TECHNICAL BULLETIN No. 282 MARCH, 1932

STRENGTH-MOISTURE RELATIONS FOR WOOD

BY

T. R. C. WILSON

Senior Engineer, Forest Products Laboratory
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UNITED STATES DEPARTMENT OF AGRICULTURE, WASHINGTON, D. C.

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INTRODUCTION

Wood in the natural state in the living tree has associated with it considerable quantities of water, usually sufficient to make it appear wet. After being converted into lumber or other usable forms or during the conversion it is commonly dried to a state such that wetness is not evident, although appreciable quantities of water remain. During subsequent use it may be soaked or otherwise so exposed as to become obviously wet, or it may be so sheltered that no wetness becomes evident. In the latter case, however, since wood is hygro-

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

scopic, its moisture condition varies with fluctuations in the temperature and the humidity, or dampness, of the air.

When the moisture content is below a certain limit changes in its value are accompanied by changes in many of the properties and characteristics of the wood. Dimensions and numerous strength properties are also affected.

Wood fibers are increased in strength by drying, and a piece of wood in an average air-dry condition may be as much as two and one-half times as strong as a similar piece in the green condition, the ratio varying with the species, with the distribution of moisture, whether uniform or nonuniform, and with the strength property considered. It is obvious then that comparisons among results of strength tests are likely to be greatly in error unless the moisture condition of test material is known in each case and allowance made for any differences that may exist.

The purpose of this bulletin is to discuss the relations between the moisture content and the strength properties of small, clear specimens of wood, to outline the development of formulas that may be used in adjusting strength values for differences in moisture content, and to make clear the applicability and limitations of these formulas. Other phases of moisture-strength relations are also discussed.

The relation of the moisture in wood to its strength properties has been discussed in two preceding publications, neither of which is now available for distribution, namely, Forest Service Bulletin 70 (*12*)[3] and Forest Circular 108 (*13*). This bulletin reviews the principal information presented in these publications and in addition gives the results of subsequent studies and tests.

The changes in strength and other properties of wood with changes in moisture can not be thoroughly understood without some knowledge of how moisture is held in wood, how wood dries, and how it takes on moisture. Also, the method of making moisture determinations is of importance in explaining some of the phenomena.

HOW MOISTURE CONTENT OF WOOD IS DETERMINED AND EXPRESSED

The usual procedure in determining moisture content is to weigh a piece of wood in its original condition and again after heating it at the temperature of boiling water (212° F. or 100° C.) until the weight becomes practically constant. The original weight minus the final weight is taken as the moisture content. This procedure results in error in some instances because substances other than water are evaporated during the heating and some substances other than wood are not evaporated. Methods that are less subject to such errors are available, but the foregoing is the standard method used in determining the moisture content of specimens of wood that have been subjected to mechanical tests and is considered to be sufficiently accurate for the purposes discussed in this bulletin.[4]

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[3] Italic numbers in parentheses refer to Literature Cited, p. 88.

[4] Varying amounts of resin are present in the wood of numerous coniferous species. The heartwood of many species contains infiltrated substances, often strongly colored, in varying amounts. Among native species redwood, various cedars, Osage-orange, and black locust are conspicuous in this respect. The presence of such materials in abnormal amounts appreciably affects the accuracy of the computed percentage moisture content. Such of the extraneous materials as are evaporated in drying the wood are counted as moisture and tend to make the moisture content too high; such as remain after drying are counted as wood and by increasing the weight on which the percentage is based tend to make the moisture content too low. None of the material from which data are presented in this bulletin was abnormal with respect to the amount of resin or other infiltrated substances present.

The relation between the weights obtained may be expressed as follows:

$$Wo - Wf = Wa \qquad (1)$$

Where Wo = original weight, Wf = final weight, and Wa = water content or moisture content by weight.

In equation (1) Wa is the moisture content in the same units as the original and final weights. If, for example, weighings were made in pounds, the moisture content could be stated as Wa pounds. Such a statement would, however, have little significance as it would not specify the quantity of wood with which the Wa pounds of water had been associated. Because the piece of wood whose moisture content is determined is usually a sample of a larger piece whose moisture content is sought, and for convenience in expressing certain relationships, the moisture content is commonly stated as a percentage. Either the original or the final weight might be employed as the base of the percentage. Accepted practice in stating the moisture content of wood [5] is to use the final weight as the base of percentages and to express the result as follows:

Per cent moisture content

$$M = 100\frac{Wa}{Wf}, 100\frac{Wo - Wf}{Wf}, \text{or } 100\left(\frac{Wo}{Wf} - 1\right) \qquad (2)$$

the three expressions after the sign of equality being identical. This practice is followed throughout this bulletin.

