TECHNICAL BULLETIN No. 305 JULY, 1932

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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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THE STRENGTH AND RELATED PROPERTIES OF REDWOOD

By R. F. LUXFORD,[1] *Associate Engineer*, and L. J. MARKWARDT, *Senior Engineer, Forest Products Laboratory*,[2] *Branch of Research, Forest Service*

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INTRODUCTION

Redwood is one of the important commercial woods of the United States. The combination of desirable qualities, including relatively high mechanical properties, medium weight, low shrinkage, ease of working, and high resistance to decay enables redwood to meet the requirements of many special as well as ordinary uses, thus giving it a high utility value.

[1] Acknowledgment is made of the cooperation and assistance of the California Redwood Association in this study, particularly that of the Pacific Lumber Co. and the Union Lumber Co.; also of that of Aldo Leopold, formerly of the Forest Service. The valuable assistance in the study rendered by the following members of the Forest Service: J. A. Newlin, B. H. Paul, A. Koehler, M. Y. Pillow, of the Forest Products Laboratory, and C. L. Hill, of the California Forest Experiment Station, is gratefully acknowledged; as are also photographs contributed by the Save-the-Redwoods League.

[2] Maintained by the U. S. Department of Agriculture at Madison, Wis., in cooperation with the University of Wisconsin.

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The redwood, as found in the virgin stands, is one of the largest trees of the world. It is long-lived, reaching an age of 1,300 years or more, and commonly attains a diameter of 5 to 10 feet, and a height of over 250 feet. (Pls. 1 to 3.) Because of its great size, the tree yields a high percentage of clear lumber.

The natural range of redwood is confined to a relatively narrow belt of northern California, extending about 500 miles along the coast and from 10 to 30 miles inland, and in addition there is a small area of some commercial importance south of San Francisco. Redwood grows at elevations ranging from sea level to about 3,000

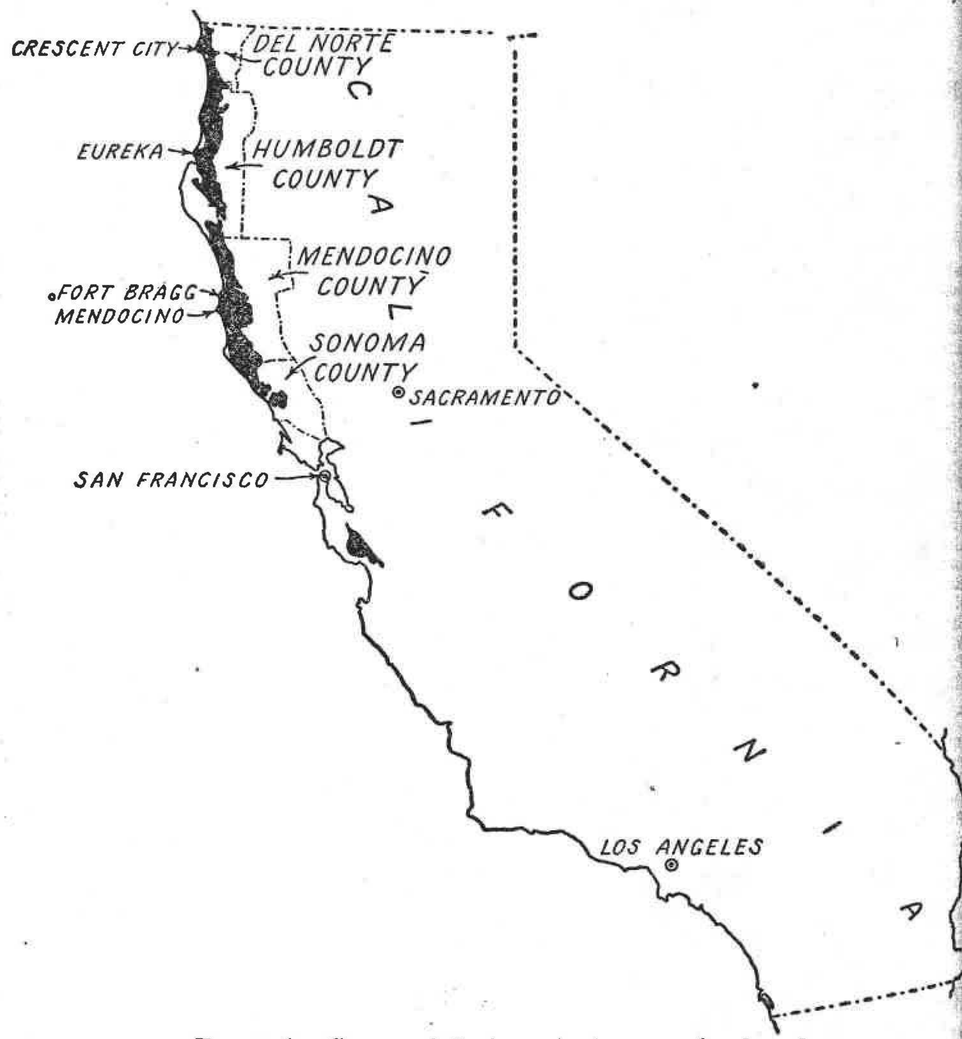
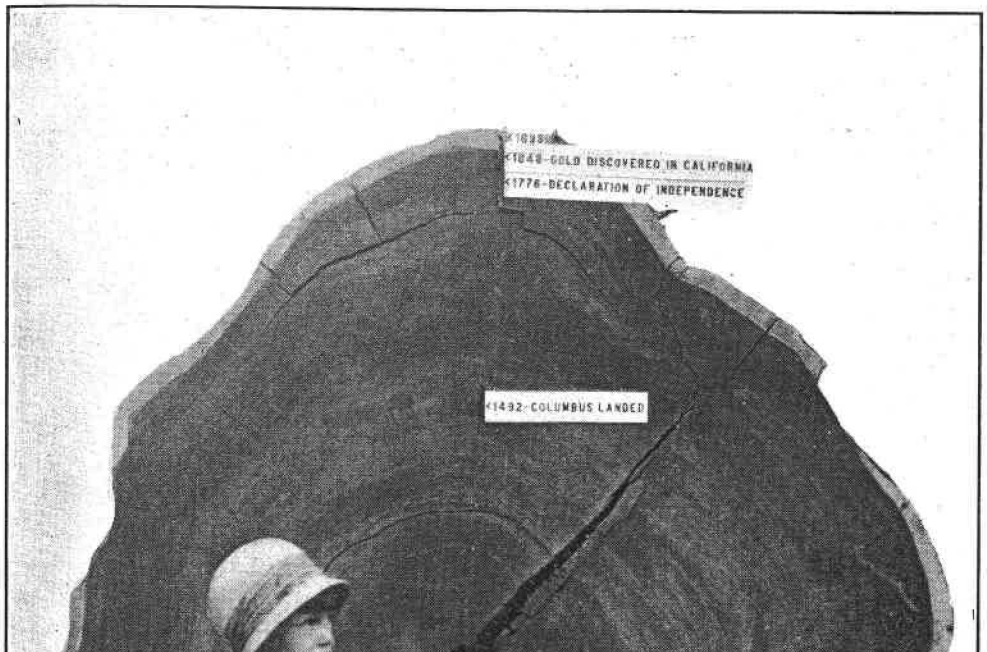


FIGURE 1.—Commercially important range of redwood

feet. The commercially important range of redwood is about 300 miles in length, as indicated by the shaded area in Figure 1. The redwood region is characterized by abundant atmospheric moisture throughout most of the year (*3*).[3]

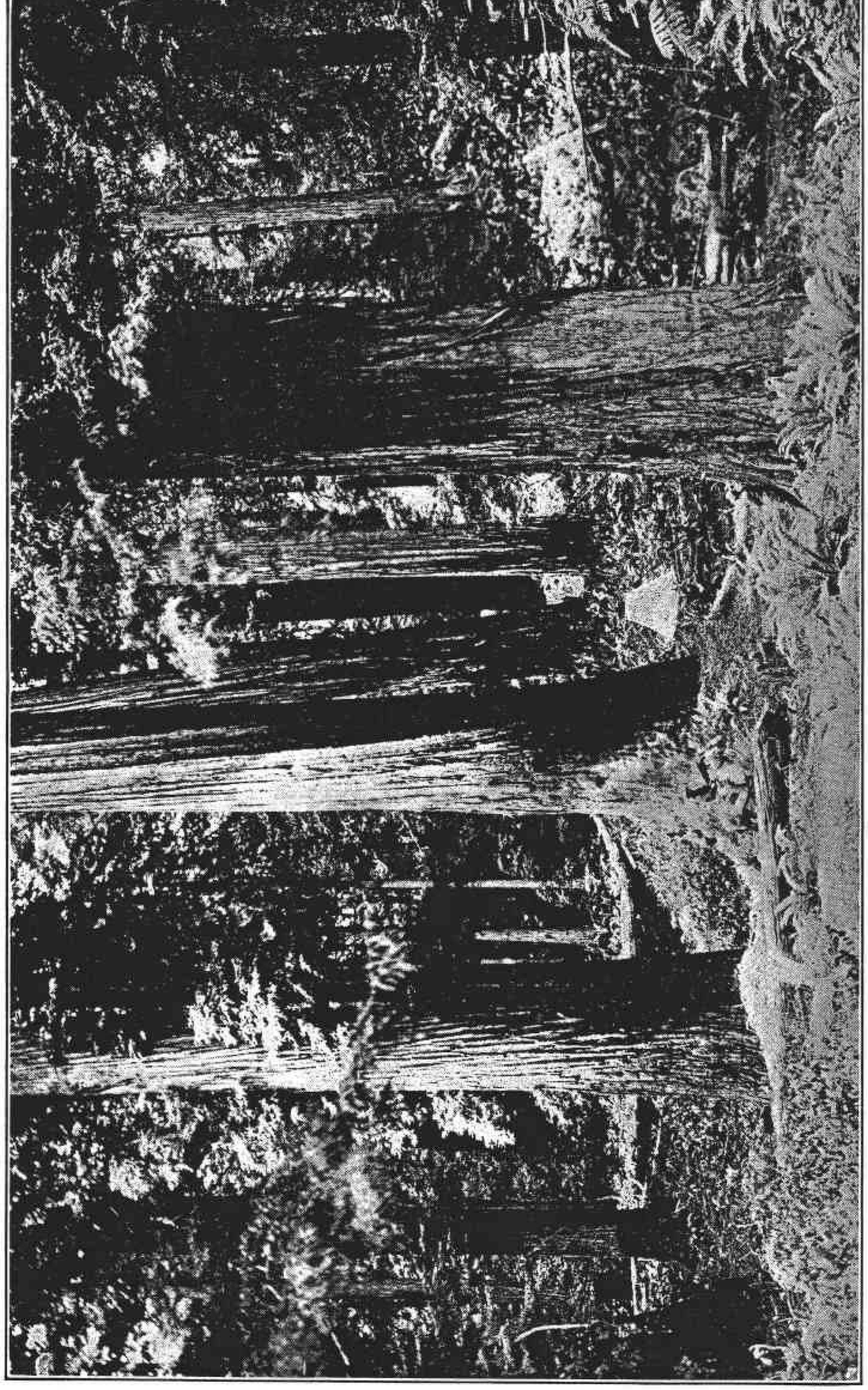
Redwood (*Sequoia sempervirens* (Lambert) Endlicher) should not be confused with big tree (*S. washingtoniana* (Winslow) Sudworth), a closely related but distinct species whose range is confined to the west side of the Sierra Nevada Mountains at elevations from 5,000 to 8,500 feet. In general, the big tree is of larger diameter

[3] Italic numbers in parentheses refer to Literature Cited, p. 48.



REDWOOD TREES ARE LONG LIVED, FREQUENTLY REACHING AN AGE OF 1,300 YEARS OR MORE

The section shown is from a tree 864 years old.



EXAMPLES OF VIRGIN-GROWTH REDWOOD GROWN UNDER FAVORABLE CONDITIONS

Redwood, as found in the virgin stands, is one of the largest trees of the world, commonly attaining a diameter of 5 to 10 feet.

and attains a greater age than the redwood but is not now of commercial importance (*13*).

The stand of virgin redwood was estimated in 1920 at about 72,000,000,000 feet, board measure (*14*), and the annual cut since then has been about 500,000,000 board feet. Although the exhaustion of virgin stands is not to be shortly anticipated, some operators have given and are giving thought to reproduction on cut-over areas, and are looking forward to continued production from second-growth stands. Since most second-growth redwood has ample growing space in its early years, the wood put on in early life is of more rapid growth, weaker, and contains more knots than the virgin-growth redwood that has grown slower under normal forest competition throughout its entire life. Economic considerations will no doubt require that the second-growth stands of redwood be cut before the competition within the stand is sufficient to result in the formation of wood comparable to that of virgin growth.

PURPOSE

The purpose of this bulletin is to present information on the physical and mechanical properties of redwood. Such information is of value to architects, engineers, manufacturers, lumbermen, and others requiring detailed information on the properties of redwood. In addition, it should be of aid to foresters contemplating management plans for reforestation by affording a comparison of the properties of second-growth redwood produced under widely different growth conditions with those of virgin-growth material.

NATURE OF STUDIES

The information on redwood presented in this bulletin resulted from an intensive sampling in the field of trees from different sites and localities for specific gravity, and from selected typical logs that were sent to the Forest Products Laboratory for comprehensive strength tests. Hence the study is discussed under two divisions; namely, (1) specific-gravity survey and (2) strength and related properties.

The specific gravity survey consisted of determining the specific gravity of specimens taken from the pith to the circumference and at intervals from the butt to the top of each of a number of redwood trees from different sites and localities.

The study of properties consisted of standard strength tests on small, clear specimens of virgin-growth and second-growth redwood from Humboldt and Mendocino Counties, Calif. In addition, information was obtained on shrinkage, the abnormal wood known as compression wood, the distribution of moisture within the tree, the effect of moisture on the strength of the wood, and the influence of substances naturally present in the wood, called extractives (p. 21).

SPECIFIC GRAVITY SURVEY

The specific gravity (p. 46) determinations were made on many small specimens from each of 56 virgin-growth and 42 second-growth trees. The trees were selected in different localities from sites (p. 46) that covered the range of growth conditions. The site classes for virgin redwood were determined in accordance with accepted silvicultural practice by the total height development of the dominant trees. The average height of the dominant trees on Site I was 251 feet and over; on Site II, 211 to 250 feet; on Site III, 171 to 210 feet; on Site IV, 131 to 170 feet; and on Site V, 130 feet and under. With second-growth redwood the site classes were based on the age and height development of the dominant and codominant trees (2). Of the second-growth trees from Mendocino County, three were from open stands, which permitted unrestricted crown development; the others were from normally well-stocked stands. (Pl. 4.) The second-growth trees from Humboldt County were all from the same stand.

SPECIFIC GRAVITY AND VARIATION

Table 1 gives the average results of the specific gravity determinations for virgin-growth redwood, and affords a means of comparing material from different sites in Humboldt and Mendocino Counties. Table 2 presents the average results of the specific gravity determinations of virgin-growth and of second-growth redwood without regard to source of material.

TABLE 1.—*Results of specific gravity determinations, by lots from different sites of virgin-growth redwood*

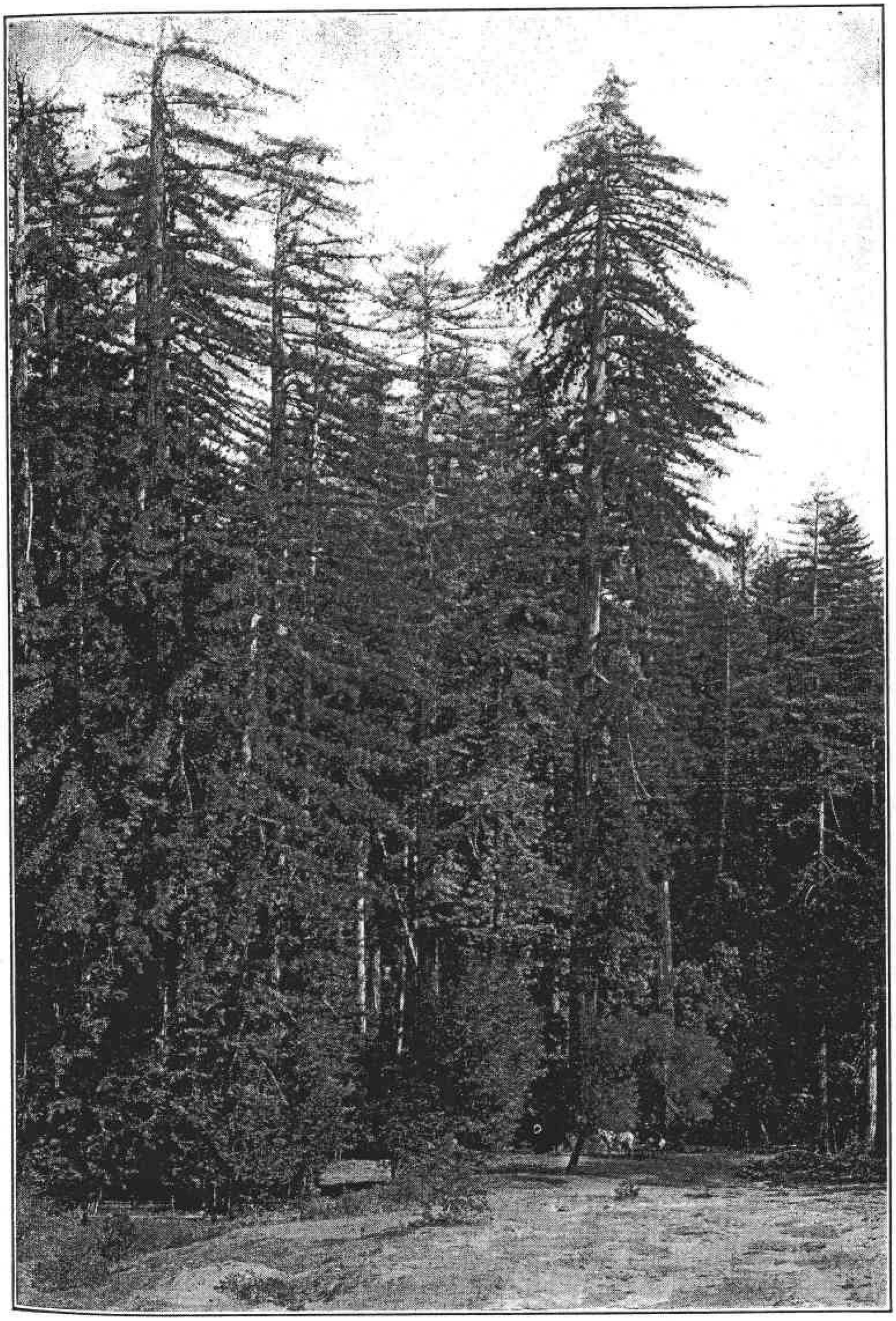
Place of growth	Lot No.	Site class No.	Trees	Specimens	Average specific gravity [1]	Probable variation of—	
						Individual tree from average	Individual specimen from average
			Number	*Number*		*Per cent*	*Per cent*
Humboldt County	3	I	5	452	0.365	8.16	9.69
Do	3	II	4	312	.364	6.90	8.21
Do	3	III	4	168	.375	3.22	9.34
Do	3	III	6	567	.364	8.30	12.15
Do	3	III	5	399	.356	9.00	11.94
Do	3	IV	5	339	.357	5.47	9.73
Total or average		I–IV	29	2,237	.363	5.99	10.60
Mendocino County	2	II	5	467	.388	2.95	9.20
Do	2	II	2	174	.393	----------	11.21
Do	1	III	5	357	.380	7.20	11.17
Do	2	III	5	302	.373	4.33	9.82
Do	1	IV	5	234	.374	1.51	9.86
Do	2	IV	5	275	.415	2.97	10.79
Total or average		II–IV	27	1,809	.387	5.00	10.36

[1] Based on the weight of the oven-dry wood and the volume when green.

