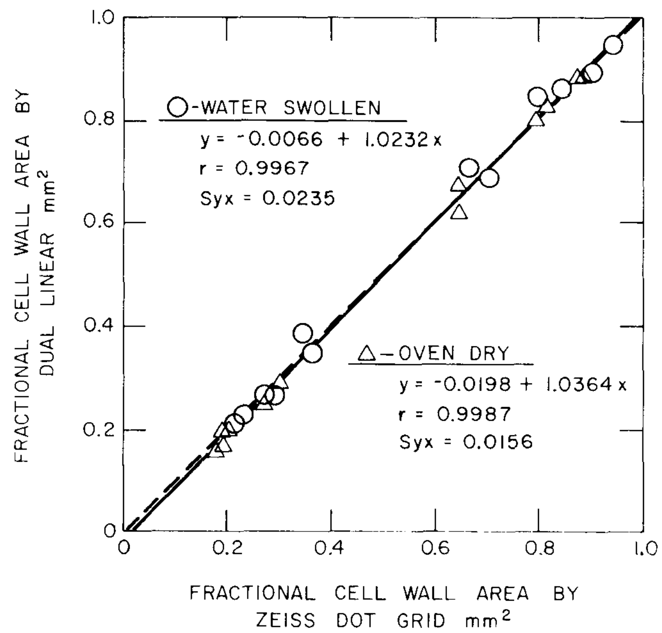

FIG. 4. Comparison of wall area determined by both the Dual-Linear and Zeiss dot-grid methods for both earlywood and latewood in the green and oven-dry condition.

RESULTS AND DISCUSSION

Multiple regression equations were developed separately for the samples measured both by the modeling and direct measuring techniques to determine the relationship between specific gravity and the two independent variables: number of cells per square millimeter X_1 and average tangential wall thickness X_2. These two variables together are associated with 90% to 99% of the specific gravity variation of the earlywood and latewood in both the water-swollen and oven-dry condition (Table 1). In all cases the association was closer for wall thickness than for number of cells per square millimeter.

The relationship between basic density (dry weight/green volume) and wall thickness was examined. Wall thickness was measured directly with the Dual-Linear (Table 1), whereas wall thickness from the dot-grid direct area measurements Z_t was estimated by Eq. (14) from Smith and Miller (1964).

Wall thickness and basic density were highly correlated ($r^2 = 0.93$ water swollen; and $r^2 = 0.96$ oven-dry); the relationships for wall thickness X_2 with specific gravity are shown in Table 1. The standard deviation about the regression indicates that wall thickness can be derived by equation with greater precision using the dot-grid system than it can be measured using the Dual-Linear. However, on the basis of a paired "*t*" test, there were no significant differences between wall thickness as estimated by equation from dot-grid data or, as measured directly, for earlywood or for latewood in either the water swollen or in the oven-dry condition. The regression relationships between estimated wall thickness Y and measured wall thickness X are given by the following equations and are demonstrated in Fig. 1.

TABLE 3. *Regression of specific gravity and ratio of wall to cross-sectional area.*