The use of the final weight, that is, the weight of the wood, as the base of the percentage is preferred because it results in percentages whose relationships are very simple. For example, if 120 units by weight of wood has associated with it 60 units of water, the moisture content is 50 per cent, and removal of 30 units, or one-half, of the water reduces the moisture content to 25 per cent, or one-half its former value. The use of the original weight, that is, the weight of the wood and water together, as a base yields percentages whose relationships are much less simple.

MOISTURE CONTENT UNDER VARIOUS CONDITIONS

Water is the principal constituent of the sap of trees. The amount of water or moisture in the wood of living trees varies greatly. In the heartwood of some coniferous species, such as Douglas fir [6] and the southern yellow pines, the moisture content is normally very low (from 25 to 50 per cent) whereas in the sapwood it is much higher (from 100 to 120 per cent or more). In some hardwood species the moisture content is very low both in heartwood and in sapwood. For example, the white ashes average about 40 to 50 per cent moisture content. Some other species, including both conifers and hardwoods, have high moisture content in all parts of the tree.

When a piece of wood is subjected to prolonged soaking in water, it eventually acquires a very high moisture content, at least in the outer portions, which are most accessible to the action of the water. The

[5] In stating the moisture content of wood pulp, the practice of the chemist in defining solutions is followed, and the weight of the combination of wood pulp and water is used as the base of percentages, for example, per cent moisture content of wood pulp equals $100\frac{Wa}{Wo}$.

[6] The standard names employed by the U. S. Forest Service for lumber and for the trees from which it is cut are used throughout this bulletin (11).

moisture content in such portions is probably limited only by the space available. That absorption of water by the heartwood of many species is comparatively slow, particularly in pieces that have not been checked in drying, is evident from the observed fact that logs and piling submerged in water for several years are not filled with water throughout.

Figure 1 shows the relation between the equilibrium moisture content of Sitka spruce and the temperature and relative humidity of the air.

For example, if a piece of Sitka spruce is exposed in air maintained at a temperature of 80° F. with relative humidity of 30 per cent it will attain a moisture content of 6 per cent and will remain at this moisture content as long as this temperature and this relative humidity are maintained. Six per cent is then the equilibrium moisture content for Sitka spruce in air at 80° and 30 per cent relative humidity. Figure 1 shows that the equilibrium moisture content value increases with increase in relative humidity and with decrease in temperature of the atmosphere. Experiments have shown that at ordinary temperatures and at relative humidities between 20 and 80 per cent, the different species of wood do not differ much with respect to equilibrium moisture content values.

After a piece of green wood has been subjected to natural atmospheric conditions for some time the moisture content at the surface comes into equilibrium with the current temperature and humidity and thereafter fluctuates with changes in these factors. The equilibrium moisture content varies from as low as 5 to 8 per cent in the more arid, to as high as 18 to 20 per cent or higher in the more humid climates, and at any place varies with changes in weather conditions. The inner portion of the piece continues to dry by transfer of moisture to the surface, where it is evaporated, until finally the center attains a moisture content such that no further drying takes place. How soon such a condition is reached depends on the size of the piece as well as on climatic conditions. If the piece of wood is quite large, such as a 12 by 12 inch by 16-foot timber, several years may be required.

By means of kiln or other artificial drying the moisture content of wood may be reduced to any desired value. Subsequent to such drying the moisture content tends to come into equilibrium with the atmospheric conditions to which the wood is exposed. There is some evidence, however, that the equilibrium moisture content may be lowered slightly by drying the wood to a very low moisture content.

HOW MOISTURE IS ASSOCIATED WITH WOOD

The structure of wood, typical examples of which are illustrated by Figures 2 and 3, allows moisture to exist in two states; as "bound" or "imbibed" moisture, absorbed within the substance of the cell walls, and as "free" water, filling or partially filling the cavities within the cells. Both states obtain in wet or green wood, the free water evidently having no particular effect on the dimensions or on the strength properties but, of course, adding to the weight.