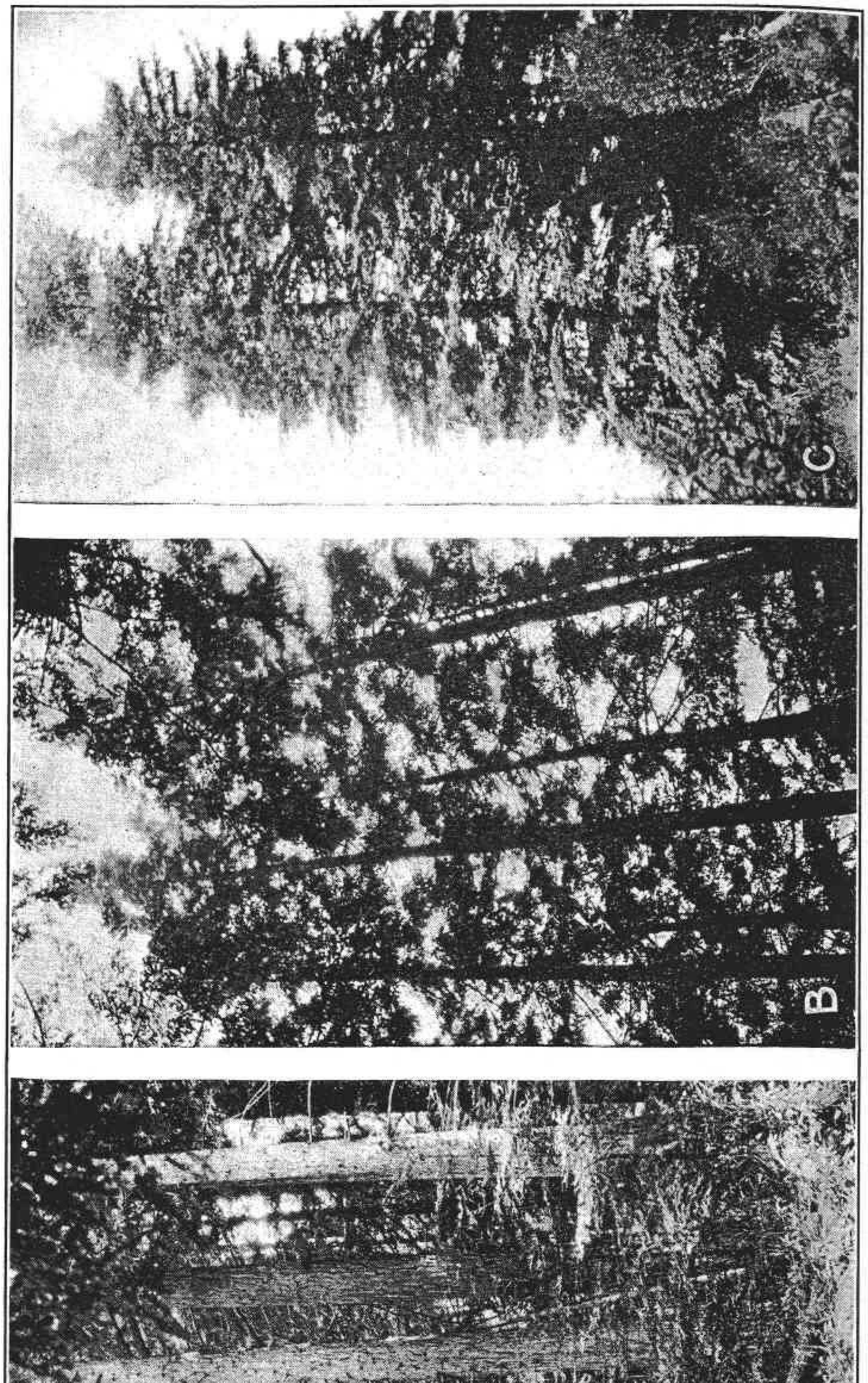
TABLE 2.—*Results of specific gravity determinations of virgin-growth and second-growth redwood*

Type of growth	Trees	Specimens	Average specific gravity [1]	Probable variation of—	
				Individual tree from average	Individual specimen from average
	Number	*Number*		*Per cent*	*Per cent*
Virgin growth	56	4,046	0.374	5.54	10.67
Second growth, closely grown	31	720	.356	4.10	8.17
Second growth, openly grown	11	267	.318	4.98	7.98

[1] Based on the weight of the oven-dry wood and the volume when green.



REDWOODS GROW TO GREAT HEIGHTS, MANY EXCEEDING 250 FEET



SECOND-GROWTH REDWOOD

A, Trunks of closely grown second-growth redwood; B, crowns of closely grown second-growth redwood; C, openly grown second-growth redwood.

The last two columns of Tables 1 and 2 are, respectively, percentage figures on the estimated probable variation in specific gravity of an individual tree as a whole from the corresponding average, and of an individual specimen of a tree from the same average. The probable variation is a value such that there is an even chance that a random specimen will not be above or below the average by more than this amount. For example, the figure 10.67 per cent, given in Table 2 as the probable variation in specific gravity of an individual specimen of virgin-grown redwood, means that there is 1 chance in 4 that a small specimen selected at random will have a specific gravity of less than 0.334, that is, $0.374-(0.1067\times0.374)$; 2 chances in 4 that it will be between 0.334 and 0.414, and 1 chance in 4 that it will be greater than 0.414. Expressed in another way, about one-half of the specimens from the virgin-growth redwood had a specific gravity between 0.334 and 0.414, the other half being divided about equally above and below these limits.

The estimated probable variation in specific gravity of an individual virgin-growth redwood tree from the average of all trees examined for the species was 5.54 per cent.

The estimated probable variation in specific gravity for an individual tree and for an individual specimen of second-growth redwood was less than for virgin growth. (Table 2.) This may, perhaps, be accounted for by the smaller size of the second-growth trees and the likelihood that because of their younger age they had not encountered the range of growth conditions experienced by the virgin-growth trees. In addition, the greater amount of extractives in the virgin-growth redwood was also a contributory factor.

Although definite information is presented on the variability of redwood, it should be noted that variability is not a characteristic of redwood alone but is common to all woods, and in fact all material. It is important to recognize in the manufacture, grading, seasoning, and selection of wood for different uses that all species exhibit variations in the properties of individual pieces, but it is even more important to know something of the extent of these variations. The information presented on the magnitude of variation in the properties of redwood, therefore, should be of particular value in the utilization of this species, since by a careful selection and classification of material of different characteristics and properties, the variability of wood, which is usually regarded as a liability, can, within limits, be made an asset. For example, the dense redwood is preferable for structural timbers, whereas the lighter weight, slow-growth redwood is preferable for such purposes as pattern stock.

SPECIFIC GRAVITY AS AFFECTED BY DISTANCE FROM PITH

Large differences were observed in the specific gravity of redwood within cross sections of the tree at any given height. In some virgin-growth trees, at a given height, a gradual decrease in specific gravity occurred in the heartwood from the pith toward the circumference, in others an increase took place, whereas in others there was but little change. (Fig. 2.) Toward the upper end of the merchantable length, however, the wood near the circumference was generally lighter in weight than at the pith. (Fig. 3.) The sapwood throughout the virgin-growth trees was consistently lighter in weight than the adjoining heartwood, apparently because of the higher content of extractives in the heartwood. The highest and lowest specific gravities of small specimens found in a single tree of virgin growth were 0.518 and 0.210, respectively, both samples coming from the butt cut.

SPECIFIC GRAVITY AS AFFECTED BY HEIGHT IN TREE

The wood at the base of the redwood trees (stump height) was found to be higher in specific gravity than that farther up the stem. (Fig. 4.) The decrease in specific gravity with increasing height in tree for virgin redwood was fairly rapid over the lower half of

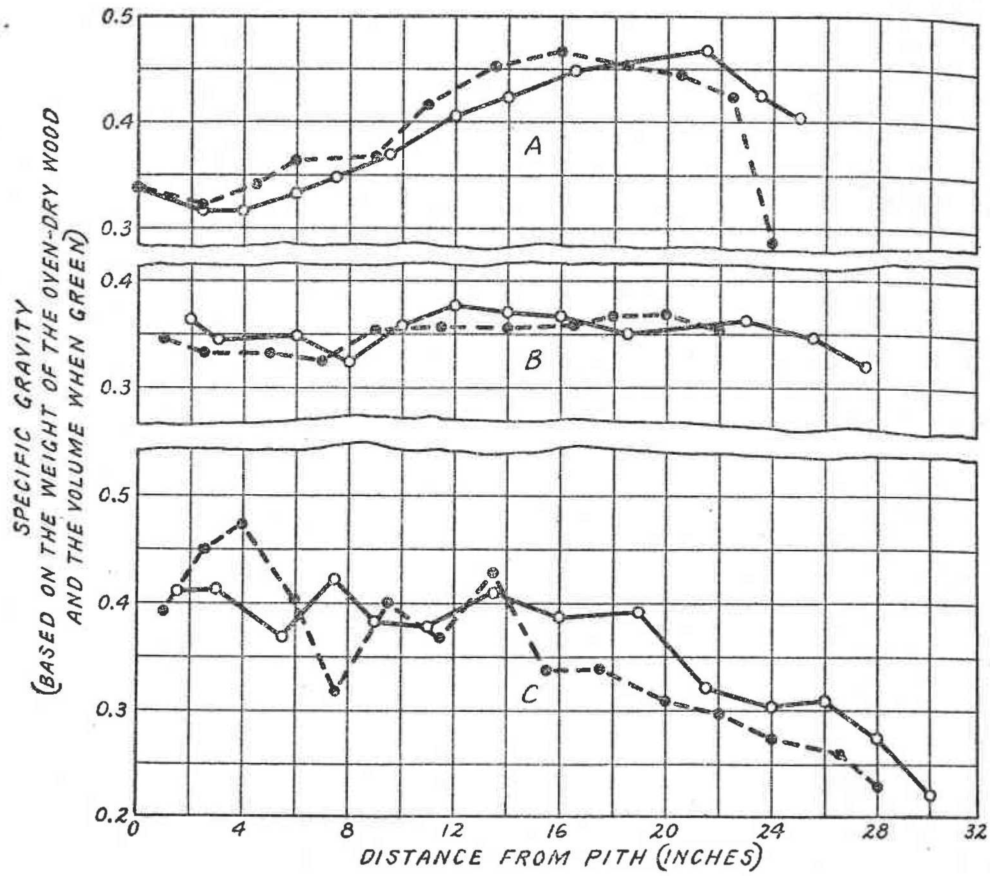


FIGURE 2.—Variation of specific gravity with distance from the pith for three different virgin-growth redwood trees at a height of 20 to 30 feet above the ground, showing (*A*) increase in specific gravity with distance from pith for greater part of diameter (*B*) little or no change, and (*C*) decrease. Each curve is distinguished by full and dotted lines representing specimens taken from opposite sides of the pith

the merchantable length and more gradual toward the top. The average difference in specific gravity of butt and top logs was about 15 per cent, which is sufficient to permit a judicious selection of material in manufacture to meet better the use requirements of service. For example, structural material that is cut from the lower logs of virgin-growth redwood will, for given defect limitations, average higher in strength than that cut from logs higher in the tree.

SPECIFIC GRAVITY VARIATION AMONG TREES

In addition to the variation of wood from different parts of the same tree, redwood, like wood of other species, showed a considerable difference in specific gravity among different trees. The greatest observed difference in average specific gravity between individual trees of virgin-growth redwood from a single site was 25 per cent, which was based on the heaviest tree (fig. 5), whereas the greatest

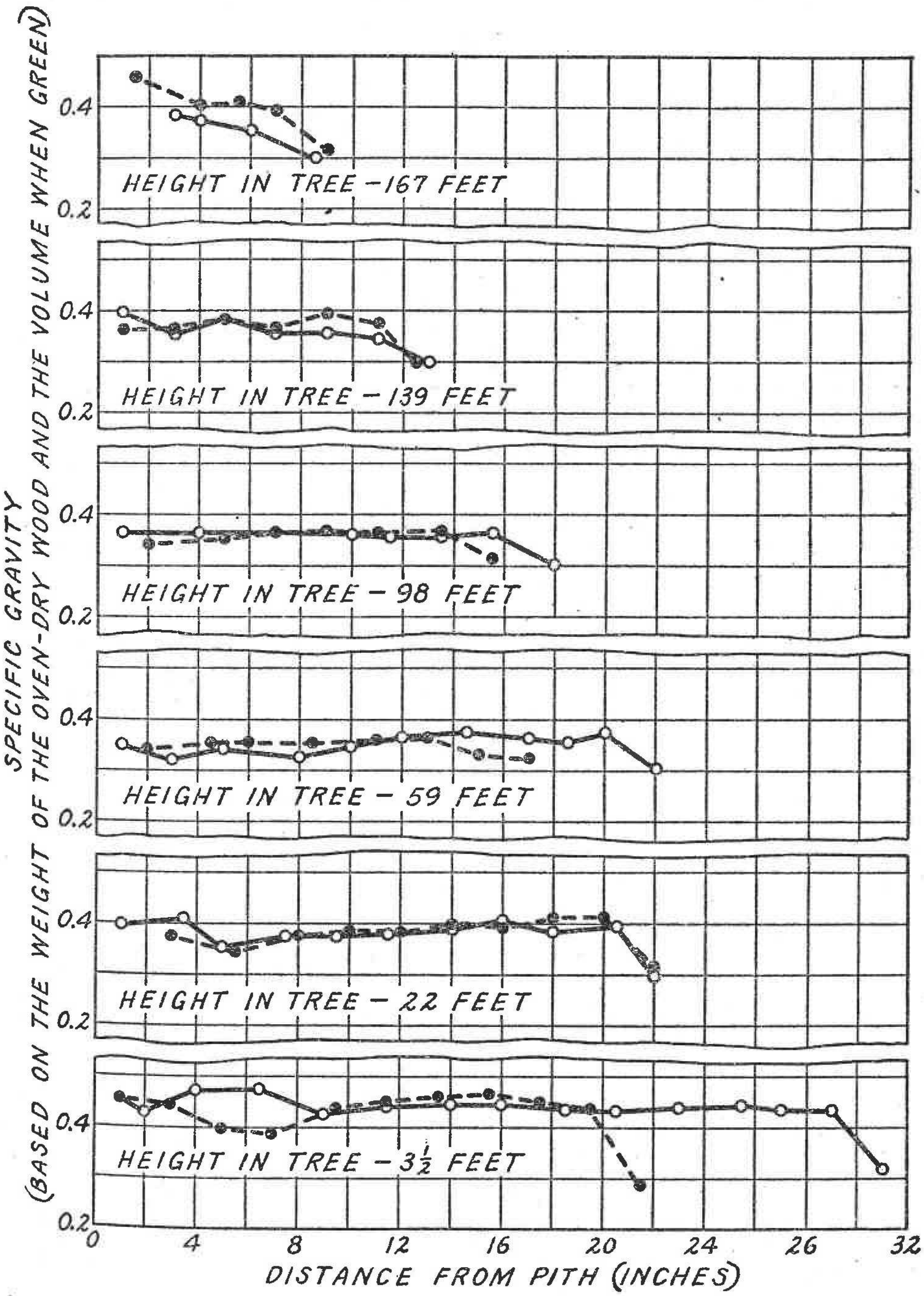


FIGURE 3.—Variation in specific gravity with distance from the pith for different heights in a selected virgin-growth redwood tree. The sharply downward trend at the outer part of the curves is due to the lower specific gravity of the sapwood as compared with the adjoining heartwood. The two curves for each height distinguished by full and dotted lines represent specimens taken from opposite sides of the pith

difference between individual trees throughout the entire range was only 30 per cent. The two trees representing these extremes were from the same county. The data indicate that growth conditions as affecting individual trees within a site and perhaps inherent differences in strains or types of trees are of greater importance in causing variations in virgin-growth redwood than geographical location within the normal range.

SPECIFIC GRAVITY AS AFFECTED BY SITE CLASSIFICATION

No definite relation was apparent between the conditions under which the redwood trees were grown, as indicated by the site classifi-

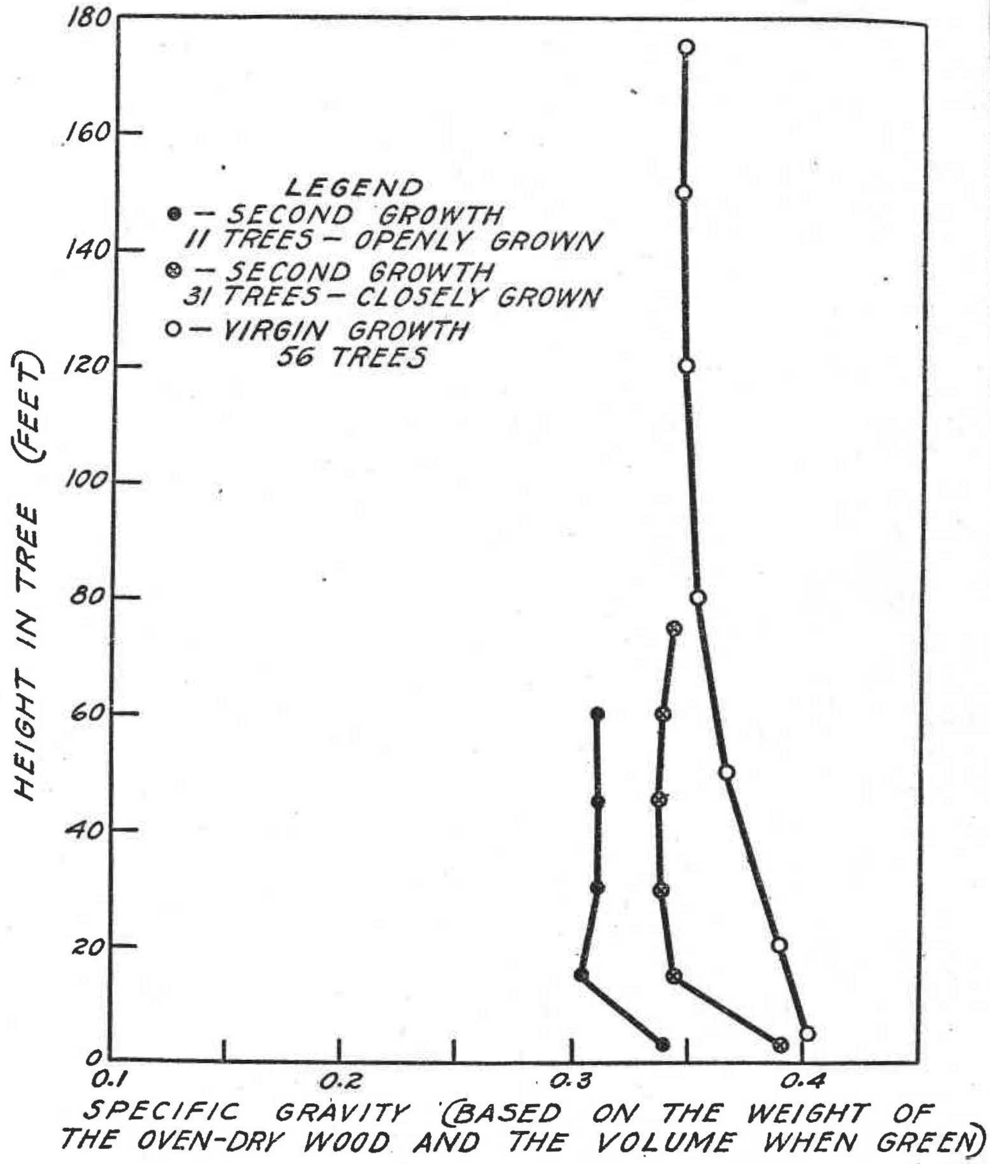


FIGURE 4.—Variation in specific gravity with height in tree for virgin-growth and second-growth redwood. Curves are the average for all trees of each type studied

cation number (p. 4), and the specific gravity of the wood. The average specific gravity values of all the virgin-growth redwood trees from Humboldt County were 0.371, 0.370, 0.367, and 0.361 for Sites I, II, III, IV, and from Mendocino County 0.387, 0.384, and 0.394 for Sites II, III, IV, respectively. (Fig. 6.) If the site quality class is a factor in influencing the specific gravity of redwood, the influence on the material sampled was so small that it is obscured by other factors. For example, the extent to which a tree is crowded has a marked influence on the character of the wood produced, as shown by the fact that in the second-growth redwood the closely grown small-crowned trees were approximately 10 per cent higher in average specific gravity than the large-crowned openly grown trees (*11*).