	Through data	Through origin
	Tracheids only	
Water swollen		
Dual-Linear[1]	$y = 0.0057 + 0.972x$; $r = 0.9963$; $S_{yx} = 0.0244$	$y = 0.9803x$; $r = 0.9993$; $S_{yx} = 0.0246$
Dot-grid[2]	$y = -0.0042 \pm 1.0009x$; $r = 0.9994$; $S_{yx} = 0.0098$	$y = 0.9948x$; $r = 0.9987$; $S_{yx} = 0.0156$
Dual-Linear on dot grid[3]	$y = -0.0066 \pm 1.023x$; $r = 0.9967$; $S_{yx} = 0.0235$	
Oven-dry		
Dual-Linear[1]	$y = 0.0193 + 1.373x$; $r = 0.9959$; $S_{yx} = 0.0405$	$y = 1.401x$; $r = 0.9989$; $S_{yx} = 0.0399$
Dot-grid[2]	$y = -0.0081 + 1.423x$; $r = 0.9969$; $S_{yx} = 0.0330$	$y = 1.411x$; $r = 0.9987$; $S_{yx} = 0.0431$
Dual-Linear on dot grid[3]	$y = -0.0198 + 1.0364x$; $r = 0.9987$; $S_{yx} = 0.0156$	
	Whole wood (tracheids, rays, and resin ducts)	
Water swollen		
Dual-Linear	$y = 0.0132 + 0.9727x$; $r = 0.9967$; $S_{yx} = 0.0243$	$y = 0.9919x$; $r = 0.9993$; $S_{yx} = 0.0240$
Dot-grid	$y = -0.0041 + 1.006x$; $r = 0.9995$; $S_{yx} = 0.0094$	$y = 0.9998x$; $r = 0.9998$; $S_{yx} = 0.0092$
Oven-dry		
Dual-Linear	$y = -0.0077 + 1.431x$; $r = 0.9953$; $S_{yx} = 0.0436$	$y = 1.419x$; $r = 0.9988$; $S_{yx} = 0.0418$
Dot-grid	$y = 0.0254 + 1.382x$; $r = 0.9962$; $S_{yx} = 0.0392$	$y = 1.420x$; $r = 0.9989$; $S_{yx} = 0.0398$

[1] Fig. 2.
[2] Fig. 3.
[3] Fig. 4.

$$\text{Green } Y = 0.1690 + 0.9499X;\ r = 0.9872;\ S_{yx} = 0.3268$$

$$\text{Dry } Y = 0.02777 + 0.9366X;\ r = 0.9951;\ S_{yx} = 0.1650$$

The relationship established by the foregoing regression gives confidence that either methodology gives equivalent values for wall thickness, specific gravity, and cell-wall area measurements in either the water-swollen or the oven-dry condition.

The relationship between cell-wall area and wood specific gravity was examined for both the rectangular lumen model (in the water-swollen and oven-dry condition) and direct dot-grid measurement (in the water-swollen and oven-dry condition) (Table 2). Cell-wall cross-sectional area correlates well ($r = 0.99$) with wood density by modeling with the Dual-Linear (Fig. 2) and by direct measurement with the superimposed dot-grid (Fig. 3). These correlations verify the modeling approach of Smith (1965) and also the comparison work by Quirk (1975) on the efficiency of the Dual-Linear as compared to the superimposed dot-grid system for intact specimens in the water-swollen and extractive-free condition. Data from the present study (Fig. 4) confirm that these two methodologies also are valid for the oven-dry condition.

Table 3 summarizes the regressions of specific gravity and the ratio of wall to cross-sectional area both for tracheids alone and for the whole wood (rays and tracheids). In addition, the regressions were forced through the origin so that the slope of the regression between specific gravity G and wall area A gives preliminary estimates of cell-wall density D for both the water-swollen (0.99 g/cc) and oven-dry condition (1.42 g/cc).

The regression relationships established for both techniques for measuring anatomic parameters give credence to the efficacy of the shrinkage values covered in the following section.

Percent shrinkage from water-swollen to oven-dry condition

Cross-sectional cell-wall area.—Table 4 summarizes the percent shrinkage in area both on a per cell and per square millimeter basis. The extent of shrinkage expressed as a percent of cell area was 26.5% for latewood and 7.1% for earlywood cells (measured either by the Dual-Linear or the dot-grid technique). The average size of a latewood cell is only 45% as large in cross-sectional area as the average earlywood cell; however, a latewood cell had 82% of its cross-sectional area occupied by cell wall compared to an average of 29% for an earlywood cell.

As expected, the smaller size and greater percent of area shrinkage in the latewood cells resulted in a larger increase in the number of cells occupying a square millimeter in the oven-dry latewood compared to the water-swollen latewood. The number of cells per unit area increased an average of 35.3% in latewood because of drying, whereas the change was only 8.3% in earlywood (as calculated from Table 2).