THE FIBER-SATURATION POINT

The theory of the fiber-saturation point was first evolved (*12*) in connection with wood to explain certain phenomena of moisture-

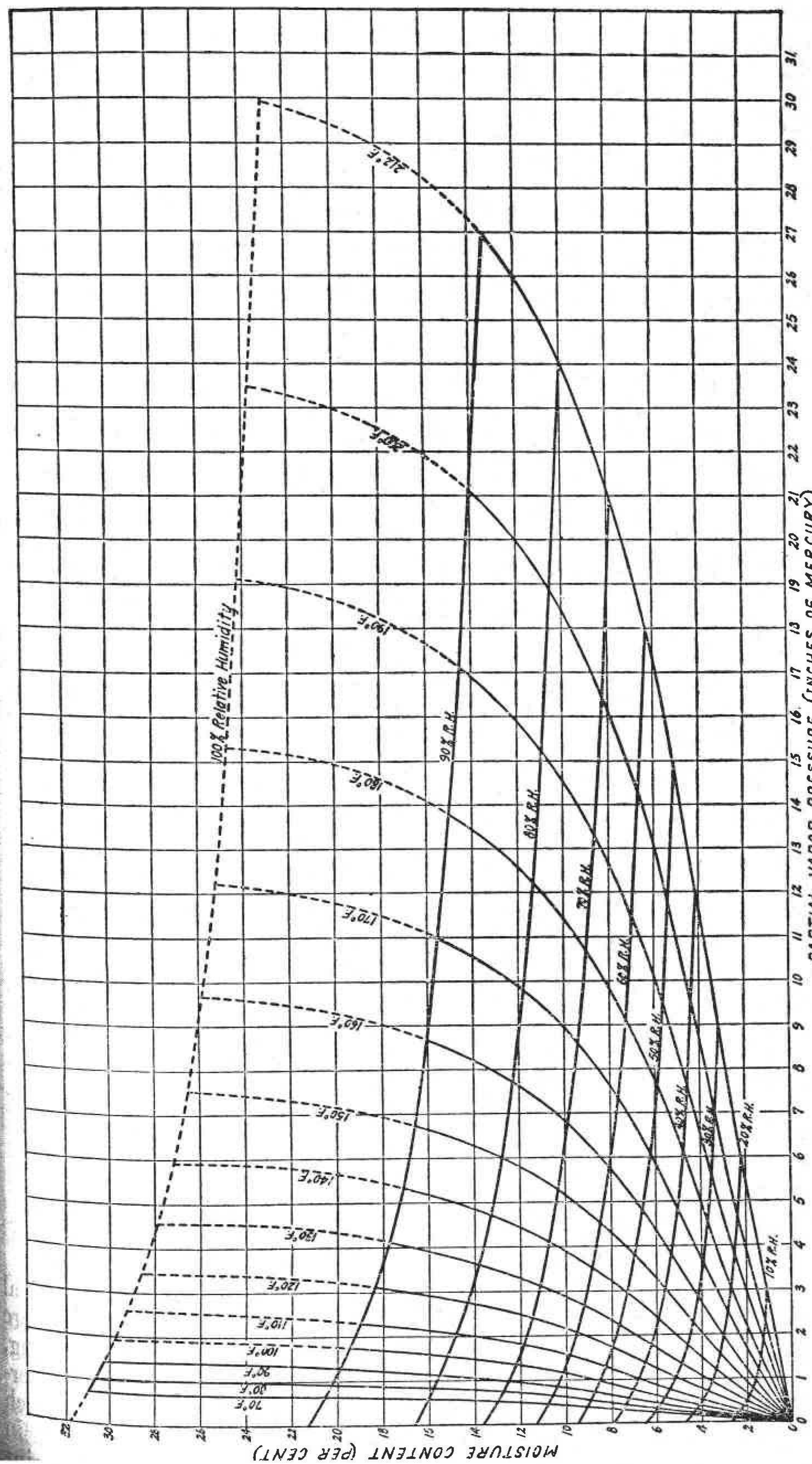

FIGURE 1.—Relation between the equilibrium moisture content of Sitka spruce and indicated values of temperature, relative humidity, and partial vapor pressure. The solid lines in the curves of this figure are based on experimental data; the dotted parts of the lines are calculated

strength and moisture-shrinkage relations. The saturation point of wood fibers may be defined theoretically as the state in which the cell walls are saturated throughout but the cavities of the fibers are entirely free from moisture. However, exactly such a state is seldom attained, except possibly by isolated fibers or by very small fragments of wood.