SPECIFIC GRAVITY AS RELATED TO REGION OF GROWTH

The influence of region of growth on the specific-gravity and strength properties, although known to be of appreciable signifi-

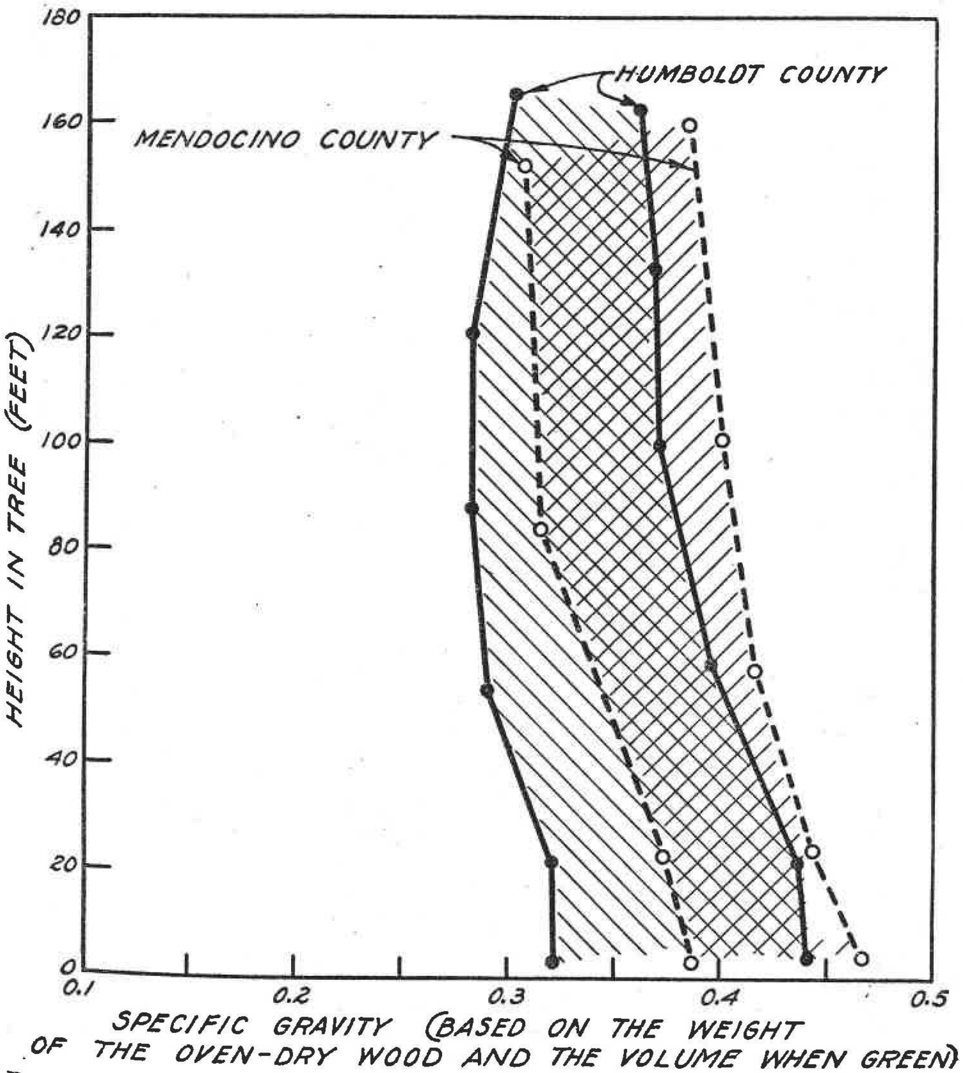


FIGURE 5.—Maximum range in the average specific gravity at various heights of individual virgin-growth redwood trees from single sites in Mendocino and Humboldt Counties

cance in some species, is often overestimated. However, producers have frequently recognized some difference in properties of virgin-growth redwood from the two principal producing regions, Humboldt and Mendocino Counties. The virgin-growth redwood from Mendocino County which was studied had an average specific gravity of 0.387; that from Humboldt County 0.363, the difference being about 6 per cent. (Table 1.) Because of the large differences in individual pieces from the same tree the average difference in specific

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gravity between counties gives no assurance that in small shipments lighter or heavier material will be obtained from one county than from the other. It would appear, however, from the information presented here that large shipments of virgin-growth redwood lum-

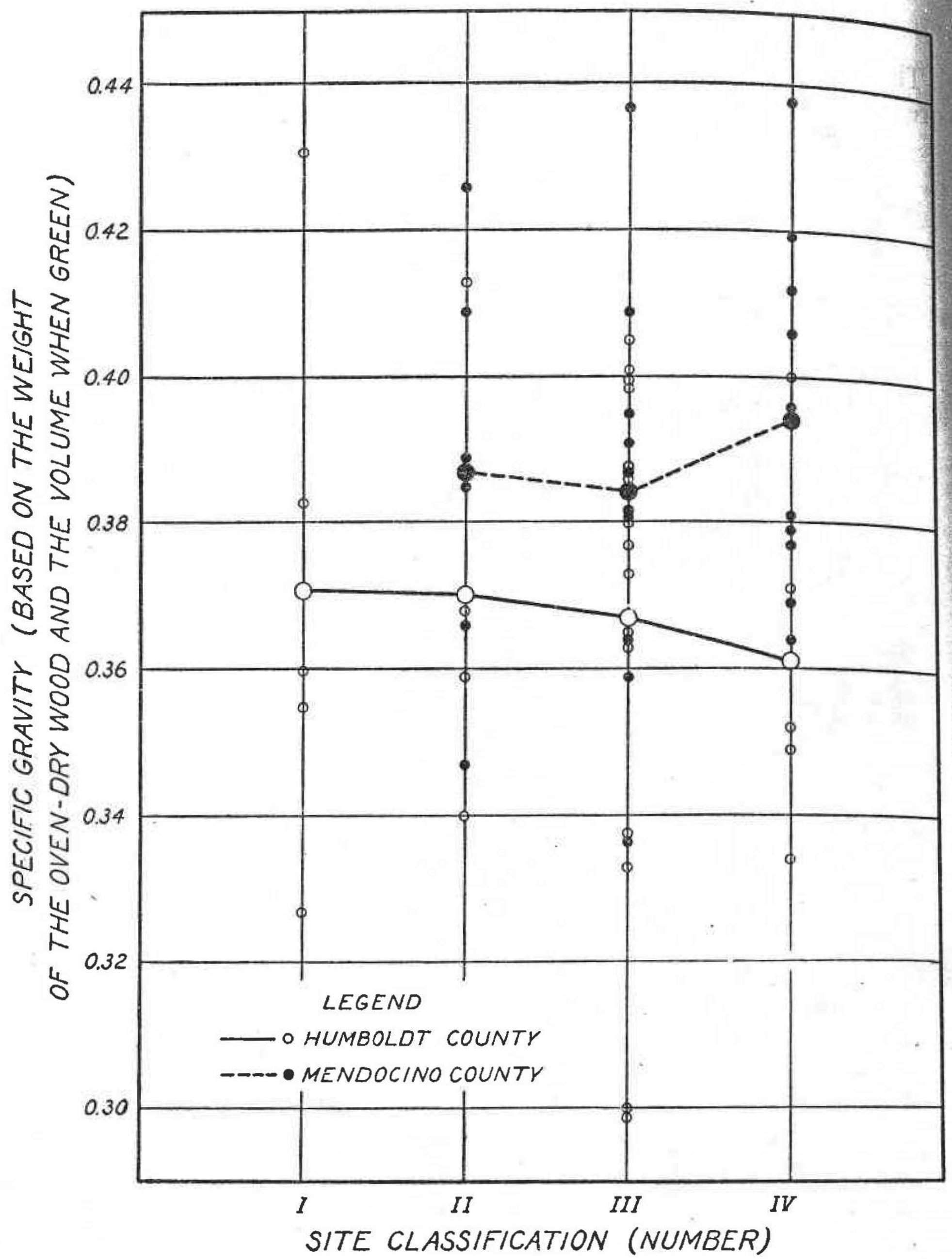


FIGURE 6.—Average specific gravity of individual virgin-growth redwood trees by site classes for Humboldt and Mendocino Counties. The full curve represents the average specific gravity of all trees for each site for Humboldt County and the dotted curve for Mendocino County. A site classified as I has dominant trees 251 feet or over; Site II, 211 to 250 feet; Site III, 171 to 210 feet; Site IV, 131 to 170 feet

ber from Mendocino County would average slightly higher in specific gravity than those from Humboldt County.

There was no significant difference in the average specific gravity of second-growth redwood from Humboldt and Mendocino Counties.

SPECIFIC GRAVITY AS RELATED TO RATE OF GROWTH

Figure 7 shows the relation between specific gravity and rate of growth in the heartwood. Rate of growth is represented by the number of annual rings per inch; the greater the number of rings per inch, the slower the growth rate. (Pl. 5.)

In general, the highest specific gravity is found in redwood having between 9 and 30 rings per inch. Low specific gravity is most commonly associated with exceptionally fast and exceedingly slow growth (*4*). Very slow growth often occurs in the outer portion of mature virgin trees.

Virgin-growth redwood from Humboldt County was found to be lighter in weight for the same rate of growth than that from Mendocino County. Second-growth redwood, on the other hand, showed practically the same relation between rate of growth and specific gravity in one county as in the other.

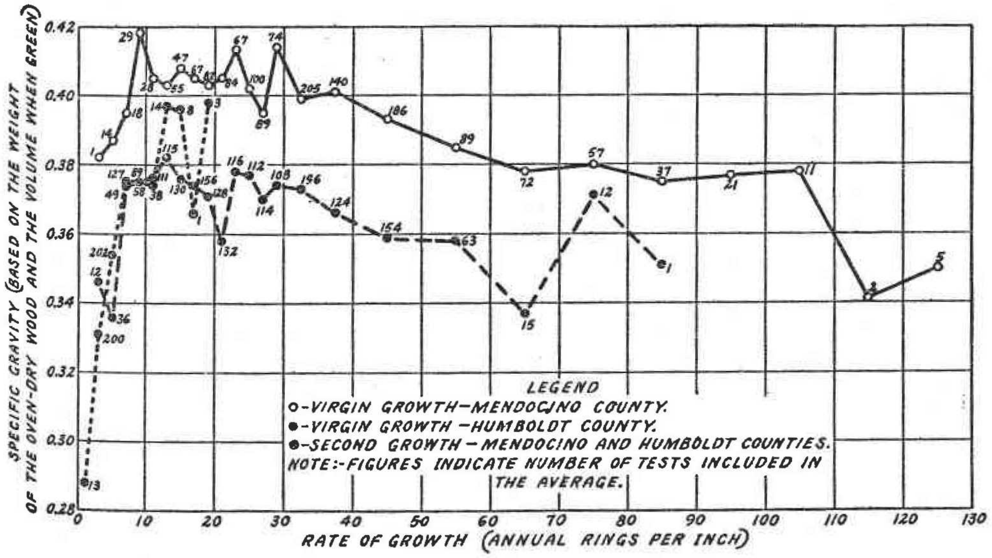


FIGURE 7.—Relation between specific gravity and rate of growth of the heartwood of redwood

EFFECT OF SPECIFIC GRAVITY ON THE UTILITY OF SECOND-GROWTH REDWOOD

The average specific gravity of second-growth redwood was less than that of virgin-growth material. The closely grown second-growth trees were about 5 per cent lower and the openly grown second-growth trees about 15 per cent lower in average specific gravity than the virgin growth. (Fig. 8.)

The significance of these differences naturally depends on the ultimate use of the wood, and it is obviously difficult to predict trends in consumption to arrive at the use requirements of the future. Considering the tree from the standpoint of structural timber, and to some extent of lumber, the advantage of wood of closely grown material over that from the openly spaced reproduction is apparent. Aside from the higher specific gravity of the clear wood of virgin-growth redwood, it is of course evident that young second-growth trees, because of the prevalence of limbs, can not be expected to yield so high a grade of timber or lumber as the virgin-growth material.

DESCRIPTION OF TEST MATERIAL AND METHOD OF TESTING FOR STRENGTH

The trees used for the strength tests were selected in the woods so as to be representative of the average and the range in specific gravity of redwood, as previously determined by the specific gravity survey. (P. 3.) Logs from trees selected in this manner give

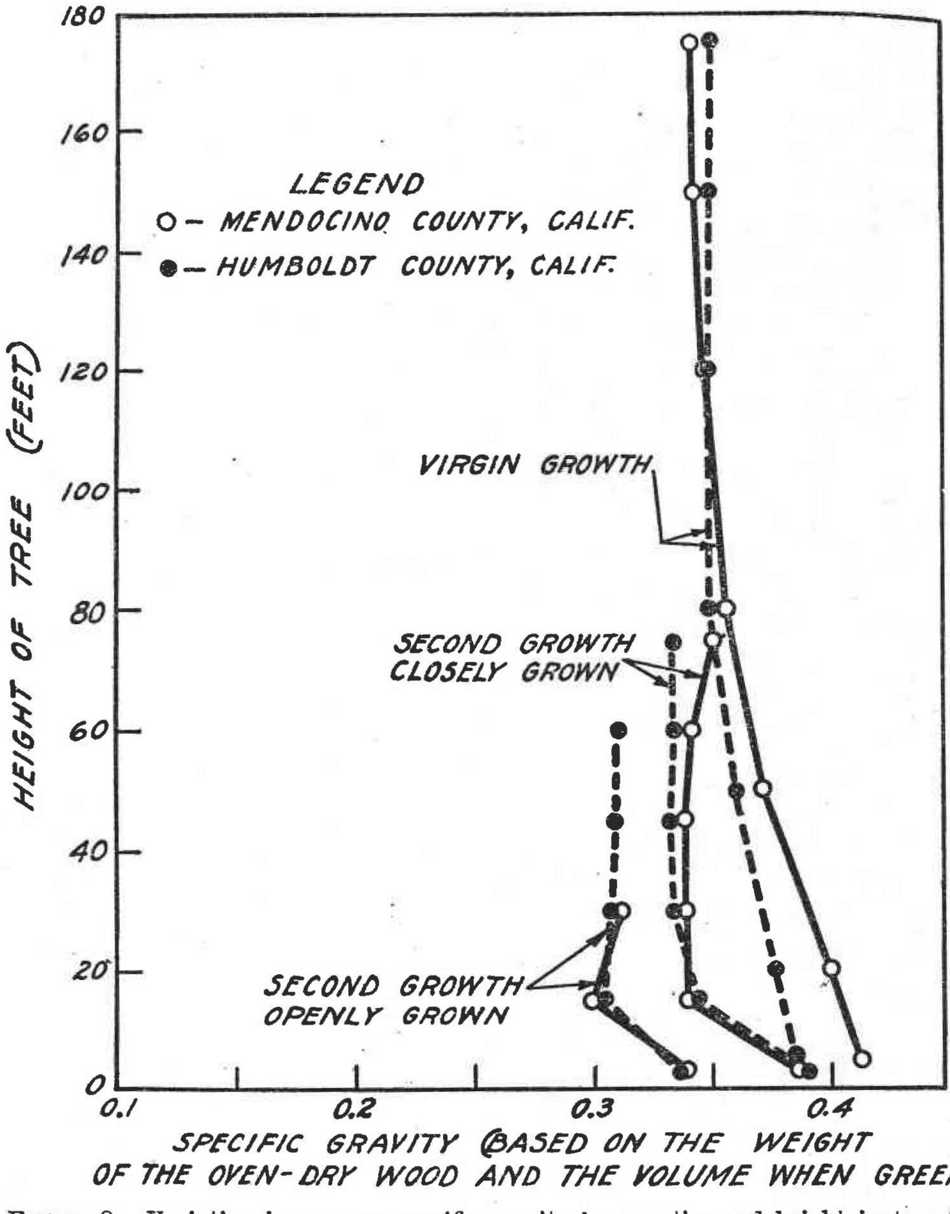
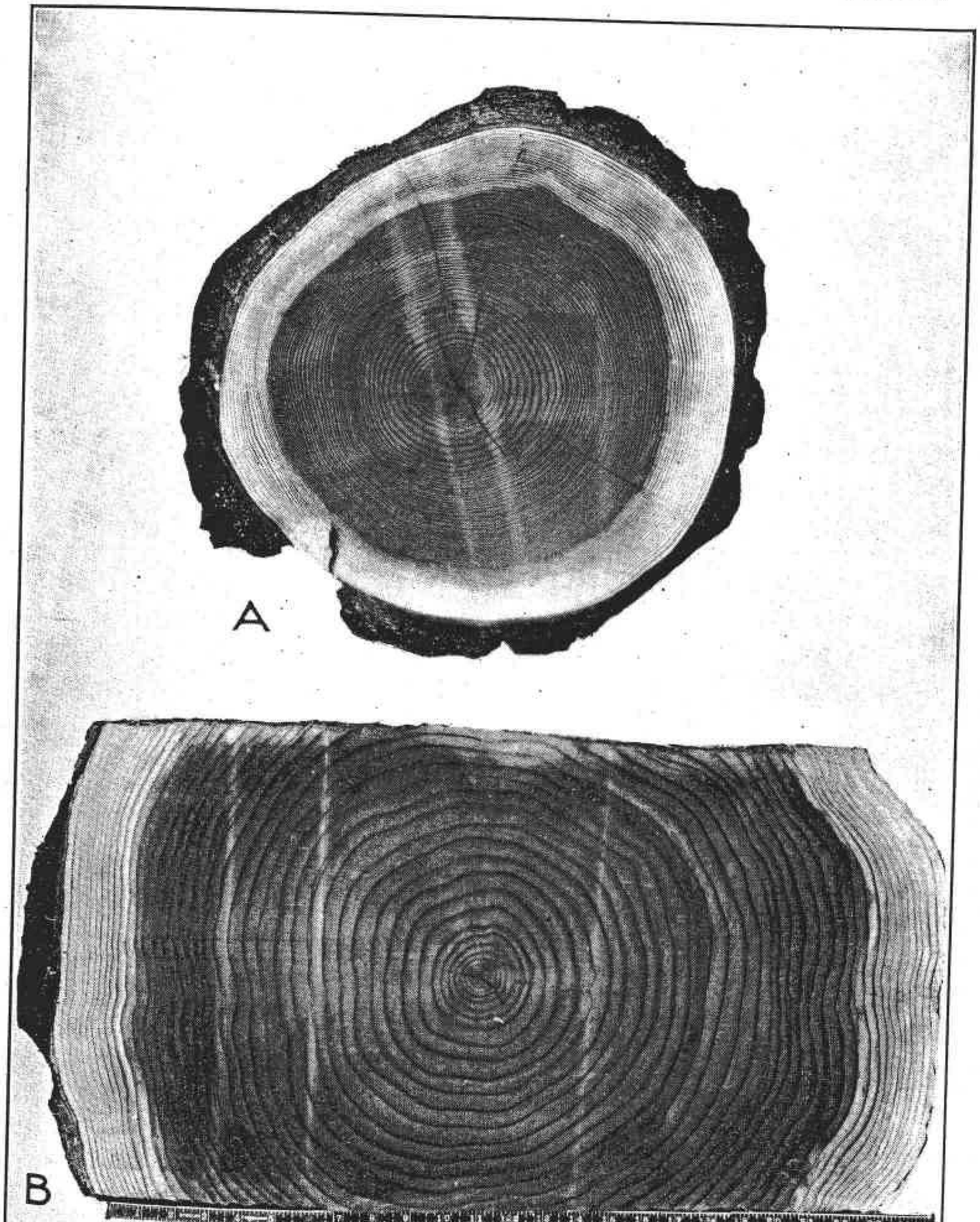


FIGURE 8.—Variation in average specific gravity by counties and height in tree for virgin-growth and second-growth redwood

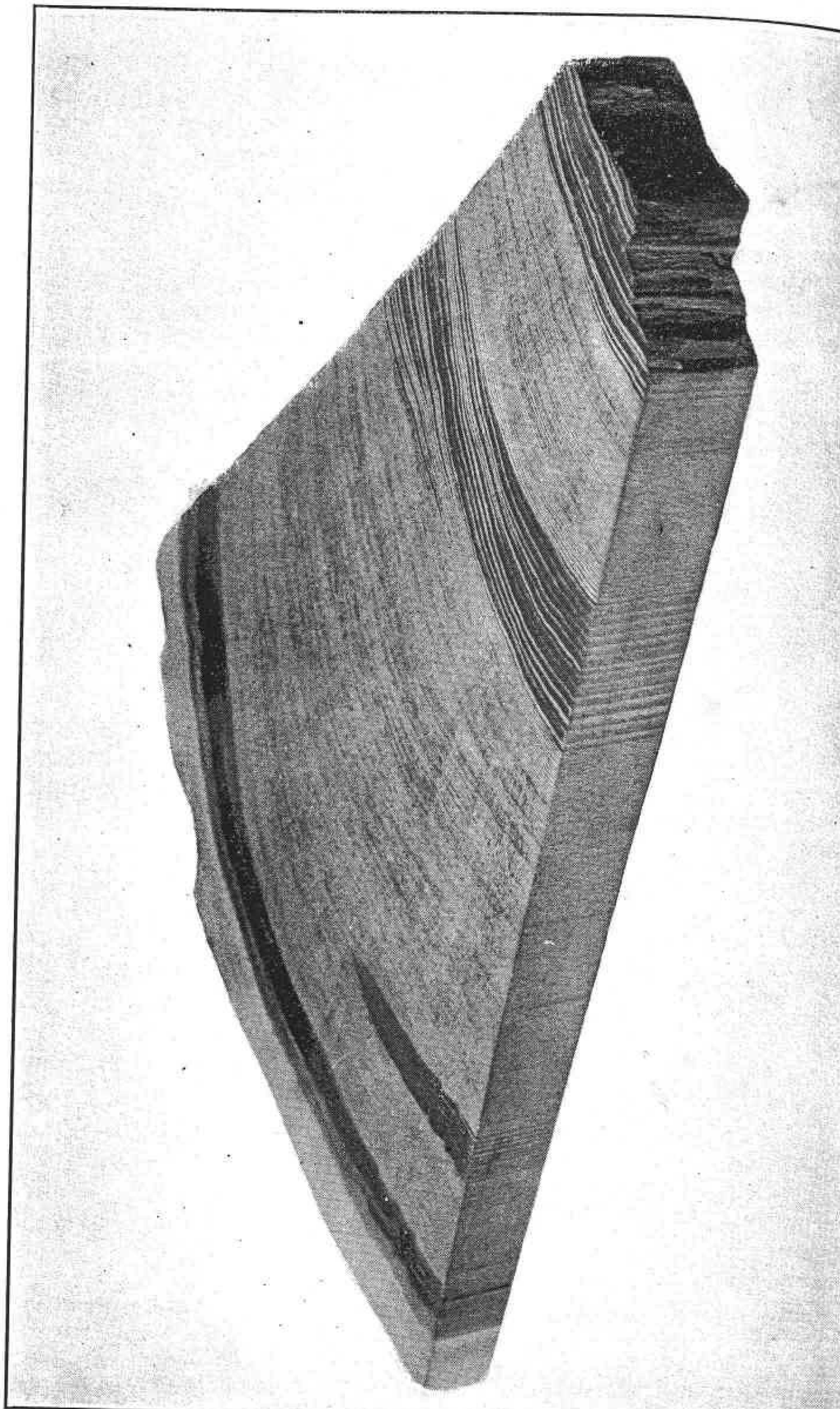
strength data considered more representative of redwood as a species than that from the same number of logs taken at random. Both virgin-growth and second-growth material from Humboldt and Mendocino counties were included in the strength study. The logs were shipped in a green condition to the Forest Products Laboratory where they were cut into small, clear specimens for testing.