Shrinkage occurring per square millimeter in cross-sectional tracheid wall area was approximately 30% (Table 4 from Eq. 6) for earlywood or for latewood. The values derived by the dot-grid technique were slightly less than those derived by cell modeling with the Dual-Linear technique.

The lumen area.—From the summary data (Table 4), it was obvious that shrink-

TABLE 4. *Percent shrinkage from green to oven-dry condition for Douglas-fir.*

	Earlywood	Latewood
	Zeiss information (area)	
Fractional cell-wall area		
Green	0.287	0.809
Shrinkage area		
Cell (4)[1]	7.13	26.53
Wall (8)	8.18	24.06
Lumen (9)	−1.06 (expands)	2.47 (contracts)
	Dual-Linear information (area)	
Fractional cell-wall area		
Green	0.286	0.823
Shrinkage area		
Cell (4)[1]	7.13	26.53
Wall (8)	9.16	24.79
Lumen (9)	−2.04 (expands)	1.74 (contracts)
	Shrinkage in cell perimeter (%)	
Cell	3.13	14.27
Lumen	−1.97 (expands)	9.51 (contracts)
	Information on lineal direction of shrinkage (%)	
Tracheids		
Tangential	6.6 (10)	14.4
Radial	0.6 (11)	14.2
Lumen		
Tangential	1.2	6.3
Radial	−5.1	−3.3
Wall thickness	31.5 (12)	21.3
Ray diameter	13.8 (13)	6.0
Wall area per square millimeter		
Dual-Linear	31.9 (6)	30.1
Zeiss	28.0	29.7

[1] Numbers in parentheses refer to equations used.

age of an entire latewood cell was greater than that for earlywood. Cell shrinkage was the net result of the behavior of both the cell wall and the lumen. By either of the two measuring techniques employed, it was determined that the lumen of the earlywood cells expanded with drying, but the lumen of latewood cells shrank. This notable behavioral difference was further examined. The proportion of cell wall to middle lamella is greater in latewood than in earlywood, the difference being essentially in the thickness of the secondary layer of the cell wall. In isolated samples of the two cell types, it would appear that there could be more resistance to lateral movement (from drying due to the higher ratio of lignified compound middle lamella to secondary S_2 wall) in earlywood compared to latewood. The probability of restraint upon drying is also reflected in the measurements of cell perimeters upon drying. In isolated earlywood, the cells tend to shrink in situ, as indicated by a small (3%) shrinkage in outer cell perimeter, while the lumen perimeter expands some 2% (Table 4). Alternatively, in the latewood cells, where there is a higher ratio of secondary wall to middle lamella, the cells shrink some

TABLE 5. *Comparison of tangential, radial, and volumetric shrinkage values from Quirk and others.*[1]

Group	Latewood	Specific gravity		Shrinkage			
		Green	Oven-dry	Radial	Tangential	Volumetric	Tangential/radial
	%						
Markwardt and Wilson (1935)							
Coastal	36	0.45	—	5.0	7.8	11.8	1.56
Intermediate	34	0.41	—	4.2	7.4	11.2	1.76
Inland	27	0.40	—	3.6	6.2	10.6	1.72
Quirk—extractive free							
Isolated specimens							
Earlywood	0	0.28	0.31	0.6	6.6	7.1	6.41
Latewood	100	0.80	1.09	14.2	14.4	26.5	1.04
Pentoney—unextracted							
Earlywood	0	—	0.39	2.4	4.8	—	2.37
Latewood	100	—	0.85	8.9	7.2	—	0.82
Vintila—unextracted							
Earlywood	0	—	0.28	2.9	5.7	8.8	1.97
Latewood	100	—	0.84	9.9	10.9	20.0	1.10
Shrinkage of whole wood							
Quirk (1975)	30	0.44	0.54	4.7	8.9	13.1	1.90
Pentoney (1953)	37	—	—	4.4	7.2	—	1.66
Vintila (1939)	40	—	—	5.2	8.2	12.2	1.58

[1] Shrinkage from water-swollen to oven-dry condition for isolated specimens of Douglas-fir earlywood and latewood in the extractive-free condition.