It is presumed that at the fiber-saturation point the shrinkage of a drying wood fiber begins, its strength properties begin to be affected,

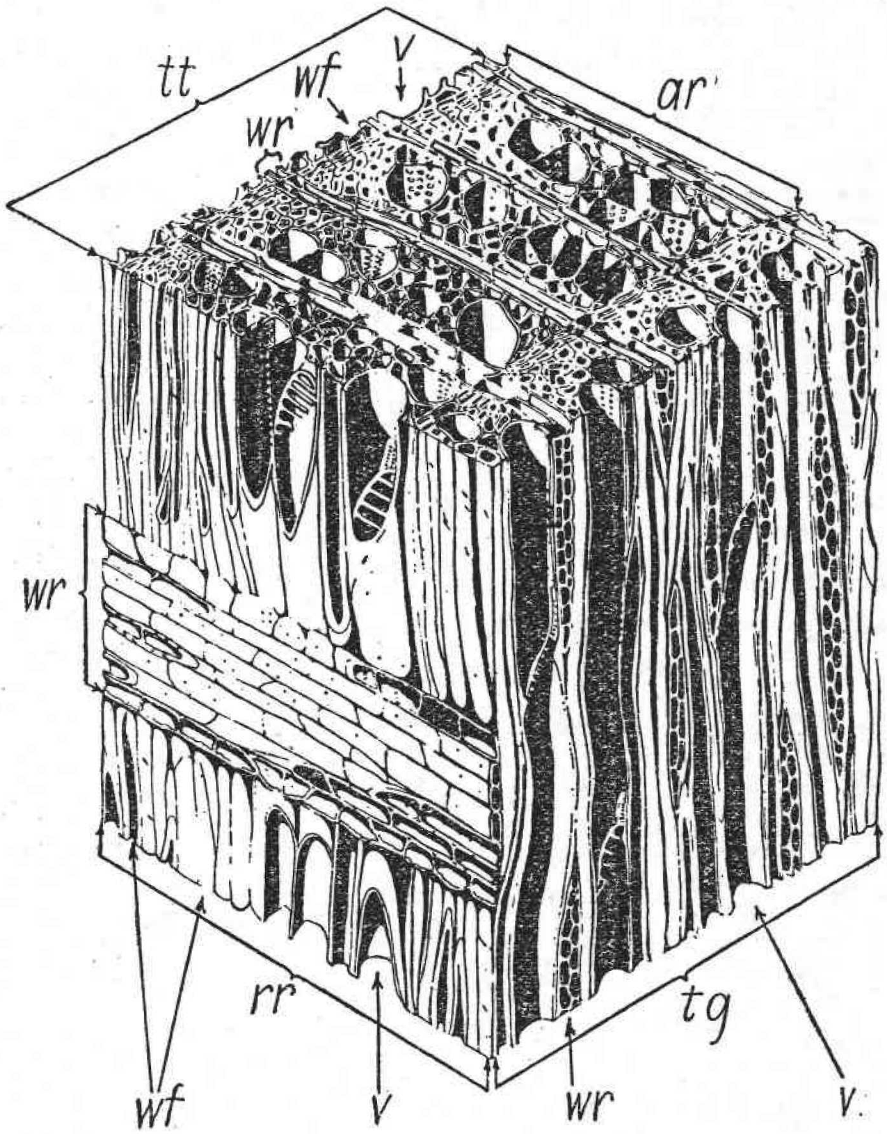

FIGURE 2.—Drawing of a highly magnified block of hardwood measuring about one-fortieth inch vertically: *tt*, Transverse surface; *rr*, radial surface; *tg*, tangential surface; *v*, vessel or pore; *wf*, woodfibers; *wr*, wood rays; *ar*, annual ring

and a change takes places in the relation between other physical properties and moisture content. Presumably also if the moisture could be kept uniformly distributed in a piece of wood during drying, the piece as a whole would exhibit similar changes when the fiber-saturation point was reached and not until then. However, such uniformity of moisture distribution is apparently unattainable in pieces of tangible size, and some parts reach the fiber-saturation point in advance of others. Consequently, changes in properties of a piece of wood occur before the average moisture content has reached the fiber-saturation point value. Because of this fact the true fiber-saturation point moisture content is not ordinarily marked by any abrupt change in graphs that represent the relation between the strength or other properties of a piece of wood and its average moisture content.