A complete series of standard strength and related tests (*1*) was made on the redwood in both the green and air-dry condition. The



CROSS-SECTIONAL VIEW OF TWO SPECIMENS OF SECOND-GROWTH REDWOOD, BOTH AT SAME SCALE, EXHIBITING A LARGE DIFFERENCE IN RATE OF GROWTH AS SHOWN BY THE WIDTH OF THE ANNUAL RINGS

A, Closely grown second-growth redwood. B, Openly grown second-growth redwood.



THE DARKER AREAS SHOWN IN THIS REDWOOD SECTION ARE COMPRESSION WOOD tests included specific gravity, shrinkage, static bending, impact bending, compression parallel to grain, compression perpendicular to grain, tension perpendicular to grain, hardness, and toughness.

RESULTS OF STRENGTH TESTS ON VIRGIN-GROWTH REDWOOD

Tables 3 and 4 present the average results of strength tests on small, clear specimens of virgin-growth redwood. Table 3, in addition to presenting comparative strength values for redwood, includes strength figures for a number of other commercial softwoods of the United States with which comparison may be desired. The strength figures are expressed as percentages, redwood being taken as 100 per cent. The comparative strength figures for redwood in Table 3 are obtained by making certain combinations of the mechanical properties given in Table 4. The comparative strength figures are based on tests of both green and air-dried wood, and consequently represent a combination of moisture conditions. A complete discussion of the method of determining the comparative strength figures, together with the data on other species, is given in United States Department of Agriculture Technical Bulletin 158 (*8*). Because the values for redwood given in the footnote of Table 3 are based on more comprehensive tests, they supersede those given in Technical Bulletin 158 (*8*).

TABLE 3.—*Average comparative properties of clear wood of virgin-growth redwood compared with a number of other species*

Commercial and botanical name of species	Trees tested	Specific gravity, oven-dry, based on volume when green	Weight per cubic foot		Shrinkage from green to oven-dry condition based on dimensions when green			Composite strength values				
			Green	At 12 per cent moisture content	Radial	Tangential	Volumetric (composite value)	Bending strength	Compressive strength (endwise)	Stiffness	Hardness	Shock resistance
1	2	3	4	5	6	7	8	9	10	11	12	13
	Number		*Pounds*	*Pounds*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Redwood [1] (Sequoia sempervirens)	16	0.39	52	28	100	100	100	100	100	100	100	100
Cedar, Port Orford (Chamaecyparis lawsoniana)	14	.40	36	29	192	172	158	99	87	123	89	122
Cedar, eastern red (Juniperus virginiana)	5	.44	37	33	129	118	116	81	84	58	150	175
Cedar, western red (Thuja plicata)	15	.31	27	23	100	125	113	72	72	79	70	80
Cedar, northern white (Thuja occidentalis)	5	.29	28	22	88	118	103	60	50	57	56	72
Cypress, southern (Taxodium distichum)	26	.42	50	32	158	155	155	95	89	99	96	117
Douglas fir (Pseudotsuga taxifolia) (Coast type)	34	.45	38	34	208	195	181	108	104	132	109	125
Douglas fir (Pseudotsuga taxifolia) (Rocky Mountain type)	10	.40	35	30	150	155	154	90	81	104	96	103
Fir, lowland white (Abies grandis)	10	.37	44	28	133	180	157	87	80	114	80	111
Fir, noble (Abies nobilis)	9	.35	30	26	188	208	188	89	74	109	72	105
Fir, silver (Abies amabilis)	6	.35	36	27	188	250	212	84	74	107	69	108
Fir, white (Abies concolor)	20	.35	47	26	133	175	142	87	71	93	78	92
Firs, white (Average of four species)	45	.35	41	26	158	198	164	87	74	103	76	102
Hemlock, western (Tsuga heterophylla)	18	.38	41	29	179	198	179	89	82	105	93	112
Pine, loblolly (Pinus taeda)	10	.50	54	38	229	188	190	112	101	121	115	143
Pine, longleaf (Pinus palustris)	34	.55	50	41	221	188	185	128	119	138	141	158
Pine, northern white (Pinus strobus)	18	.34	36	25	96	150	124	76	65	87	65	85
Pine, shortleaf (Pinus echinata)	12	.49	51	38	212	205	191	117	101	124	126	171
Pine, sugar (Pinus lambertiana)	9	.35	51	25	121	140	118	77	66	82	70	85
Pine, western white (Pinus monticola)	14	.36	35	27	171	185	176	83	73	100	65	100
Pine, ponderosa (Pinus ponderosa)	31	.38	45	28	162	158	145	78	67	82	76	89
Spruce, Sitka (Picea sitchensis)	25	.37	33	28	179	188	173	87	73	105	81	117

[1] Columns 6 to 13 are based on figures for comparative properties for redwood of 2.4, 4, 67, 83, 103, 137, 54, and 65, respectively, which, owing to the greater number of tests, supersede the comparative figures given in U. S. Department of Agriculture Technical Bulletin 158 (*8*).

TABLE 4.—*Average mechanical properties of redwood* [1]

[Based on tests of small [2] clear specimens in the green and air-dry condition [3]]

Common and botanical name	Trees tested	Rings per inch	Moisture content	Specific gravity, oven dry, based on—Volume when green or at 12 per cent moisture	Specific gravity, oven dry, based on—Volume when oven dry	Weight per cubic foot	Shrinkage from green to oven-dry condition, based on dimensions when green—Volumetric	Shrinkage—Radial	Shrinkage—Tangential	Static bending—Fiber stress at elastic limit	Static bending—Modulus of rupture	Static bending—Modulus of elasticity	Static bending—Work in bending—To elastic limit	Static bending—Work in bending—To maximum load	Impact bending—Fiber stress at elastic limit	Impact bending—Work in bending to elastic limit	Impact bending—Height of drop causing complete failure (50-pound hammer)	Compression parallel to grain—Fiber stress at elastic limit	Compression parallel to grain—Maximum crushing strength	Compression perpendicular to grain—fiber stress at elastic limit	Shearing strength parallel to grain	Tension perpendicular to grain	Hardness, load required to embed a 0.444-inch ball to one-half its diameter—End	Hardness—Side
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Number	*Number*	*Per cent*			*Lbs.*	*Per cent*	*Per cent*	*Per cent*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*1,000 lbs. per sq. in.*	*In.-lbs. per cu. in.*	*In.-lbs. per cu. in.*	*Lbs. per sq. in.*	*In.-lbs. per cu. in.*	*Ins.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs. per sq. in.*	*Lbs.*	*Lbs.*
Redwood (Sequoia sempervirens): Green	16	29	112	0.39	0.42	52	6.8	2.4	4.0	4,820	7,500	1,180	1.18	7.4	8,920	3.2	21	3,730	4,200	520	800	260	570	410
Seasoned	------	------	12	.40	------	28	------	------	------	6,980	10,100	1,350	2.07	6.9	10,250	3.6	19	4,740	6,200	870	940	240	800	480

[1] Comparable data on other species are presented in the U. S. Department of Agriculture Bulletin 556 (*9*).
[2] Test specimens 2 by 2 inches in section. Bending specimens 30 inches long; others shorter, depending on kind of test.
[3] Values for seasoned material are adjusted to an average air-dry condition of 12 per cent moisture content.

Table 4 presents values for redwood in a green and air-dry condition, based on tests of small, clear specimens (*1*). The values of Table 4 are comparable to the values for other species given in United States Department of Agriculture Bulletin 556 (*9*) and are used by engineers and architects for calculating the load-carrying capacity of wood, and in arriving at safe working stresses (*8*) for structural timbers containing defects.

RESULTS OF STRENGTH TESTS ON SECOND-GROWTH REDWOOD

There is comparatively little second-growth redwood, and from a commercial standpoint it is of practically no importance at the present time. The detailed strength values for second-growth have therefore been presented in the Appendix. The second-growth redwood used for the strength tests was classified according to whether it was from dense stands or from openly grown stands. The second-growth redwood from the dense stands was somewhat lower in weight and strength than the virgin-growth redwood, but, like virgin-growth redwood, had relatively high strength values for its weight.

Relatively few second-growth redwood trees from open stands are to be found. Those tested were lighter than either virgin-growth redwood or second-growth redwood from dense stands, and were also lower in some important strength properties than would be expected from their weight.

FACTORS AFFECTING THE PROPERTIES AND USES OF REDWOOD

Since second-growth redwood is not of commercial importance at the present time, the following discussion of properties and uses is concerned chiefly with virgin-growth redwood.

RELATION BETWEEN SPECIFIC GRAVITY AND STRENGTH

Strength studies on many species of wood have shown that there is a definite relation between the specific gravity of wood (oven dry) and its several strength properties (*10*). In general, the higher the weight of the dry wood, the greater is the strength. This relation of weight and strength holds among the different species of wood and also among individual boards of any one species.

Frequently a given species is characteristically high or low in different properties as compared with other species of the same specific gravity. It is rare that any species is, for its weight, exceptional in all of its strength properties.

The weight-strength relations for individual boards of any one species are often different from the weight-strength relations based on a number of different species. Curves illustrating the relationship between specific gravity and a number of strength properties of virgin-growth redwood in a green condition, based on values of individual tests, are shown in Figures 9 to 11. While there is a general relation between specific gravity and strength, there is still considerable deviation of individual values from the curve best representing the plotted points. In the curves illustrated, side hardness increases most rapidly with an increase in specific gravity, maximum crushing strength next, and modulus of rupture least rapidly.[4]

It may be noted that when a property increases rapidly with specific gravity, as, for example, hardness, a small difference in specific gravity accounts for a relatively large difference in that property. Thus in redwood, if one board is twice as high as another in specific gravity, it would be expected to have not twice, but four

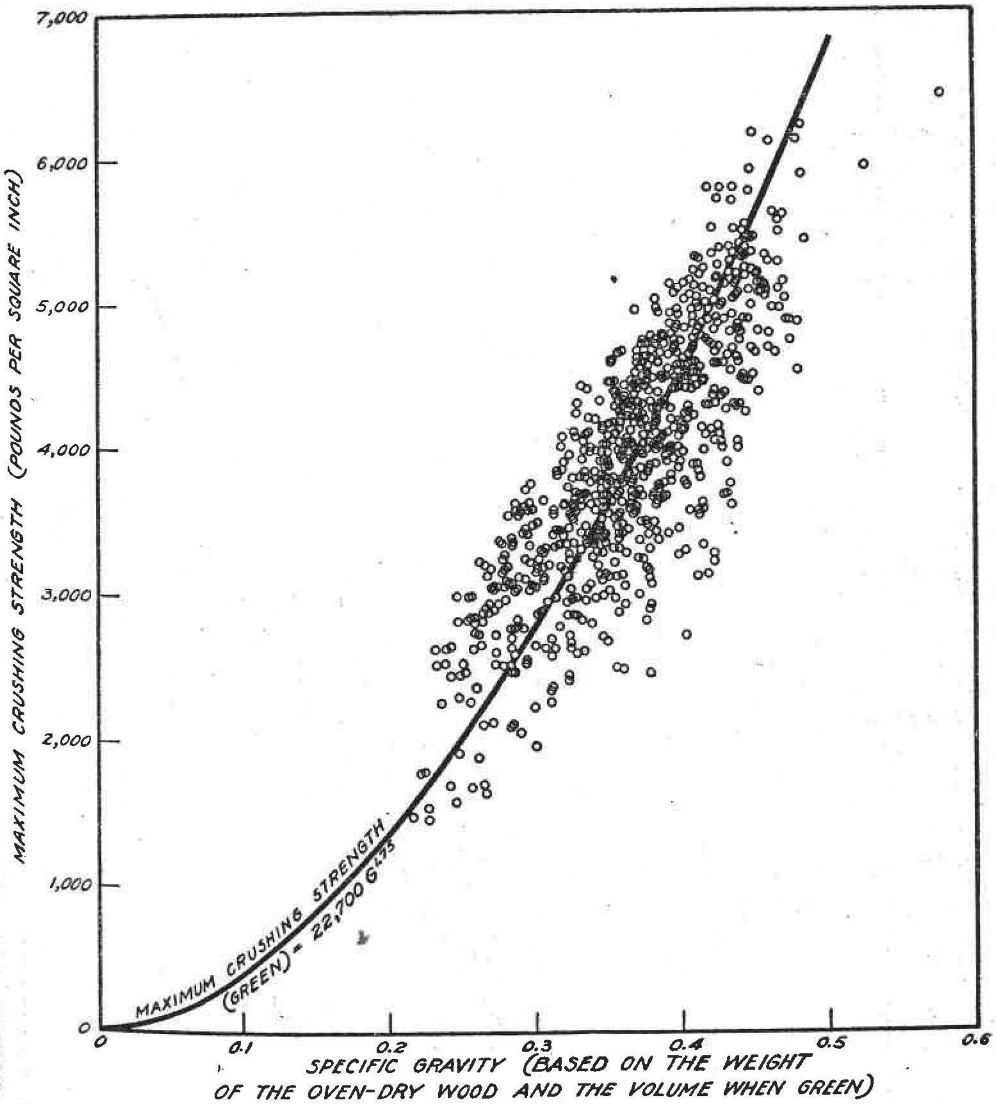


FIGURE 9.—Relation of maximum crushing strength of green virgin-growth redwood to specific gravity

times the hardness, as this property varies as the square of the specific gravity.

In bending strength, crushing strength, and hardness, the values for virgin-growth redwood are somewhat higher for the specific gravity than would be expected from the average behavior of other

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[4] The equations for specific gravity-strength curves for green redwood are as follows: Side hardness $=2{,}780\ G^2$; maximum crushing strength $=22{,}700\ G^{1.75}$; and modulus of rupture $=31{,}100\ G^{1.5}$. Among different species the power of G for these properties has been found to be 2.25, 1.00, and 1.25, respectively; G in all cases representing the specific gravity, oven dry, based on volume when green.

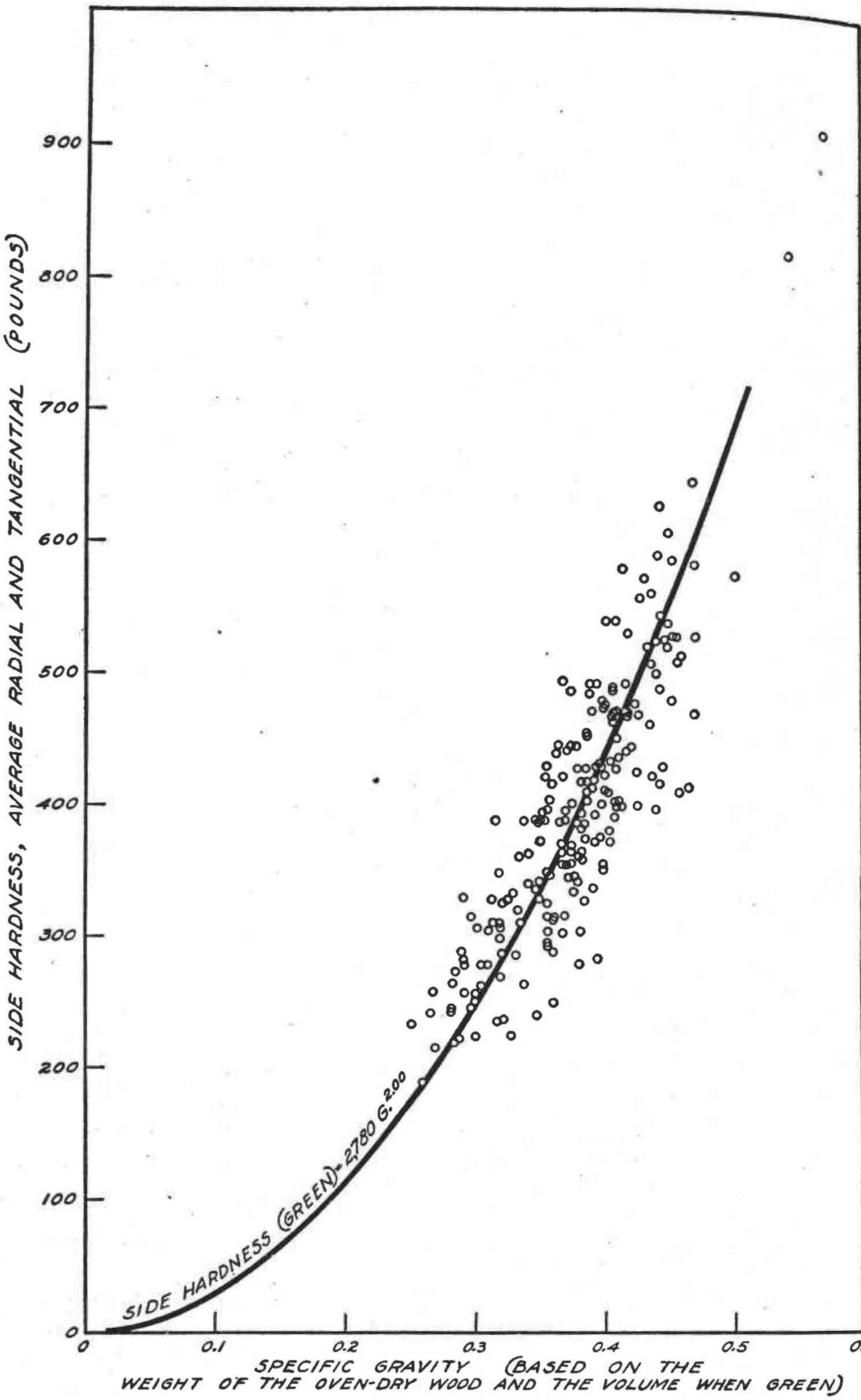

Figure 10.—Relation of side hardness of green virgin-growth redwood to specific gravity

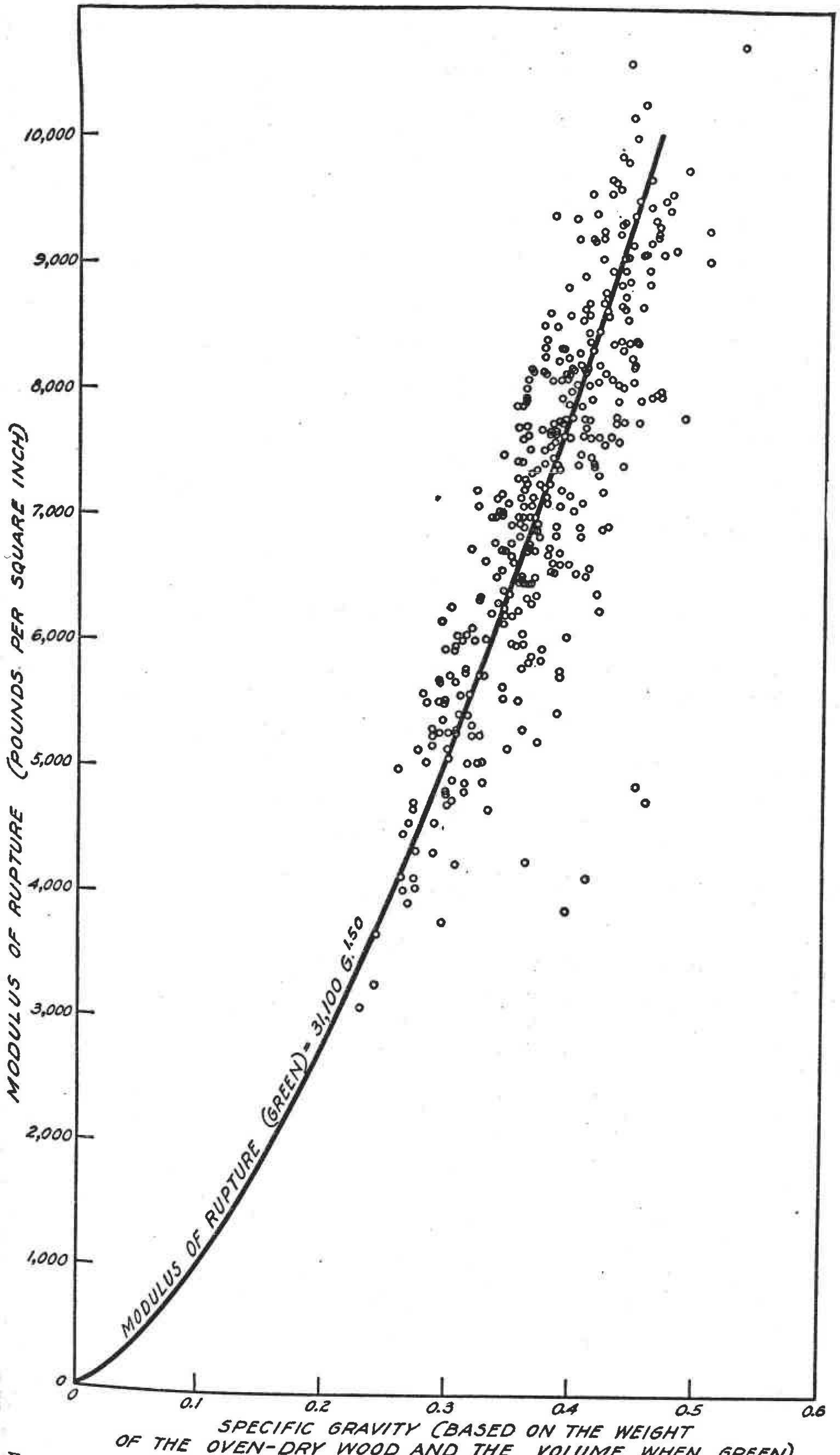

FIGURE 11.—Relation of modulus of rupture of green virgin-growth redwood to specific gravity

species, while the values for shock resistance as measured by total work in static bending and height of drop in impact bending are somewhat lower. (P. 43.)