14.3% in outer cell perimeter and the lumen perimeter contracts 9.5%. These shifts indicate a greater influence on the secondary wall over the restraining lignified middle lamella. These data support the similar findings of Matsumoto (1950) and Kelsey (1963).

Average tracheid diameter.—In the tangential plane the latewood tracheids were just slightly less in diameter than the average earlywood cell. In the radial direction the earlywood cell diameters were 2.2 times greater than those of latewood. The tangential to radial (T/R) ratio of cell diameters was 1.315 for latewood cells in the water-swollen condition and 1.312 when the cells were dry. Thus, the latewood cells retained integrity upon drying, and shrinkage was similar in both planes. This uniformity was further illustrated in the overall lineal shrinkage measurements showing that latewood shrank 14.4% tangentially and 14.2% radially. The T/R ratio for earlywood cells in the water-swollen condition was 0.725; upon drying it was 0.681. Therefore, upon drying the earlywood cells did not retain integrity, and shrinkage was dissimilar in the two planar directions. This nonuniformity was apparent in the overall lineal shrinkage measurements showing that earlywood shrank 6.6% in the tangential plane but only 0.6% in the radial plane. From these data the obvious conclusion is that the shrinkage mechanism within the earlywood is not the same tangentially and radially.

Average tracheid wall thickness.—Summary data (Table 4) on the lineal measurements of shrinkage show that the walls of earlywood cells shrank more (9.2% by dot-grid or 8.2% by Dual-Linear) in thickness than those of latewood. These data, along with earlier evidence on earlywood lumen expansion and behavior of cell perimeters upon drying, indicate that the earlywood cell walls, having a fairly low ratio of secondary wall to middle lamella, are restrained by the more rigid lamella. Since a differential effect could be expected, earlywood walls subsequently shrink more in thickness with moisture loss than do latewood cell walls.

In the first part of this study, it had been determined that wall thickness was highly correlated with basic density. For this reason a number of measurements relative to the cell wall were examined as predictors of the T/R shrinkage ratio for whole wood. Nakato (1958c) considered cell-wall structure responsible for anisotropic shrinkage. He attributed the variation in shrinkage and also shrinkage anisotropy to the ratio of the number of cell walls per unit length in either planar direction. For his data the ratio of the number of walls in the tangential to radial plane between latewood and earlywood was 1.93, similar to a T/R ratio of 1.90 established in this study for whole wood of Douglas-fir in the extracted condition (Table 5).

Another alternative examined was the cumulative wall thickness ratio following the same format as above for number of walls. In this case the cumulative tangential to radial wall thickness per millimeter of planar direction between latewood and earlywood was 1.93, also in close agreement with the T/R ratio for whole wood. At the same time we examined the cell form factor or tangential to radial cell diameter ratio between latewood and earlywood. This figure also was 1.93 and, therefore, a good predictor of the T/R shrinkage for the whole wood.

The above data on wall thickness measurements support the hypothesis of Nakato (1958c) on predicting whole wood shrinkage by the ratio of the number of cross walls in planar direction between latewood and earlywood. The data also support the conclusions by Boyd (1974a) on the quantitative effect of cell form factor and wall thickness as main shrinkage determinants.

Width of rays.—On a percentage basis latewood contained slightly more (0.5%) but narrower rays than earlywood. Linear measurements with the Dual-Linear (Table 4) show that the rays in earlywood shrank more than twice as much (2.3×) in the tangential plane as those in latewood.

Comparisons of transverse shrinkage.—Table 5 summarizes the tangential, radial, and volumetric shrinkage values derived in this study on shrinkage from water-swollen to oven-dry condition for isolated specimens of earlywood and of latewood of Douglas-fir in the extractive-free condition. Data are given from earlier studies by Pentoney (1953) and Vintila (1939) on the shrinkage of isolated, but unextracted, specimens of earlywood and of latewood of Douglas-fir. Included also are the shrinkage values for Douglas-fir whole wood in the unextracted condition from Markwardt and Wilson (1935). The general conclusions for these data are similar to those of Pentoney and Vintila in that:

a) Tangential shrinkage of latewood is greater than tangential shrinkage of earlywood.

b) In latewood the radial shrinkage is almost as great as the tangential shrinkage, but in the earlywood the tangential shrinkage is at least two times that of the radial shrinkage.

c) The tangential and radial shrinkage of whole wood lies between the extremes of shrinkage found in isolated earlywood or latewood.