RELATION BETWEEN MOISTURE AND STRENGTH

Small, clear pieces of wood in drying from the green condition usually increase in most strength properties after reaching the fiber-saturation point. (P. 43.) The amount of the increase depends upon the extent of the drying, the property under consideration, and the species. Though redwood increases in many strength properties during seasoning, the increase is less than for most species. A few properties, particularly those indicative of shock resistance, as measured by total work in static bending and height of drop, show for redwood, as for numerous other species, an actual decrease due to seasoning.

STRENGTH AS RELATED TO HEIGHT IN TREE

In many species, the wood from near the ground is heavier and in some strength properties, particularly shock resistance, excels that from higher in the tree. However, this was not so in virgin-growth redwood as the butt cuts, although of slightly higher specific gravity than the next adjoining logs, were actually somewhat lower in many strength properties. The top logs were appreciably lighter and consistently lower in strength than the butt cuts or material directly above the butt. In other words, the strongest virgin-growth redwood, all properties considered, comes from just above the butt cuts. (P. 39.)

MOISTURE DISTRIBUTION WITHIN THE TREE

All living trees contain moisture, a considerable proportion of which must usually be removed from the lumber or other products by seasoning to condition it for service. The amount of moisture found in the tree varies greatly among different species, and often in different parts of the same tree (*6*). Figure 12 illustrates the average distribution of moisture for the heartwood and the sapwood throughout the height in tree, and is based on data from 43 virgin-growth redwood trees.

It is evident from Figure 12 that the sapwood is appreciably higher in moisture content than the heartwood, and tends to increase slightly in moisture with height in tree. The heartwood, on the other hand, decreases rapidly in moisture content (p. 45) from a value of about 150 per cent at the stump of an average individual tree to about 60 per cent at mid-height, and then maintains this condition fairly uniformly to the top of the merchantable length. At the base of the tree the moisture content of the heartwood increased appreciably from the pith outward, but at a height of 60 feet or more it became more uniform throughout the cross section.

Although Figure 12, which is based on averages, shows very uniform and consistent relations, individual trees may differ considerably from these values in the amount and distribution of moisture.

The relatively high moisture content of the heartwood, particularly in the butt cuts, necessitates the removal of large quantities of water in seasoning. This, together with the fact that the moisture moves much more slowly from the heartwood than from the sapwood, accounts for the relatively slow drying of material from the butt logs. The difference in moisture content between the butt and upper cuts emphasizes the desirability of avoiding in commercial kiln drying the mixing of both classes of stock.

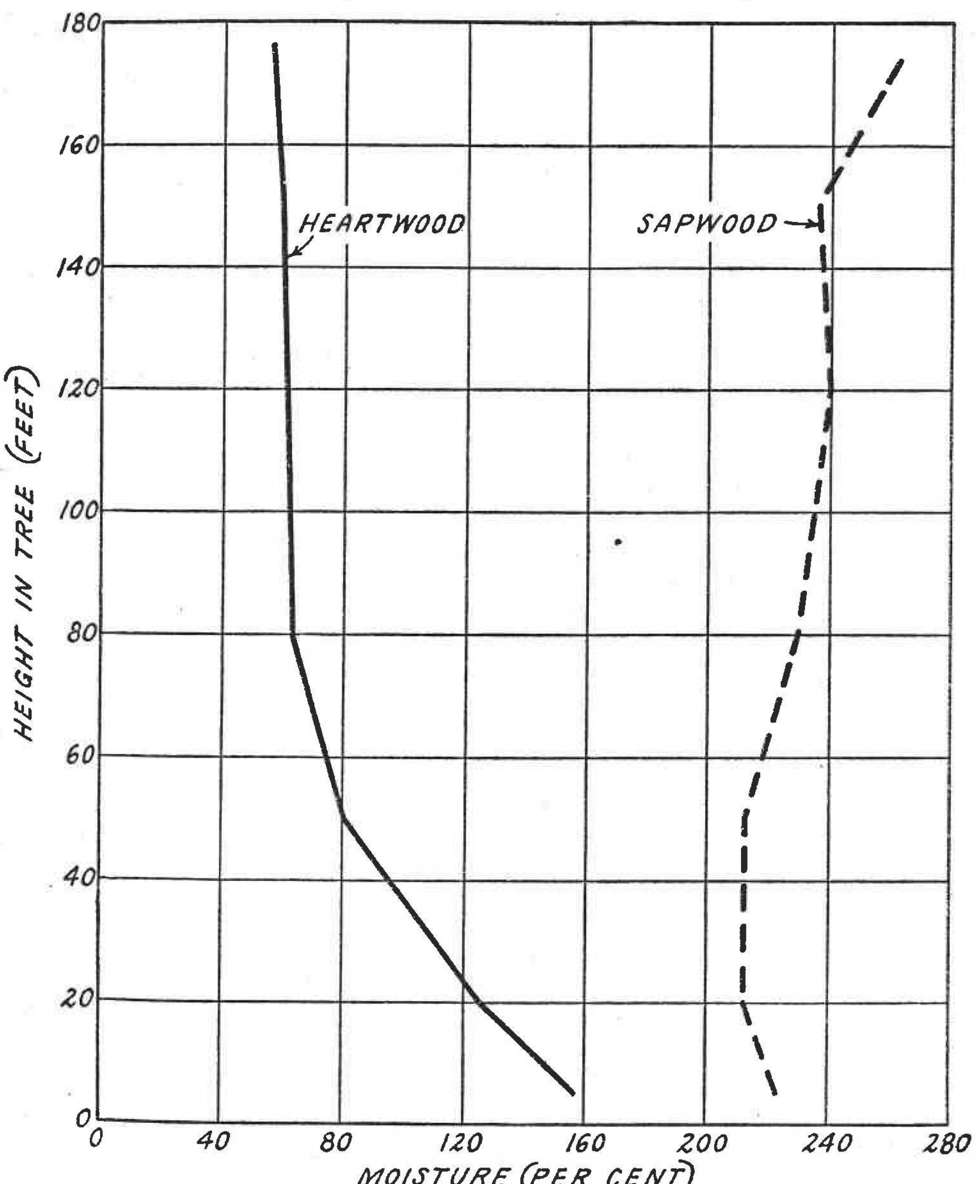

FIGURE 12.—Average distribution of moisture content of heartwood and sapwood in virgin-growth redwood trees relative to height

PROPERTIES AS AFFECTED BY EXTRACTIVES

The wood of many species contains considerable quantities of complex substances, such as resins, gums, oils, and other so-called extractives, many of which impart to the wood special characteristics or have an important commercial value. The amount of extractives frequently varies greatly within a single tree. In the virgin-growth redwood trees examined, the greatest range in the heartwood extractives within a single tree was from about 5 to 28 per cent, whereas the sapwood extractive content varied from about 4 to 8 per cent, based on the weight of the oven-dry wood. Second-growth redwood showed a smaller variation. In virgin-growth redwood the hot-water extractives averaged about 10 to 15 per cent for the heartwood, whereas in the sapwood the extractive content was only about 3 to 6 per cent. The extractives in the heartwood of redwood are reddish, which accounts for the distinctive color of the wood. Extractives affect the strength properties of redwood, the amount of the effect depending on the amount and distribution of extractives present, the moisture condition of the wood, and the particular strength property under consideration (7). Of the properties studied, the compressive strength parallel to the grain and the bending strength appear to be increased by the presence of extractives; the compressive strength to a greater extent. On the other hand, shock resistance under some conditions appears actually to be decreased.

Considering the effect of extractives, it seems very probable that they are largely responsible for certain strength properties of redwood being relatively high while others are lower than would be expected from the specific gravity of the wood; and for the somewhat lower than normal increase in strength with seasoning, although for more important properties the strength when dry is higher than the weight-strength relations would indicate. The relatively low shrinkage and high resistance to decay of redwood are also probably due to extractives.

RADIAL AND TANGENTIAL SHRINKAGE

For practically all uses, the characteristic shrinking and swelling of wood with moisture changes are undesirable, although the degree of shrinkage permissible differs greatly in different uses. The relatively low shrinkage of the heartwood across the grain commends redwood for uses where this property is important. Measurements on virgin-growth redwood gave values of average shrinkage as shown in Table 5.

TABLE 5.—*Shrinkage of virgin-growth redwood from the green to the oven-dry condition, in percentage, based on dimensions when green*

Shrinkage	Heartwood	Sapwood
Radial	2.4	3.2
Tangential	4.0	5.2
Volumetric	6.7	----------

The shrinkage from the green condition to an air-dry condition of approximately 12 per cent moisture would be about one-half of that given.

The sapwood of both virgin-growth and second-growth redwood shrinks considerably more than the heartwood, but since virgin-growth redwood has only a narrow band of sapwood, most of which is removed in manufacture, the shrinkage of the heartwood is the more important. The radial and tangential shrinkage of the sapwood of virgin-growth redwood corresponds very closely with that to be expected from the specific gravity or weight, whereas the heartwood shrinks only about 65 per cent as much as would be expected from its specific gravity.

Since the heartwood and sapwood are from all appearances structurally the same, and the primary difference between heartwood and sapwood is extractives, it would seem that the extractives are the cause of the relatively low shrinkage of the heartwood. Certain sugars injected into wood will materially reduce the shrinkage, and it is possible that extractives in redwood act in a similar manner in reducing shrinkage.

COMPRESSION WOOD AND ENDWISE SHRINKAGE

Compression wood, which is found in redwood and other softwoods, is an abnormal growth frequently occurring on the underside of leaning trees and limbs of the various softwood (coniferous) species. It is denser and harder than the normal wood, is characterized by wide annual-growth rings, and includes what appears to be an excessive summer-wood growth. The contrast in color between spring wood and summer wood is usually less in compression wood than in normal wood. (Pl. 6.)

Of the 56 virgin-growth trees examined in the specific gravity survey (p. 3), 62 per cent contained some compression wood. However, out of a total of 4,046 specimens 2 by 2 inches square, cut from the 56 virgin trees, only 3.7 per cent contained compression wood; that is, when compression wood was present it usually made up but a very small proportion of the total volume of the trees.

The endwise, or longitudinal, shrinkage in the normal wood of practically all species including redwood is so small as to be relatively unimportant. Compression wood, however, has an endwise shrinkage so great as to materially affect its use. The maximum endwise shrinkage in compression wood in the redwood studied was 1.6 per cent from a green to an oven-dry condition, an equivalent of slightly over 3 inches in a 16-foot board if it were oven dried from a green condition (*5*).

That the bulk of redwood does not shrink excessively along the grain is shown in Table 6, in which are given, for both virgin-growth and second-growth, the percentage of the total number of specimens falling within narrow shrinkage classes. This table shows that out of 438 specimens of virgin-growth redwood, 85.8 per cent shrank less than 0.2 per cent along the grain in drying from the green to the oven-dry condition. In drying to an air-dry condition of about 12 per cent moisture content, only about one-half as much shrinkage would occur.

TABLE 6.—*Frequency distribution of longitudinal shrinkage of redwood*

Shrinkage class [1]	Virgin growth [2]		Second growth			
			Closely grown [3]		Openly grown [4]	
	In class	In class and below	In class	In class and below	In class	In class and below
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
0 to 0.04 per cent	3.8	3.8	20.2	20.2	4.3	4.3
0.05 to 0.09 per cent	25.6	29.4	7.1	27.3	18.1	22.4
0.10 to 0.14 per cent	40.4	69.8	26.5	53.8	12.9	35.3
0.15 to 0.19 per cent	16.0	85.8	10.7	64.5	20.7	56.0
0.20 to 0.24 per cent	4.5	90.3	19.1	83.6	14.6	70.6
0.25 to 0.29 per cent	3.2	93.5	2.2	85.8	6.0	76.6
0.30 to 0.34 per cent	1.6	95.1	4.1	89.9	5.3	81.9
0.35 to 0.39 per cent	1.4	96.5	1.9	91.8	6.0	87.9
0.40 to 0.44 per cent	.5	97.0	1.6	93.4	1.7	89.6
0.45 to 0.49 per cent	.9	97.9	1.4	94.8	2.6	92.3
0.50 to 0.54 per cent	.5	98.4	1.4	96.2	1.7	94.0
0.55 to 0.59 per cent	.7	99.1	1.6	97.8	1.7	95.7
0.60 to 0.64 per cent	.9	100.0	0.0	97.8	.9	96.6
0.65 to 0.69 per cent	----	----	.3	98.1	1.7	98.2
0.70 to 0.79 per cent	----	----	.6	98.7	.9	99.1
0.80 to 0.89 per cent	----	----	.8	99.5	.9	100.0
0.90 to 0.99 per cent	----	----	.5	100.0	----	----

[1] The average shrinkage per specimen was 0.145 per cent for virgin growth, 0.165 for closely grown second growth, and 0.219 for openly grown second growth.
[2] Based on 438 specimens.
[3] Based on 366 specimens.
[4] Based on 116 specimens.

Where compression wood is present in the same board with normal wood, the unequal endwise shrinkage in the two parts causes bowing and crooking, which is usually a more serious disadvantage than direct shortening. Material containing pronounced compression wood is undesirable for practically all lumber uses and should be rejected.

COMPARISON OF THE STRENGTH OF COMPRESSION WOOD AND NORMAL REDWOOD

Strength tests were made both on normal redwood and on pronounced compression wood from the same trees. (Table 7.) Although the compression wood averaged about 35 per cent higher in specific gravity than the normal wood, it was actually lower in a number of strength properties, being decidedly lower in stiffness. In those properties in which it did excel normal wood it was in most cases but little better. Weight for weight, it was much inferior to normal wood in all properties studied.

TABLE 7.—*Ratio of strength of compression wood to normal wood for virgin-growth redwood*

Property	Ratio of compression wood to normal wood	
	Green	Air dry
	Per cent	*Per cent*
Specific gravity [1]	135	133
Static bending:		
Modulus of rupture	102	87
Modulus of elasticity	62	63
Work to maximum load	92	108
Compression parallel to grain: Maximum crushing strength	117	101
Toughness	84	100

[1] Based on the weight of the oven-dry wood and volume when green.

SUMMARY

The redwood studied was higher in such properties as bending strength, crushing strength, and hardness than would be expected from its specific gravity, while in shock resistance it was usually somewhat lower.

Redwood in the form of small specimens increased in strength in drying, although the relative increase was less than for most species. A few properties, particularly those indicative of shock-resisting ability frequently showed a decrease due to drying.

The virgin-growth redwood from Mendocino County was somewhat stronger than that from Humboldt County, but the differences in most strength properties were not so great as would be expected from the differences in weight.

The strongest virgin-growth redwood, all properties considered, came from just above the butt log.

The moisture in the heartwood of the virgin-growth redwood studied varied from an average of about 140 to 175 per cent at the stump of individual trees, to about 60 per cent at mid height, beyond which point it remained almost uniform throughout the rest of the tree. The moisture in the sapwood averaged over 200 per cent throughout the entire height of the tree.

The extractives in the wood affected the strength of the redwood studied, increasing such properties as bending strength and compressive strength, while shock resistance under some conditions was actually decreased.

The shrinkage across the grain of the heartwood of the redwood studied was relatively low. The low shrinkage appeared to be due primarily to the extractives in the heartwood, as the sapwood, which had a lower extractive content, was considerably higher in shrinkage.

Occasional pieces of redwood, like those of other softwood species, contained compression wood in varying degrees. Compression wood has a much higher endwise shrinkage than normal wood and is also deficient in strength for its weight and therefore boards containing much of it should be discarded for most lumber uses.

APPENDIX

DETAILED DATA FROM THE SPECIFIC GRAVITY SURVEY

COLLECTION OF SAMPLES

The samples collected in the specific gravity survey consisted of whole or partial cross sections taken at different heights from each of 27 virgin-growth and 24 second-growth trees from Mendocino County and from 29 virgin-growth and 18 second-growth trees from Humboldt County, Calif. From these sections, approximately 4,000 specific gravity specimens were taken for the virgin-growth material and 1,500 for the second-growth. The second-growth trees consisted of 31 closely grown and 11 openly grown trees.

METHOD

Partial sections including the pith and a little more than half the cross section of the log were obtained from the virgin-growth trees. (Fig. 13.) These sections were approximately 6 inches in length (along the grain), and were sawed out at average heights of 4, 23, 60, 104, 148, and 188 feet above the ground. (Fig. 14.) Specific gravity specimens approximately 2 by 2 by 6 inches in size were cut from these partial sections from bark to bark, along a diametrical line. The specific gravity determinations, based on green volume and oven-dry weight, were made at temporary field headquarters. The specimens were then sent to the Forest Products Laboratory where specific gravity determinations, based on oven-dry volume and weight, were made.

The sections from the second-growth redwood trees comprised the entire cross section of the log and were taken at heights of approximately 2, 14, 37, and 62 feet above the ground. Specific gravity specimens about 2 by 2 by 6 inches in size were taken through the pith from bark to bark.

The second-growth redwood sections were sent to the Forest Products Laboratory to have their specific gravity determined. The sections from the second-growth trees were cut 1 to 1½ feet in length to make it possible, despite some loss of moisture from the ends during transit, to obtain green material for the specific gravity tests.

The specific gravity determinations were made by the immersion method (*1*). Volumetric-shrinkage measurements from the green to the oven-dry condition were also obtained as a part of this procedure.

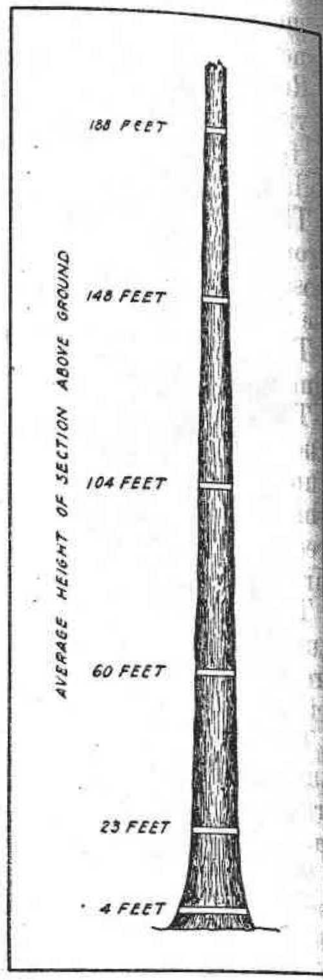

FIGURE 14.—Diagram showing position of sections taken at various tree heights

RESULTS

Table 8 gives values of the probable variation in the specific gravity of virgin-growth redwood in individual specimens by trees, sites, lots, and counties and in individual trees with similar grouping. Table 8 also shows the effect on specific gravity and its variation when pieces containing compression wood are rejected. In addition, it permits a comparison of redwood from the whole tree with that from the second log.

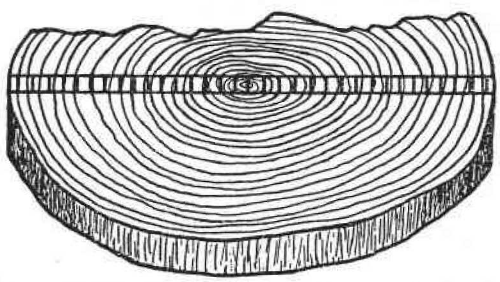

FIGURE 13.—Diagram showing method of taking specific gravity specimens from bark to bark across tree sections

TABLE 8.—*Probable variation values of the specific gravity of virgin-growth and second-growth redwood*

VIRGIN GROWTH

Place of growth: County	Place of growth: Land description	Lot number	Site class or stocking	Tree identification number	All bolts: Specimens containing compression wood	All bolts, All specimens: Specimens	All bolts, All specimens: Specific gravity [1]	All bolts, All specimens: Probable variation [2] of individual specimen from corresponding average	All bolts, Without compression wood: Specimens	All bolts, Without compression wood: Specific gravity [1]	All bolts, Without compression wood: Probable variation [2] of individual specimen from corresponding average	Second section, All specimens: Specimens	Second section, All specimens: Specific gravity [1]	Second section, All specimens: Probable variation [2] of individual specimen from corresponding average	Second section, Without compression wood: Specimens	Second section, Without compression wood: Specific gravity [1]	Second section, Without compression wood: Probable variation [2] of individual specimen from corresponding average	Trees	Specific gravity [1]	Probable variation [2] of an individual tree from corresponding average
					Number	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*
Mendocino	T. 17 N., R. 16 W.	1	IV	15	3	64	0.377	10.58												
				16	2	71	.369	9.35												
				17	1	26	.379	4.54												
				18	6	48	.381	9.51												
				19	0	25	.364	9.95												
				Total or average		234	.374	9.86	222	0.370	8.90	59	0.384	7.06	55	0.379	6.07	5	0.374	1.51
		1	III	20	5	114	.337	11.77												
				21	2	82	.395	8.99												
				22	8	77	.391	8.80												
				23	4	31	.437	8.04												
				24	0	53	.409	7.67												
				Total or average		357	.380	11.17	338	.377	10.88	91	.396	9.63	83	.390	9.46	5	.394	7.20
		Total or average lot 1				591	.379	10.59				150	.391	8.82	138	.386	8.41	10	.384	5.02

[1] Specific gravity based on green volume and oven-dry weight.
[2] These percentage values are obtained by dividing the actual probable variation by the corresponding average specific gravity. For example, tree No. 1 (second growth) has an actual probable variation in specific gravity of 0.0292, an average specific gravity of 0.362, and the percentage probable variation is 0.0292 divided by 0.362 times 100 or 8.07 per cent.

TABLE 8.—*Probable variation values of the specific gravity of virgin-growth and second-growth redwood*—Continued

VIRGIN GROWTH—continued

Place of growth: County	Place of growth: Land description	Lot number	Site class or stocking	Tree identification number	All bolts: Specimens containing compression wood	All bolts, All specimens: Specimens	All bolts, All specimens: Specific gravity	All bolts, All specimens: Probable variation of individual specimen from corresponding average	All bolts, Without compression wood: Specimens	All bolts, Without compression wood: Specific gravity	All bolts, Without compression wood: Probable variation of individual specimen from corresponding average	Second section, All specimens: Specimens	Second section, All specimens: Specific gravity	Second section, All specimens: Probable variation of individual specimen from corresponding average	Second section, Without compression wood: Specimens	Second section, Without compression wood: Specific gravity	Second section, Without compression wood: Probable variation of individual specimen from corresponding average	Trees	Specific gravity	Probable variation of an individual tree from corresponding average
					Number	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*
Mendocino	T. 19 N., R. 16 W.	2	II	25	0	95	.389	8.07												
				26	12	64	.387	10.25												
				27	5	110	.385	9.96												
				28	0	96	.366	9.40												
				29	1	102	.409	7.30												
				Total or average		467	.388	9.20	449	.383	8.83	114	.408	8.77	110	.406	8.40	5	.387	2.95
		2	II	30	0	72	.347	10.75												
				31	1	102	.426	8.06												
				Total or average		174	.393	11.21	173	.392	11.31	45	.408	10.48	44	.407	10.54	2		
		2	IV	32	2	55	.406	8.31												
				33	1	44	.396	8.68												
				34	4	45	.438	8.85												
				35	2	60	.412	12.74												
				36	0	71	.419	11.82												
				Total or average		275	.415	10.79	266	.412	10.54	80	.416	8.28	79	.415	8.17	5	.414	2.97

		2	III	37	5	62	.381	10.95												
				38	1	52	.359	7.33												
				39	1	86	.364	9.76												
				40	2	60	.381	8.63												
				41	2	42	.387	7.89												
				Total or average		302	.373	9.82	291	.370	9.32	79	.388	8.22	77	.387	7.98	5	.374	4.33
		Total or average lot 2				1,218	.391	10.20				318	.406	8.97	310	.404	8.75	17	.391	4.41
		Total or average lots 1 and 2				1,809	.387	10.36				468	.401	9.01				27	.388	4.48
Humboldt	T. 1 S., R. 2 E.	3	II	1	6	81	0.368	7.54												
				2	0	66	.359	8.66												
				3	0	56	.413	6.55												
				14	0	109	.340	4.68												
				Total or average		312	.364	8.21	306	0.363	8.09	77	0.372	7.85	76	0.371	7.68	4	0.370	6.90
		3	III	4	1	25	.399	11.57												
				5	6	84	.365	9.10												
				6	0	18	.386	8.90												
				7	3	41	.373	6.56												
				Total or average		168	.375	9.34	158	.373	9.16	36	.398	9.12	32	.396	9.50	4	.381	3.22
		3	III	8	16	99	.399	11.65												
				9	0	46	.337	8.61												
				10	0	104	.380	7.93												
				11	0	83	.405	8.89												
				12	0	103	.377	11.43												
				47	0	132	.300	6.90												
				Total or average		567	.364	12.15	551	.360	11.40	123	.385	11.65	113	.374	10.34	6	.366	8.30
		3	I	48	0	74	.355	7.45												
				49	0	100	.360	8.45												
				50	0	56	.431	7.02												
				51	1	104	.383	6.31												
				52	0	118	.327	8.66												
				Total or average		452	.365	9.69	452	.365	9.69	91	.377	9.21	91	.377	9.21	5	.371	8.16
		3	III	53	4	80	.387	8.96												
				54	1	89	.333	10.17												
				55	0	84	.299	7.90												
				56	2	55	.363	5.98												
				57	17	91	.401	11.62												
				Total or average		399	.356	11.94	375	.349	10.00	92	.364	11.71	87	.358	10.98	5	.357	9.00

TABLE 8.—*Probable variation values of the specific gravity of virgin-growth and second-growth redwood*—Continued

VIRGIN GROWTH—continued

Place of growth: County	Place of growth: Land description	Lot number	Site class or stocking	Tree identification number	All bolts: Specimens containing compression wood	All bolts, All specimens: Specimens	All bolts, All specimens: Specific gravity	All bolts, All specimens: Probable variation of individual specimen from corresponding average	All bolts, Without compression wood: Specimens	All bolts, Without compression wood: Specific gravity	All bolts, Without compression wood: Probable variation of individual specimen from corresponding average	Second section, All specimens: Specimens	Second section, All specimens: Specific gravity	Second section, All specimens: Probable variation of individual specimen from corresponding average	Second section, Without compression wood: Specimens	Second section, Without compression wood: Specific gravity	Second section, Without compression wood: Probable variation of individual specimen from corresponding average	Trees	Specific gravity	Probable variation of an individual tree from corresponding average
					Number	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*
		3	IV	58	0	71	.349	8.41												
				59	7	45	.371	8.58												
				60	1	64	.352	8.72												
				61	11	99	.334	10.36												
				62	4	60	.400	7.25												
				Total or average		339	.357	9.73	316	.352	8.90	91	.354	9.01	87	.350	8.52	5	.361	5.47
		Total or average lot 3				2,237	.363	10.60				510	.373	10.40	486	.368	9.78	29	.367	5.99
Mendocino and Humboldt.		Grand total or average lots 1, 2, and 3				4,046	.374	10.67				978	.386	9.92	934	.383	9.62	56	.377	5.54

SECOND GROWTH

Mendocino	T. 17 N., R. 16 and 17 W.	4	III	1	0	22	0.362	8.07												
				2	0	22	.353	5.31												
				3	0	14	.369	7.99												
				4	0	30	.323	9.17												
				5	0	18	.375	10.17												
				Total or average		106	.352	9.18	106	0.352	9.18	28	0.335	5.98	28	0.335	5.98	5	0.356	4.46
		4	III	6	4	26	.358	10.84												
				7	4	28	.356	7.22												
				8	0	22	.363	8.05												
				9	0	13	.367	7.40												
				Total or average		89	.360	8.67	81	.354	7.70	26	.339	6.63	24	.333	5.59	4	.361	1.12
		4	II	10	0	28	.325	4.74												
				11	0	15	.343	3.10												
				12	10	27	.459	4.68												
				13	0	24	.327	5.08												
				14	0	32	.335	6.60												
				24	0	27	.375	5.15												
				10, 11, 13, 14, 24		126	.341	6.54	126	.341	6.54	35	.328	5.26	35	.328	5.26	5	.341	4.63
				Total or average		153	.362	13.78	143	.353	9.15	42	.349	10.21	40	.341	8.61			
		4	IV	17	0	18	.383	7.24												
				18	1	26	.368	5.83												
				19	0	16	.377	8.34												
				Total or average		60	.375	7.15	59	.373	6.97	20	.354	3.32	20	.354	3.32	3	.376	1.92
		4	II	20	0	22	.380	5.43												
				21	2	24	.379	5.96												
				22	0	24	.348	7.94												
				23	3	21	.349	9.52												
				Total or average		91	.364	7.81	86	.359	7.22	24	.349	6.83	24	.349	6.83	4	.364	4.06
		4	Closely grown.	1-11, 13, 14, 17-24		472	.356	8.20				133	.339	6.03				21	.358	3.63
		4	Openly grown.	25	0	20	.365	6.60	20	.365	6.60	6	.346	4.90	6	.346	4.90			
				26	0	27	.306	6.12												
				27	0	22	.288	7.05												
				26 and 27		49	.298	6.88	49	.298	6.88	18	.277	4.32	18	.277	4.32			
				Total or average		69	.317	9.31	69	.317	9.31	24	.294	7.95	24	.294	7.95	3	.320	12.02

TABLE 8.—*Probable variation values of the specific gravity of virgin-growth and second-growth redwood*—Continued

SECOND GROWTH—continued

Place of growth: County	Place of growth: Land description	Lot number	Site class or stocking	Tree identification number	All bolts: Specimens containing compression wood	All bolts, All specimens: Specimens	All bolts, All specimens: Specific gravity	All bolts, All specimens: Probable variation of individual specimen from corresponding average	All bolts, Without compression wood: Specimens	All bolts, Without compression wood: Specific gravity	All bolts, Without compression wood: Probable variation of individual specimen from corresponding average	Second section, All specimens: Specimens	Second section, All specimens: Specific gravity	Second section, All specimens: Probable variation of individual specimen from corresponding average	Second section, Without compression wood: Specimens	Second section, Without compression wood: Specific gravity	Second section, Without compression wood: Probable variation of individual specimen from corresponding average	Trees	Specific gravity	Probable variation of an individual tree from corresponding average
					Number	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*	*Number*		*Per cent*
Humboldt	T. 5 N., R. 1 E.	5	III	29	0	28	.315	7.13												
				30	0	24	.381	7.08												
				35	0	22	.319	6.22												
				36	0	24	.346	8.42												
				37	1	28	.344	7.25												
				Total or average	------	126	.341	8.61	125	.340	8.59	34	.322	4.44	34	.322	4.44	5	.341	6.03
		5	III	31	4	22	.397	4.86												
				32	0	25	.351	4.84												
				33	0	24	.351	4.94												
				34	1	26	.377	6.58												
				48	0	25	.374	7.31												
				Total or average	------	122	.370	6.62	117	.368	6.53	35	.369	5.08	35	.369	5.08	5	.370	4.10
		5	Closely grown.	Total or average	------	248	.355	8.13	------	------	------	69	.346	6.71	------	------	------	10	.356	5.36

				38	0	29	.327	4.45												
				39	0	27	.335	5.97												
				Total or average	------	56	.331	5.39	56	.331	5.39	20	.316	4.52	20	.316	4.52	2	------	------
		5	Openly grown.	40	0	29	.301	8.17												
				41	0	22	.333	7.26												
				42	1	20	.331	6.88												
				Total or average	------	71	.319	8.27	70	318	8.15	25	.304	7.75	24	.300	6.89	3	.322	5.29
				44	0	39	.294	6.22												
				45	0	17	.330	7.33												
				46	0	15	.311	5.65												
				Total or average	------	71	.306	7.30	71	.306	7.30	25	.289	4.46	25	.289	4.46	3	.312	5.50
Mendocino and Humboldt.		4 and 5.	do	Total or average	------	198	.318	7.45	------	------	------	70	.302	6.46	------	------	------	8	.320	3.63
			do	------	------	267	.318	7.98	------	------	------	94	.300	6.87	------	------	------	11	.320	4.98
			Closely grown.	------	------	720	.356	8.17	------	------	------	202	.342	6.31	------	------	------	31	.357	4.10

The figures for probable variation are expressed in percentages of the corresponding average specific gravities to simplify comparisons. In calculating the probable variation of an individual specimen from the average, the usual formula was used, which assumes a normal distribution, as follows:

$$\text{Probable variation} = 0.6745\sqrt{\frac{\Sigma v^2}{n}}$$

Where v=residual between average specific gravity and each observed value
n=total number of specimens.

In calculating the probable variation of an individual tree from the average of the different tree groupings, correction was made for size of sample by multiplying the probable variation by $\sqrt{\frac{n}{n-2}}$, where n equals number of samples (*12*).

DETAILED DATA ON STRENGTH AND ASSOCIATED PROPERTIES OF REDWOOD

SELECTION OF TREES FOR STRENGTH TESTS

Specific gravity determinations were made in the field on about three times the number of trees required for the strength tests. The specific gravity determinations for each tree were confined to specimens from a section taken about 20 feet above the ground. The specimens were cut consecutively from bark to bark through the pith. This method gave results regarded as representative of the tree, and only those trees which best represented the range and average specific gravity of the species, as determined by the specific gravity survey (p. 3), were selected for the strength tests.

All logs chosen were from freshly cut trees and had the bark intact. It is common practice in the redwoods to peel the logs and then burn over the logged area or else first burn and then peel. Either method results in a large reduction of moisture in the logs, and the logs no longer remain representative of green stock. As green material is essential for the strength tests, the logs for this purpose could not be selected at the time of the usual logging operations but were cut and transported from the woods in advance of the main cut. A full and complete description of the trees and sites was also desired, and it was possible to obtain this only by working ahead of the regular logging operations.

The selection of second-growth trees was based on specific gravity determinations made on increment borings obtained in the usual manner. As second-growth redwood is not now being cut commercially, the increment-boring method eliminated the necessity of cutting and sampling more second-growth than would actually be used for test purposes.

STRENGTH OF REDWOOD

Table 9 presents actual test results for virgin-growth and second-growth redwood, together with a percentage figure representing the relation of these actual results to the value which would be expected for the species on the basis of the specific gravity-strength equation for the corresponding property. The equation value was obtained by substituting the specific gravity of redwood in the previously established general formulas expressing the relation of specific gravity to strength as determined by tests on 166 species (*8*). The percentage figures given are useful in considering the degree to which redwood differs, weight for weight, from the general average trend of other species.

Table 10 gives data on the mechanical properties of virgin-growth redwood by counties; Table 11 data on the mechanical properties of virgin-growth redwood as related to height in tree.

TABLE 9.—*Test-strength values of green and air-dried virgin-growth*[1] *and second-growth*[2] *redwood, and ratios of test values to values normally expected by specific gravity as indicated by tests of other species*

Description and property	Unit	Green						Air-dried					
		Virgin growth		Second growth				Virgin growth		Second growth			
				Closely grown		Openly grown				Closely grown		Openly grown	
		Description and test values	Ratio[3]	Description and test values	Ratio[3]	Description and test values	Ratio[3]	Description and test values	Ratio[3]	Description and test values	Ratio[3]	Description and test values	Ratio[3]
Lot No.		6, 7, and 8		7 and 8		7 and 8		6, 7, and 8		7 and 8		7 and 8	
Number:													
Trees		16		8		6		16		8		6	
Rings per inch		29		7		3		29		7		3	
Specific gravity:													
Volume as tested[4]		0.39		0.33		0.29		0.40		0.35		0.31	
Oven-dry volume		0.416		0.361		0.310							
Shrinkage:													
In volume	Per cent of dimensions when green	6.7		7.4		6.3							
Radial—sapwood	do	[5] 3.2		2.9		2.6							
Radial—heartwood	do	2.4		2.1		1.6							
Tangential—sapwood	do	[5] 5.2		5.9		5.0							
Tangential—heartwood	do	4.0		4.5		4.0							
Moisture content	Per cent	112		112		146		12.0		12.0		12.0	
Static bending:													
Specific gravity		0.388		0.331		0.297		0.405		0.350		0.308	
Fiber stress at elastic limit	Pounds per square inch	4,820	1.53	3,560	1.40	2,750	1.26	6,980	1.32	5,470	1.22	4,290	1.15
Modulus of rupture	do	7,500	1.38	6,060	1.38	4,600	1.22	10,100	1.24	8,310	1.20	6,460	1.12
Modulus of elasticity	1,000 pounds per square inch	1,176	1.28	1,002	1.29	642	.94	1,350	1.20	1,124	1.15	762	.88
Work to elastic limit	Inch-pounds per cubic inch	1.18	1.97	0.73	1.55	0.68	1.74	2.07	1.49	1.50	1.29	1.37	1.46
Work to maximum load	do	7.4	1.07	6.1	1.22	5.1	1.24	6.9	1.07	5.7	1.11	4.7	1.15
Work total	do	14.1	.90	10.3	.92	6.4	.74	8.6	.74	6.8	.76		
Impact bending (50-pound hammer):													
Specific gravity		0.393		0.334		0.292		0.408		0.347		0.301	
Fiber stress at elastic limit	Pounds per square inch	8,920	1.22	7,230	1.22	5,860	1.16	10,250	1.04	9,080	1.08	6,830	.98
Modulus of elasticity	1,000 pounds per square inch	1,410	1.23	1,188	1.22	848	1.00	1,660	1.23	1,478	1.25	1,012	.97
Work to elastic limit	Inch-pounds per cubic inch	3.2	1.23	2.5	1.25	2.3	1.36	3.6	.90	3.2	.97	2.7	1.00
Drop causing complete failure	Inches	20.9	.94	17.8	1.11	14.1	1.08	18.8	.99	15.6	1.04	10.9	.92

[1] The test values on virgin-growth redwood are for material from 20 to 32 feet above the ground.
[2] The test values on second-growth redwood are for material from 8 to 16 feet above the ground.
[3] Ratio of test values to values normally expected of a species of corresponding specific gravity as determined by equations based on tests of 166 species (*8*).
[4] Average of static bending, impact bending, compression perpendicular to grain, and hardness tests.

TABLE 9.—*Test-strength values of green and air-dried virgin-growth and second-growth redwood, etc.*—Continued

Description and property	Unit	Green						Air-dried					
		Virgin growth		Second growth				Virgin growth		Second growth			
				Closely grown		Openly grown				Closely grown		Openly grown	
		Description and test values	Ratio	Description and test values	Ratio	Description and test values	Ratio	Description and test values	Ratio	Description and test values	Ratio	Description and test values	Ratio
Compression parallel to grain:													
Specific gravity		0.380		0.318		0.282		0.402		0.344		0.303	
Crushing strength at elastic limit	Pounds per square inch	[5] 3,730	1.82	2,820	1.63	1,820	1.20	[5] 4,740	1.35	3,820	1.25	2,690	.99
Maximum crushing strength	do	4,200	1.60	3,280	1.48	2,320	1.19	6,200	1.27	5,270	1.23	3,860	1.02
Modulus of elasticity	1,000 pounds per square inch	[5] 1,488	1.31	1,212	1.26	774	.92	[5] 1,550	1.15	1,260	1.07	820	.78
Compression perpendicular to grain:													
Specific gravity		0.385		0.329		0.293		0.402		0.351		0.310	
Fiber stress at elastic limit	Pounds per square inch	524	1.46	348	1.46	314	1.66	868	1.49	653	1.51	561	1.71
Shearing strength:													
Radial	do	788	1.04	703	1.14	581	1.10	957	.96	933	1.10	788	1.11
Tangential	do	818	1.01	750	1.14	703	1.25	933	.87	939	1.02	951	1.25
Average	do	803	1.02	726	1.14	642	1.18	945	.91	936	1.06	870	1.18
Tension perpendicular to grain:													
Radial	do	273	1.00	270	1.38	215	1.42	232	.78	218	.96	161	.90
Tangential	do	238	.67	311	1.23	314	1.62	240	.66	337	1.21	327	1.50
Average	do	256	.82	290	1.30	264	1.53	236	.72	278	1.10	244	1.23
Hardness: [6]													
Specific gravity		0.378		0.324		0.292		0.404		0.347		0.305	
End	Pounds	569	1.27	469	1.58	388	1.64	800	1.32	720	1.61	594	1.75
Radial	do	404	1.00	341	1.27	270	1.27	490	1.05	383	1.10	311	1.18
Tangential	do	423	1.02	360	1.31	299	1.37	470	.98	426	1.20	369	1.37
Average radial and tangential	do	414	1.01	350	1.29	284	1.32	480	1.01	404	1.15	340	1.28
Cleavage:													
Radial	Pounds per inch of width	177	1.08	172	1.46	142	1.56	143	.79	134	.96	118	1.08
Tangential	do	159	.83	183	1.34	169	1.59	153	.75	175	1.11	192	1.56
Average	do	168	.94	178	1.39	156	1.59	148	.76	154	1.04	155	1.34
Tension parallel to grain:													
Specific gravity				0.307		0.290							
Maximum tensile strength	Pounds per square inch	9,450		7,290		4,420		10,080		10,320		6,590	
Toughness: [7]													
Specific gravity		[5] 0.389		0.340		0.294		[5] 0.394		0.345		0.302	
Radial	Inch-pounds per specimen	[5] 57.6		62.8		46.7		[5] 49.6		45.7		29.6	
Tangential	do	[5] 105.5		94.5		55.1		[5] 76.0		63.3		34.6	
Average	do	81.6		78.6		50.9		62.8		54.5		32.1	

5 Lots 7 and 8 only.
6 Load required to embed a 0.444-inch ball to one-half its diameter.
7 Specimens ⅝ by ⅝ by 10 inches, tested over an 8-inch span with load applied on tangential face nearest the pith.