From the work of Nearn (1955) on the effect of extractives on shrinkage, it was expected that tangential and radial shrinkage would be greater in the extractive-free specimens compared to the unextracted ones. Volumetric shrinkage was, as expected, 2% more for extracted than unextracted for the whole wood. Table 5 values from this study compared to values quoted from Markwardt and Wilson (1935).

Researchers other than Pentoney and Vintila have sought to explain the T/R ratio in whole wood specimens of species other than Douglas-fir through shrinkage measurements of isolated earlywood and latewood components. But, as pointed out earlier, conclusions have been the same: other mechanisms are involved that have as yet not been sufficiently elucidated to allow a comprehensive and adequate explanation of anisotropic shrinkage in wood.

Since past investigations on single causative factors have failed to elucidate the anisotropic shrinkage, several researchers (Barber and Meyland 1964; Barber 1968; Cave 1972; Meyland 1972) have developed theoretical models as a rational basis for predicting shrinkage behavior. The models have been demonstrated to be qualitatively compatible with shrinkage behavior at least under the specified conditions. However, to be quantitatively compatible, future models constructed for shrinkage should include component entries that allow for differential behavior of structural entities such as those annotated in Table 4 (lineal measurements on shrinkage, shrinkage in cell perimeter, etc.).

Summary of transverse shrinkage.—The data support the concept of Mörath (1932) that the differential shrinkage of wood is related to the alternation of latewood and earlywood increments within the annual ring. The data also support the findings of other researchers that latewood and earlywood do not shrink in a similar fashion. The data show differences in latewood and earlywood behavior in perimeter shrinkage, lumen shrinkage, wall thickness shrinkage, and also differences in the tangential to radial cell diameter ratio upon drying. The data support the work of Nakato showing that the ratio of the number of cell walls in the tangential and radial plane between latewood and earlywood is a good predictor of the T/R shrinkage ratio for whole wood.

In any case, the cell wall and its structure are implicated in anisotropic shrinkage. This would be expected since wall thickness was shown to be highly correlated with basic density. Undoubtedly future models constructed for shrinkage will be more comprehensive and will take into account the behavioral differences that are measurable between latewood and earlywood.

CONCLUSIONS

1. Either one of two independent measuring techniques is statistically reliable for estimating cell-wall area and specific gravity of the wood, in either the water-swollen or oven-dry condition.
2. Cell-wall thickness is highly correlated with basic density.
3. Cell-wall density can be estimated from the slope of the regression between specific gravity and fractional cell-wall area.
4. The efficiency of either technique is comparable for measuring anatomic parameters.
5. Earlywood and latewood shrinkage are unalike, supporting the theory of Mörath (1932) that differential shrinkage is related to the alternation of latewood and earlywood increments within the annual ring.

6. Cell lumens and cell perimeters of earlywood and of latewood do not shrink alike.

7. The compound middle lamella plays a role in the behavior of wall shrinkage especially in earlywood.

8. Shrinkage in wall thickness in earlywood and latewood differs.

9. Data support the works of Nakato: concluding that the ratio of the number of cell walls in the tangential and radial plane between latewood and earlywood is a good predictor of the T/R shrinkage ratio for whole wood.

Present data do not refute the work of others but rather support other independent studies on shrinkage behavior of wood during drying. The study demonstrates that the shrinkage of earlywood and of latewood are unalike and the differences can be effectively measured by both the Dual-Linear and dot-grid techniques. Further, it demonstrates the necessity for additional factors such as lineal measurements of shrinkage of both earlywood and of latewood to be included in future models on wood shrinkage.

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