TABLE 10.—*Average mechanical properties of virgin-growth redwood*[1] *as related to locality of growth*

Description and property	Unit	Green: Mendocino County	Green: Humboldt County	Green: Ratio Mendocino to Humboldt County	Air-dried: Mendocino County	Air-dried: Humboldt County	Air-dried: Ratio Mendocino to Humboldt County
Lot No.		6 and 7	8		6 and 7	8	
Trees	Number	9	7		9	7	
Rings per inch	do	33	25	1.32	32	25	1.28
Specific gravity:							
Volume as tested[2]		0.40	0.370	1.08	0.42	0.39	1.08
Oven-dry volume		0.422	0.411	1.03			
Shrinkage:							
In volume	Per cent of dimensions when green	6.7	6.8	.99			
Radial—sapwood	do	[3] 3.3	3.1	1.06			
Radial—heartwood	do	[3] 2.3	2.3	1.00			
Tangential—sapwood	do	[3] 4.8	5.6	.86			
Tangential—heartwood	do	[3] 3.7	4.1	.90			
Moisture content	Per cent	104	120		12	12	
Static bending:							
Specific gravity		0.405	0.370	1.09	0.418	0.392	1.07
Fiber stress at elastic limit	Pounds per square inch	5,030	4,620	1.09	7,300	6,640	1.10
Modulus of rupture	do	7,640	7,350	1.04	10,450	9,680	1.08
Modulus of elasticity	1,000 pounds per square inch	1,178	1,175	1.00	1,360	1,330	1.02
Work to elastic limit	Inch-pounds per cubic inch	1.33	1.04	1.28	2.24	1.84	1.22
Work to maximum load	do	7.5	7.4	1.01	7.5	6.4	1.17
Work, total	do	14.5	13.7	1.06	9.0	8.3	1.08
Impact bending (50-pound hammer):							
Specific gravity		0.407	0.379	1.07	0.427	0.388	1.10
Fiber stress at elastic limit	Pounds per square inch	9,310	8,520	1.09	10,600	9,840	1.08
Modulus of elasticity	1,000 pounds per square inch	1,431	1,389	1.03	1,700	1,625	1.05
Work to elastic limit	Inch-pounds per cubic inch	3.4	3.0	1.13	3.9	3.4	1.15
Drop causing complete failure	Inches	21.8	20.0	1.09	19.3	18.3	1.05
Compression parallel to grain:							
Specific gravity		0.398	0.361	1.10	0.419	0.386	1.09
Crushing strength at elastic limit	Pounds per square inch	[3] 3,880	3,580	1.08	[3] 4,860	4,620	1.05
Maximum crushing strength	do	4,290	4,110	1.04	6,490	5,960	1.09
Modulus of elasticity	1,000 pounds per square inch	[3] 1,550	1,425	1.09	[3] 1,630	1,476	1.10
Compression perpendicular to grain:							
Specific gravity		0.395	0.375	1.05	0.415	0.389	1.07
Fiber stress at elastic limit	Pounds per square inch	524	523	1.00	930	813	1.14

[1] Test values are for material from 20 to 32 feet above ground.
[2] Average of static bending, impact bending, compression perpendicular to grain, and hardness tests.
[3] Lot 7 only.

TABLE 10.—*Average mechanical properties of virgin-growth redwood as related to locality of growth*—Continued

Description and property	Unit	Green			Air-dried		
		Mendocino County	Humboldt County	Ratio Mendocino to Humboldt County	Mendocino County	Humboldt County	Ratio Mendocino to Humboldt County
Shearing strength:							
Radial	do	775	802	.97	1,000	909	1.10
Tangential	do	820	816	1.00	985	883	1.11
Average	do	798	809	.99	992	896	1.11
Tension perpendicular to grain:							
Radial	do	267	279	.96	248	218	1.14
Tangential	do	229	248	.92	245	234	1.05
Average	do	248	264	.94	246	226	1.09
Hardness: [4]							
Specific gravity		0.399	0.357	1.12	0.415	0.393	1.06
End	Pounds	569	569	1.00	846	757	1.12
Radial	do	416	392	1.06	508	471	1.08
Tangential	do	428	418	1.02	477	461	1.03
Average radial and tangential	do	422	405	1.04	492	466	1.06
Cleavage:							
Radial	Pounds per inch of width	170	184	.92	153	130	1.18
Tangential	do	144	174	.83	158	146	1.08
Average	do	157	179	.88	156	138	1.13
Tension parallel to grain:							
Maximum tensile strength	Pounds per square inch	9,800	9,100	1.08	10,500	9,650	1.09
Toughness: [5]							
Specific gravity		[3] 0.394	0.384	1.03	[3] 0.403	0.386	1.04
Radial	Inch-pounds per specimen	[3] 57.4	57.7	.99	[3] 50.6	48.9	1.03
Tangential	do	[3] 118.4	92.6	1.28	[3] 76.2	75.3	1.01
Average	do	[3] 87.9	75.2	1.17	[3] 63.4	62.1	1.02

[3] Lot 7 only.
[4] Load required to embed a 0.444-inch ball to one-half its diameter.
[5] Specimens 5/8 by 5/8 by 10 inches, tested over an 8-inch span with load applied on tangential face nearest the pith.

TABLE 11.—*Average mechanical properties of virgin-growth redwood as related to height in tree*

Description and property	Unit	Comparison of butt and second logs [1]						Comparison of top and second logs [1]					
		Green			Air-dried			Green			Air-dried		
		Butt logs	Second logs	Ratio butt to second logs	Butt logs	Second logs	Ratio butt to second logs	Top logs	Second logs	Ratio top to second logs	Top logs	Second logs	Ratio top to second logs
Lot Nos		7 and 8	7 and 8		7 and 8	7 and 8		7 and 8	7 and 8		7 and 8	7 and 8	
Trees	Number	5	5		5	5		10	10		10	10	
Rings per inch	do	28	29	0.97	27	28	0.96	33	32	1.03	34	31	1.10
Moisture content	Per cent	158	120	1.32	12.0	12.0		66	110	.60	12	12	
Static bending:													
Specific gravity		0.392	0.392	1.00	0.417	0.409	1.02	0.350	0.380	.92	0.361	0.394	.92
Fiber stress at elastic limit	Pounds per square inch	4,520	4,630	.98	6,480	6,630	.98	3,920	4,430	.89	5,810	6,470	.90
Modulus of rupture	do	7,120	7,550	.94	9,410	10,100	.93	6,270	7,180	.87	8,530	9,660	.88
Modulus of elasticity	1,000 pounds per square inch	1,090	1,248	.87	1,266	1,400	.90	958	1,164	.82	1,110	1,323	.84
Work to elastic limit	Inch-pounds per cubic inch	1.08	0.99	1.09	1.89	1.80	1.05	0.91	0.97	.94	1.72	1.79	.86
Work to maximum load	do	7.6	7.7	.99	5.8	7.0	.83	5.8	7.3	.80	5.6	6.6	.85
Work total	do	14.0	15.1	.93	8.2	9.3	.87	7.6	13.4	.57	6.4	8.4	.75
Impact bending (50-pound hammer):													
Specific gravity		0.402	0.400	1.00	0.422	0.411	1.03	0.348	0.382	.91	0.362	0.394	.92
Fiber stress at elastic limit	Pounds per square inch	8,510	8,710	.98	9,050	9,940	.91	7,340	8,470	.87	9,430	9,650	.98
Modulus of elasticity	1,000 pounds per square inch	1,290	1,429	.90	1,595	1,796	.89	1,137	1,358	.84	1,400	1,640	.85
Work to elastic limit	Inch-pounds per cubic inch	3.1	3.0	1.03	3.0	3.2	.94	2.7	3.0	.90	3.6	3.3	1.09
Drop causing complete failure	Inches	21.0	22.0	.95	17.3	20.0	.87	15.8	20.0	.79	15.9	18.4	.87
Compression parallel to grain:													
Specific gravity		0.383	0.379	1.01	0.420	0.405	1.04	0.334	0.364	.92	0.358	0.388	.92
Crushing strength at elastic limit	Pounds per square inch	3,370	3,980	.85	4,320	5,020	.86	2,840	3,600	.79	3,810	4,680	.81
Maximum crushing strength	do	4,050	4,330	.94	6,360	6,370	1.00	3,430	4,050	.85	5,440	6,030	.90
Modulus of elasticity	1,000 pounds per square inch	1,277	1,542	.83	1,425	1,582	.90	1,220	1,459	.84	1,285	1,530	.84
Compression perpendicular to grain:													
Specific gravity		0.394	0.392	1.00	0.418	0.403	1.04	0.346	0.373	.93	0.359	0.392	.92
Fiber stress at elastic limit	Pounds per square inch	490	513	.96	862	812	1.06	425	520	.82	671	800	.84
Shearing strength:													
Radial	do	728	774	.94	800	895	.89	732	751	.98	883	878	1.01
Tangential	do	835	758	1.10	882	890	.99	726	775	.94	833	882	.94
Average	do	782	766	1.02	841	892	.94	729	763	.96	858	880	.98
Tension perpendicular to grain:													
Radial	do	254	292	.87	181	218	.83	283	288	.98	223	229	.97
Tangential	do	257	252	1.02	229	231	.99	252	254	.99	256	245	1.04
Average	do	256	272	.94	205	224	.92	268	271	.99	240	237	1.01

[1] The second logs were from 20 to 32 feet above ground.

TABLE 11.—*Average mechanical properties of virgin-growth redwood as related to height in tree*—Continued

Description and property	Unit	Comparison of butt and second logs						Comparison of top and second logs					
		Green			Air-dried			Green			Air-dried		
		Butt logs	Second logs	Ratio butt to second logs	Butt logs	Second logs	Ratio butt to second logs	Top logs	Second logs	Ratio top to second logs	Top logs	Second logs	Ratio top to second logs
Hardness: [2]													
Specific gravity		0.389	0.383	1.02	0.415	0.410	1.01	0.349	0.364	.96	0.360	0.394	.91
End	Pounds	570	538	1.06	782	780	1.00	488	536	.91	707	762	.93
Radial	do	427	390	1.09	509	501	1.02	345	378	.91	412	456	.90
Tangential	do	441	410	1.07	497	475	1.05	340	396	.86	401	435	.92
Average radial and tangential	do	434	400	1.08	503	488	1.03	342	387	.88	406	446	.91
Cleavage:													
Radial	Pounds per inch of width	173	185	.94	122	136	.90	181	183	.99	147	138	1.07
Tengential	do	173	157	1.10	156	145	1.08	170	162	1.05	168	151	1.11
Average	do	173	171	1.01	139	140	.99	176	172	1.02	158	144	1.10
Tension parallel to grain:													
Maximum tensile strength	Pounds per square inch	8,090	9,800	.83	10,660	10,980	.97	8,410	9,340	.90	8,280	10,310	.80
Toughness: [3]													
Specific gravity		0.408	0.399	1.02	0.418	0.401	1.04	0.353	0.382	.92	0.363	0.386	.94
Radial	Inch-pounds per specimen	67.5	63.7	1.06	54.7	53.7	1.02	46.0	53.9	.85	38.0	47.1	.81
Tangential	do	99.1	111.7	.89	79.8	86.3	.92	71.2	95.8	.74	55.5	72.2	.77
Average	do	83.3	87.7	.95	67.2	70.0	.96	58.6	74.8	.78	46.8	59.6	.79

[2] Load required to embed a 0.444-inch ball to one-half its diameter.
[3] Specimens ⅝ by ⅝ by 10 inches, tested over an 8-inch span with loads applied on tangential face nearest the pith.

VARIABILITY IN THE STRENGTH OF REDWOOD

Table 12 lists the probable variation values of the specific gravity and several strength properties of virgin-growth and the second-growth redwood from second logs, representing material 8 to 30 feet above the ground. These values were calculated by the usual formula, as given on page 34.

TABLE 12.—*Percentage probable variation*[1] *in strength and related properties of an individual redwood specimen from the corresponding average*

Property	Virgin-growth redwood[2] (lot Nos. 6, 7, and 8)		Second-growth redwood[3]			
			Closely grown (lot Nos. 7 and 8)		Openly grown (lot Nos. 7 and 8)	
	Green	Air-dry[4]	Green	Air-dry[4]	Green	Air-dry[4]
Specific gravity, based on green or air-dry volume	8.7	8.1	7.0	6.9	10.5	10.3
Shrinkage:						
Radial	16.5	----------	17.9	----------	34.0	----------
Tangential	15.2	----------	16.0	----------	17.0	----------
Volumetric	11.1	----------	15.7	----------	10.2	----------
Static bending:						
Fiber stress at elastic limit	14.9	12.8	10.8	10.8	20.8	17.2
Modulus of rupture	12.3	11.4	9.4	11.4	17.4	16.1
Modulus of elasticity	15.5	12.3	16.4	15.9	18.3	18.3
Work to elastic limit	31.7	21.0	17.6	14.8	28.8	20.7
Work to maximum load	20.0	21.9	20.3	24.9	25.3	31.3
Impact bending:						
Fiber stress at elastic limit	11.4	14.3	10.0	13.2	13.8	18.4
Work to elastic limit	14.6	25.8	14.4	23.1	17.9	25.5
Maximum drop (50-pound hammer)	14.2	18.2	18.4	26.1	28.1	31.2
Compression parallel to grain:						
Fiber stress at elastic limit	16.2	16.7	14.0	16.3	23.4	24.5
Maximum crushing strength	12.9	12.6	10.1	10.1	19.2	16.3
Compression perpendicular to grain:						
Fiber stress at elastic limit	22.2	20.8	14.5	15.4	32.5	20.8
Hardness:						
End	12.6	11.7	9.3	7.4	19.5	17.0
Radial and tangential	15.8	15.7	11.2	13.0	18.1	21.2
Radial only	15.3	16.1	12.0	13.5	18.7	21.8
Tangential only	16.0	15.2	9.8	11.9	16.8	19.0
Shear:						
Radial and tangential	11.6	17.6	7.8	9.2	16.1	17.4
Radial only	11.3	18.2	8.9	8.9	13.9	15.9
Tangential only	11.9	16.7	5.2	9.3	15.1	15.9
Toughness:						
Radial and tangential	35.4	29.0	32.8	35.1	37.1	29.1
Radial only	27.4	23.1	24.1	39.1	36.4	25.9
Tangential only	30.3	26.0	30.0	29.7	36.0	29.9
Tension parallel to grain	14.6	19.3	8.3	18.7	20.5	17.8

[1] Probable variation of the entire trees is about 1 to 2 per cent higher than shown here.
[2] Specimen taken 20 to 30 feet above the ground
[3] Specimen taken 8 to 16 feet above the ground
[4] Average moisture content of air-dry material varied from 10½ to 12 per cent for different tests.

The percentage probable variation of specific gravity is lower than that of any of the strength properties. Such properties as modulus of rupture, maximum crushing strength, and hardness have a percentage probable variation from one to two times that of the specific gravity. Shock resistance as measured by work to maximum load in static bending, maximum drop in impact bending and toughness are usually most variable, often having a percentage probable variation four times that of specific gravity.

Since the probable variation values in Table 12 are based on samples from the second logs only, they are somewhat lower (probably about 1 to 2 per cent) than would obtain for samples representing the entire trees. For example, if the table gives a value of 17 per cent, the probable variation of a random specimen from entire trees, or the species average, is probably 18 to 19 per cent.

EXPLANATION OF TERMS AND METHODS EMPLOYED

Air-dry.—Air-dry is a very general term and may mean any degree of dryness from about 6 per cent moisture, which may be obtained in very dry climates, to over 30 per cent moisture, as in timber dried to reduce its shipping weight. The degree of dryness which will be attained in timber depends upon the species, size, and the conditions under which the material is dried, especially such as humidity, method of piling, shelter, and time of drying.

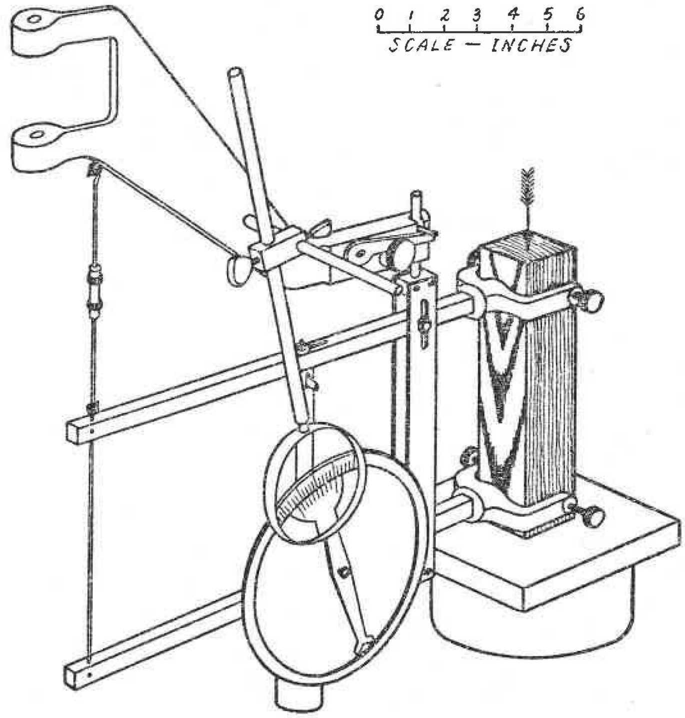

FIGURE 15.—Diagrammatic sketch of compressometer and method of conducting compression-parallel-to-grain test

Compression parallel to grain.—In the compression parallel to grain test a 2 by 2 by 8 inch block is compressed in the direction of its length. (Fig. 15.) Deformation is measured between two collars attached 6 inches apart on the specimen.

Compression perpendicular to grain.—In the compression perpendicular to grain test, a block 2 by 2 inches in cross section and 6 inches long is laid upon its side and pressure applied to it through a metal plate 2 inches wide laid across the center of the piece and at right angles to its length. (Fig. 16.) Hence but one-third of the surface is directly subjected to compression. The strength value obtained in this test is the fiber stress at elastic limit. It represents the maximum stress at right angles to the grain that can be applied to the timber without injury. It is important in computing the bearing area for beams, stringers, and joists, and in comparing species for railroad ties.

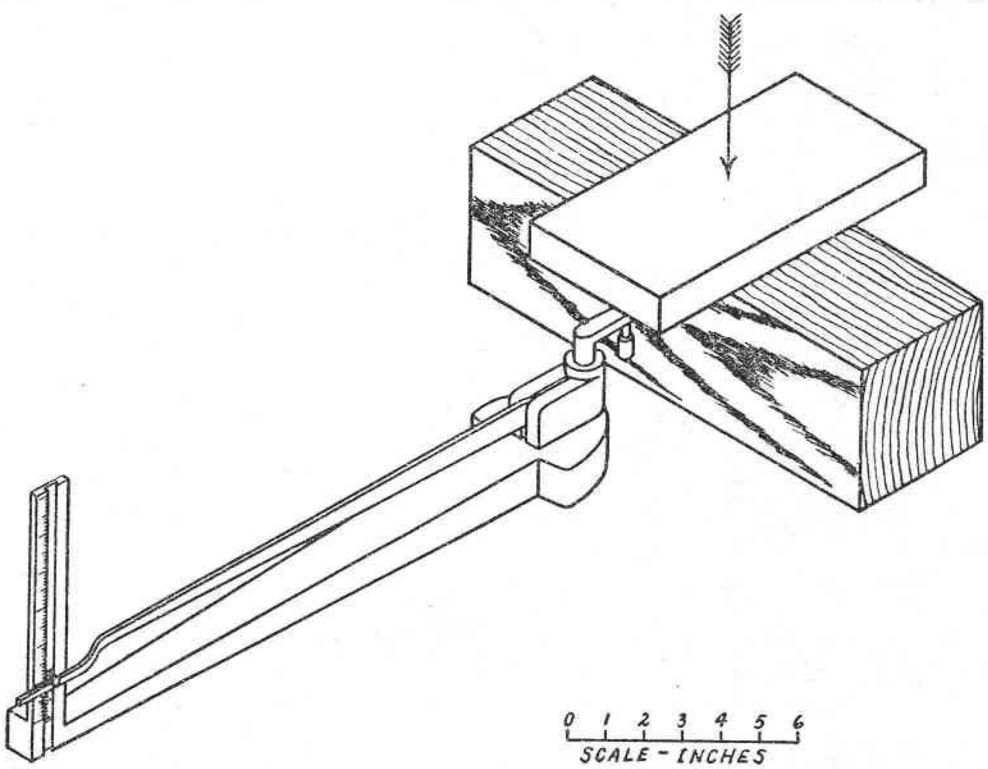

FIGURE 16.—Diagrammatic sketch of method of conducting compression-perpendicular-to-grain test

Elastic limit.—The elastic limit is that point where the distortion ceases to be in proportion to the load. For example, if a beam deflects one-sixteenth of an inch with a 50-pound load, it will deflect one-eighth of an inch with 100 pounds, and so on, each additional load of 50 pounds causing an additional deflection of one-sixteenth of an inch until the "elastic limit" is reached, after which the deflections increase more rapidly than the increase in load. The elastic limit is subject to the personal equation in its determination and for this reason can not be evaluated precisely.

Extractives.—Extractives, as the word is here used, are defined as that portion of the wood that will dissolve when the wood is placed in an inert solvent. They are known, for example, as cold-water, hot-water, or alcohol-soluble extractives, the name depending upon the solvent used.

Fiber stress at elastic limit.—Fiber stress at elastic limit is the stress obtained in a timber by loading it to its elastic limit. It is the greatest stress the timber will take under a given loading and return to its former position. Fiber stress at elastic limit in impact bending is approximately double the fiber stress at elastic limit in static bending. This is an expression of the fact that a small beam, if suddenly strained, bends approximately twice as far to the elastic limit as when loaded slowly. (See also elastic limit, above.)

Fiber - saturation point.—Green wood usually contains "absorbed" water within the cell walls and "free" water in the cell cavities. In drying, the water in the cell cavities is the first to be evaporated. The fiber-saturation point is that point at which no water exists in the cell cavities of the timber, but at which the cell walls are still saturated with moisture. The fiber-saturation point varies with the species. The ordinary proportion of moisture at the fiber-saturation point is from 22 to 30 per cent of the dry weight of the wood.

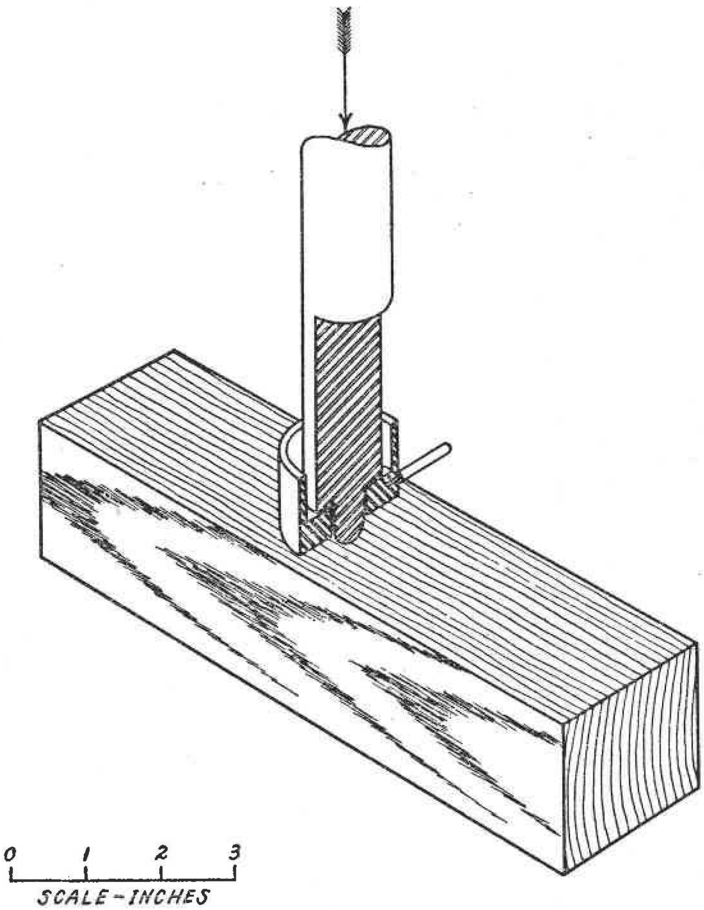

FIGURE 17.—Diagrammatic sketch of method of conducting hardness test

Green.—Green is the condition of timber with respect to moisture as taken from the living tree. Immediately upon being sawed from the tree, lumber begins to lose moisture and otherwise change its condition. The rapidity of these changes is determined by such factors as the species, humidity, heat, and circulation of air.

Hardness.—Hardness is tested by measuring the load required to embed a 0.444-inch ball to one-half its diameter in the wood. (Fig. 17.) The hardness test is applied to end, radial, and tangential surfaces of the timber. End hardness is usually greater than side hardness. The quality represented by the hardness figures is important in woods for paving blocks, railroad ties, furniture, and flooring.

Height of drop.—Height of drop relates to impact bending and is the distance from which a hammer is dropped to produce failure of a standard-sized specimen. It represents a quality important in articles that are occasionally stressed under a shock beyond their elastic limit, such as handles and implement parts.

Impact bending.—Impact bending tests are made on beams to determine the resistance to rapidly applied loads. Beams 2 by 2 by 30 inches are used in this test on a 28-inch span. A 50-pound hammer is dropped upon the beam at the center of the span, first from a height of 1 inch, next 2 inches, and so on up to 10 inches, then increasing 2 inches at a time until complete failure occurs. The deflections of the specimen are recorded on a revolving drum by a pointer attached to the hammer. This pointer also records the position the specimen assumes after the shock. Thus data are obtained for determining the various properties of the wood when subjected to shock.

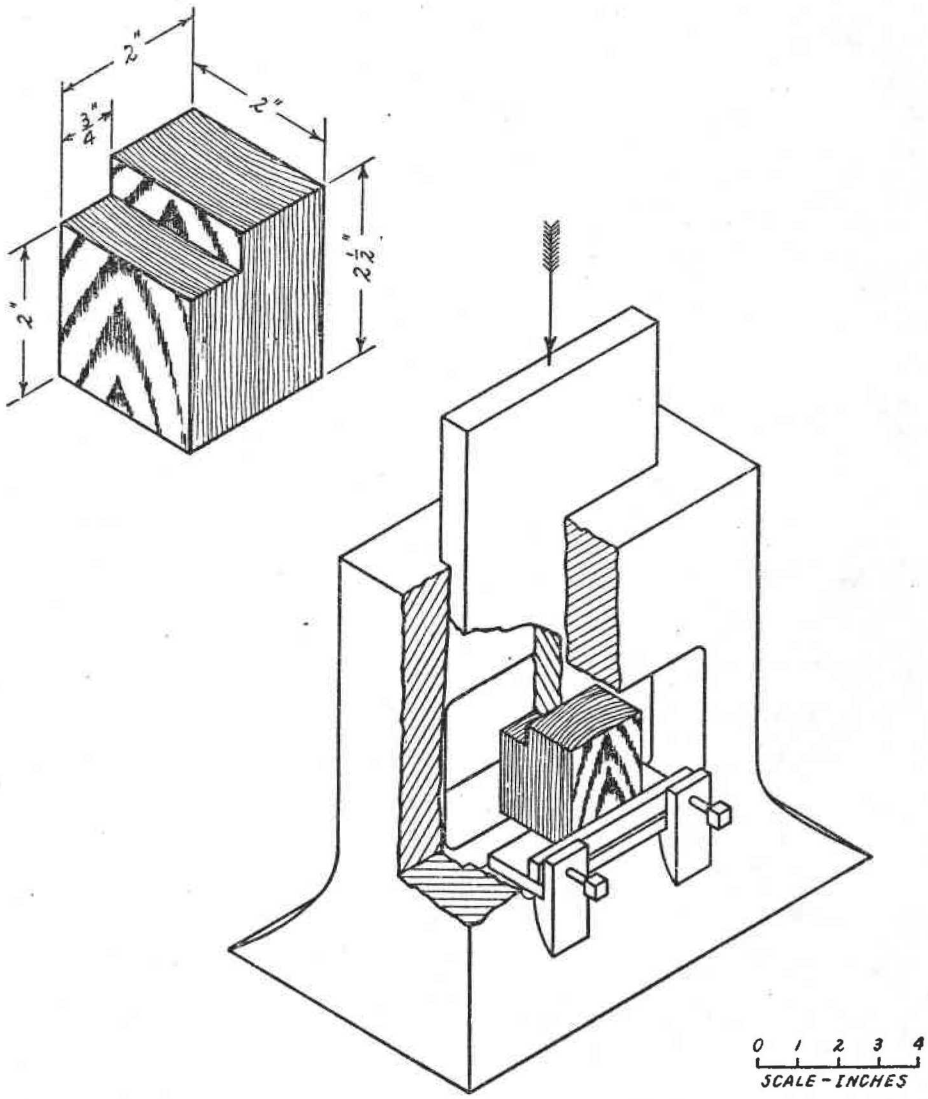

FIGURE 18.—Diagrammatic sketch of method of conducting shear-parallel-to-grain test, with details of test specimen

Maximum crushing strength.—The maximum crushing strength in compression parallel to grain is the maximum ability of a short block to sustain a slowly applied load. It is obtained by dividing the maximum load obtained in the test by the area of cross section of the block. This property is important in estimating the strength of short columns.

Mechanical properties.—Mechanical properties are the properties of wood which enable it to resist deformations, loads, shocks, or forces. Thus the ability to resist shearing forces is a mechanical property of timber.

Modulus of elasticity.—Modulus of elasticity is the ratio of stress per unit area to corresponding strain per unit length, the distortion or strain being within the elastic limit. It is a measure of the stiffness or rigidity of a material. In the case of a beam, modulus of elasticity is a measure of its resistance to deflection. Deflection under a given load varies inversely as the modulus of elasticity; that is, a beam with a high modulus deflects but little. Modulus of elasticity is of value in computing the deflections of joists, beams, and stringers, and in computing safe loads for long columns. The values given are derived from the static-bending test, but are applicable to both beams and long columns. Numerically, the modulus of elasticity of a material is the force in pounds required to stretch a sample of that material with a cross-sectional area of 1 square inch to double its length, on the assumption that the fibers would not be stressed beyond their elastic limit. Rubber has a very low modulus of elasticity, while that of steel is very high.

Modulus of rupture.—Modulus of rupture is the computed fiber stress in the outermost fibers of a beam at the maximum load and is a measure of the ability of a beam to support a slowly applied load for a very short time. The formula by which modulus of rupture is computed is the same as that for computing the fiber stress at elastic limit, the maximum load being substituted for the elastic-limit load. The assumptions on which this formula are based hold only up to the elastic limit; hence modulus of rupture is not a true fiber stress. It is, however, a universally accepted term, and the values are quite comparable for various species and sizes of timber. It is a definite

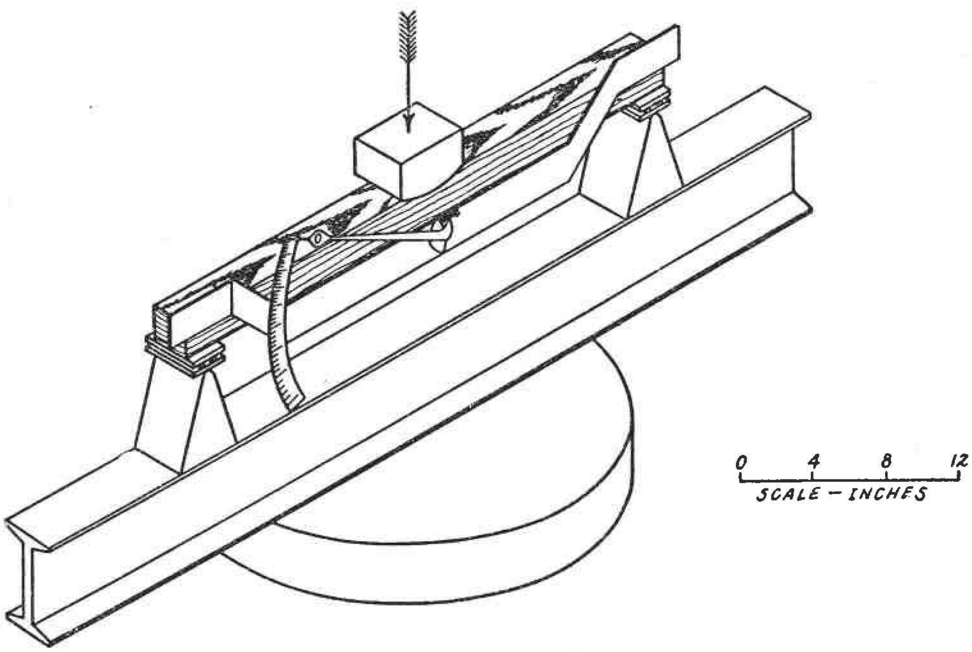

FIGURE 19.—Diagrammatic sketch of method of conducting static-bending test

quantity, and the personal factor does not enter to any great extent into obtaining it. It is consequently not so subject to error as the fiber stress at elastic limit, and for that reason is used more than any other value to represent the bending strength of wood.

Moisture content.—Moisture content is the weight of water contained in the wood, expressed as a percentage of the weight of the oven-dry wood.

Shearing strength parallel to grain.—The shearing test is made by applying force to a 2 by 2 inch lip projecting from the side of a block. (Fig. 18.) The shearing stress is the maximum force required to shear off the projection divided by the area of the plane of failure. Shearing strength parallel to the grain is a measure of the ability of timber to resist the slipping of one part upon another along the grain. Shearing stress is produced to a greater or less degree in most uses of timber. It is most important in beams, where it is known as horizontal shear, the stress tending to cause the upper half of the beam to slide upon the lower. It is also important in the design of various kinds of timber joints.

Shrinkage from the green to an oven-dry condition.—When wood is dried below the fiber-saturation point (see definition, p. 43), shrinkage begins and continues until the moisture is all driven off. Shrinkage along the length of timber is very small. Shrinkage in directions at right angles to the grain is very much greater. Radial shrinkage is about three-fifths as great as tangential shrinkage. Shrinkage in volume is, of course, the resultant of shrinkages along the fibers and in the radial and tangential directions. However, shrinkage in volume and radial and tangential shrinkages were independently determined in the series of tests reported on in this bulletin. All shrinkage values given here are expressed in percentages of the original or green dimensions, and represent total shrinkage to a zero moisture condition. Shrinkage to an air-dry condition of about 12 per cent moisture is sometimes more and sometimes less than half the total shrinkage. Radial shrinkage is the measure of the change in width of a quarter-sawed or edge-grained board. Tangential shrinkage is the measure of the change in width of a flat-sawed board.

Site.—A site is an area considered with respect to its forest producing power as influenced by climate, altitude, soil, slope, aspect, and other local influencing conditions.

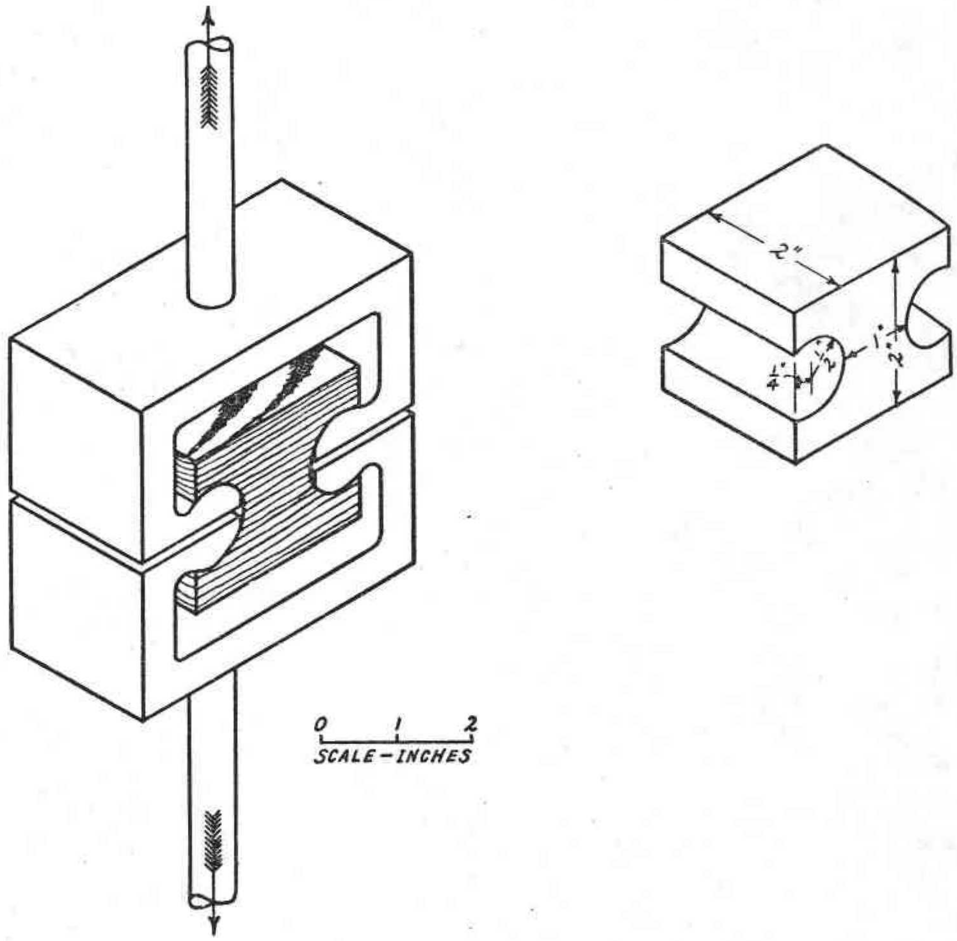

FIGURE 20.—Diagrammatic sketch of method of conducting tension-perpendicular-to-grain test, with details of test specimen

Specific gravity.—Specific gravity is the weight of any given substance divided by the weight of an equal volume of pure water at its greatest density. The weight of wood in a given volume changes with the shrinkage and swelling caused by changes in moisture. Consequently, specific gravity is an indefinite quantity unless the circumstances under which it is determined are specified. All specific gravity figures given in this bulletin are based on the weight of the wood when oven dry. The moisture condition at which the volume was determined is stated in each instance.

Static bending.—The static-bending test is made on beams to determine the resistance to slowly applied loads. A 2 by 2 by 30 inch beam is used on a 28-inch span. Loading is applied at the center of the span and at a constant rate of deflection until the beam fails. (Fig. 19.) Readings of load and deflection are taken simultaneously. The values derived from this test are applicable to beams of different size by the use of a formula, except for the defects that occur in the larger sizes.

Strain.—The deformation or distortion produced by a stress or force is known as strain.

Stress.—Stress is distributed force. Fiber stress is the distributed force tending to compress, tear apart, or change the relative position of the wood fibers. Stress is measured by the force per unit area. Thus a short column 2 inches square (4 square inches) and supporting a load of 2,000 pounds will be under a stress or fiber stress of 500 pounds per square inch.

Tangential.—Tangential means tangent to or parallel to the curves of the annual rings in a cross section. Thus a tangential surface is a surface perpendicular to the radius of a tree.

Tension perpendicular to grain.—The tension-perpendicular-to-grain tests are made on specimens 2 inches square and 2½ inches long, the tension area being 1 by 2 inches. The tension force is applied perpendicular to the grain. (Fig. 20.) The values are of use in estimating the resistance of timber to the splitting actions of bolts and other fastenings.

Total work.—Total work in static bending, like work to maximum load, is a measure of toughness or shock resistance under bending stresses. In the

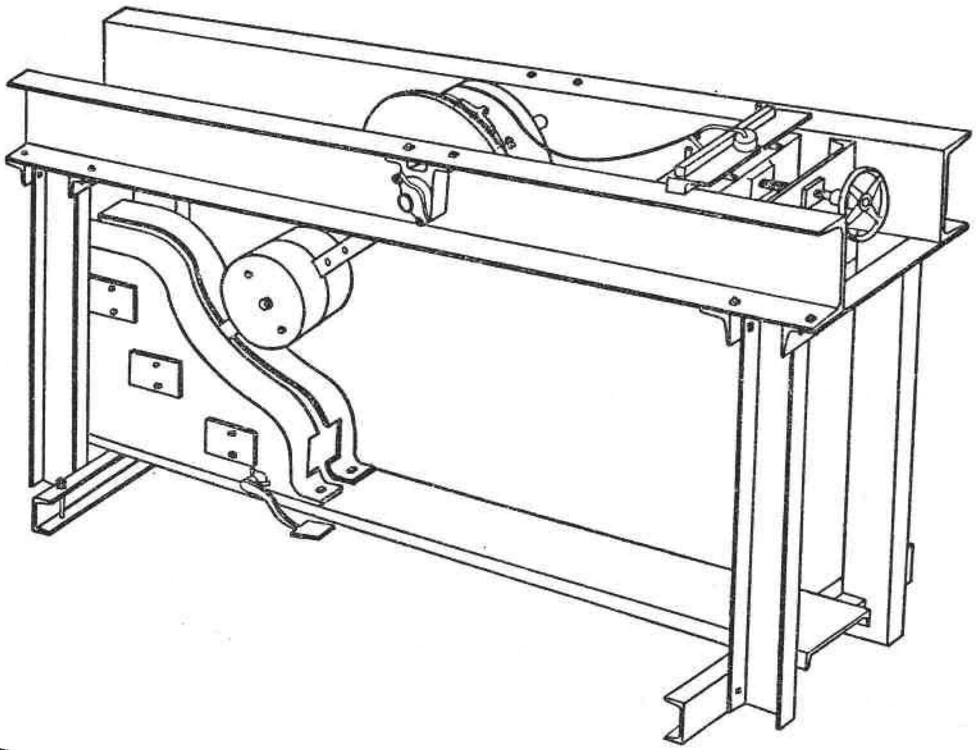

FIGURE 21.—Diagrammatic sketch of Forest Products Laboratory toughness testing machine

standard test specimen total work represents the work absorbed to a 6-inch deflection or until the beam fails to support a load of 200 pounds.

Toughness test.—The toughness test is made on small beams to determine the resistance to a rapidly applied load. The standard specimens for use in the test are ⅝ by ⅝ by 10 inches, supported over an 8-inch span. They are loaded at the center by means of a tup and a stirrup that slips over the specimen. (Fig. 21.) The Forest Products Laboratory toughness machine operates on the pendulum principle, but it differs essentially from other types in that the load is applied to the specimen by means of a cable fastened around a drum mounted on the axis of the pendulum.

Toughness.—Toughness in wood is the ability to absorb energy or work under load.

Work to elastic limit.—Work to elastic limit in bending is a measure of the work which a beam is able to resist or the shock which it can absorb up to the elastic limit.

Work to maximum load.—Work to maximum load in static bending represents the ability of the timber to absorb shock with a slight permanent or semi-permanent deformation and with some injury to the timber. Wood, especially in small sizes, can be bent somewhat beyond its elastic limit with only slight injury if the load is removed at once. Work to maximum load is a measure of the combined strength and toughness of a material under bending stresses. Superiority in this quality is the characteristic which makes hickory better than ash, and oak better than longleaf pine, for such uses as handles and vehicle parts.

Radial.—Radial means extending outward from a center or an axis. Thus a radial surface in a tree is one extending from the pith of the tree outward, such as the wide faces of a quarter-sawed board.

Rings.—Rings are those circular markings around the center of a tree section that are produced by the contrast between spring wood and summer wood. One ring, known as an annual ring, consists of a layer of spring wood and a layer of summer wood.

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