The first systematic study by the Forest Service of the relations between the moisture content of wood and its strength properties

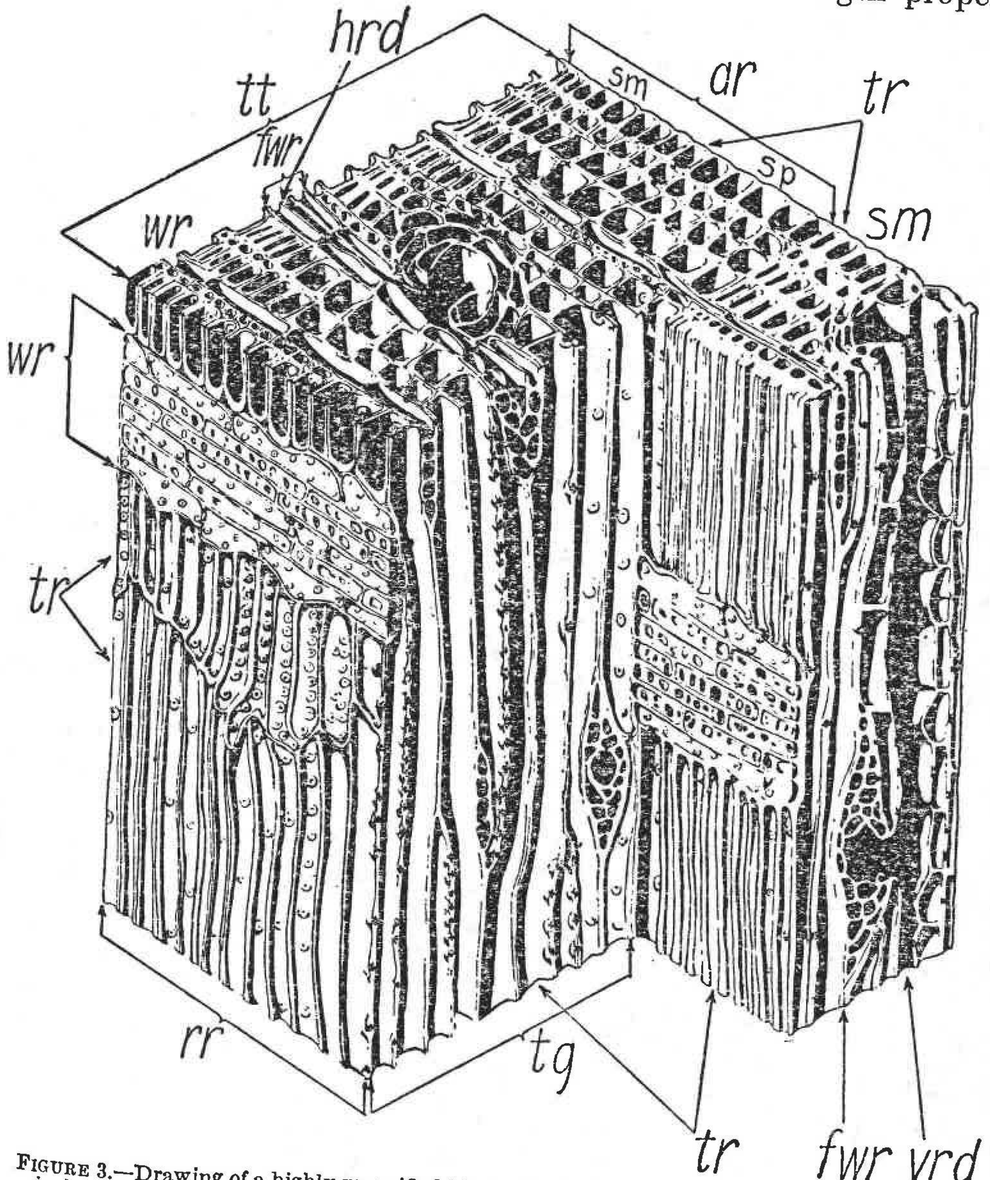

FIGURE 3.—Drawing of a highly magnified block of softwood measuring about one-fortieth inch vertically: *tt*, Transverse surface; *rr*, radial surface; *tg*, tangential surface; *ar*, annual ring; *sm*, summer wood; *sp*, spring wood; *tr*, tracheids, or fibers; *hrd*, horizontal resin duct; *fwr*, fusiform wood ray; *wr*, wood rays

consisted of a series of tests conducted by H. D. Tiemann in 1903 and 1904. European investigators had previously tested wood in various stages of seasoning and had demonstrated the fact of increase in strength with loss of moisture. However, the existence of the fiber-saturation point had not been recognized, and the fiber-saturation-point theory as applied to strength properties and shrinkage was first announced in Forest Service Bulletin 70 (*12*), which presented the results of the Forest Service tests. Some typical moisture-strength curves as originally derived from these early tests are reproduced in Figure 4.

If the moisture is quite nonuniformly distributed in a piece of wood, the outer shell may be well below the fiber-saturation point while the

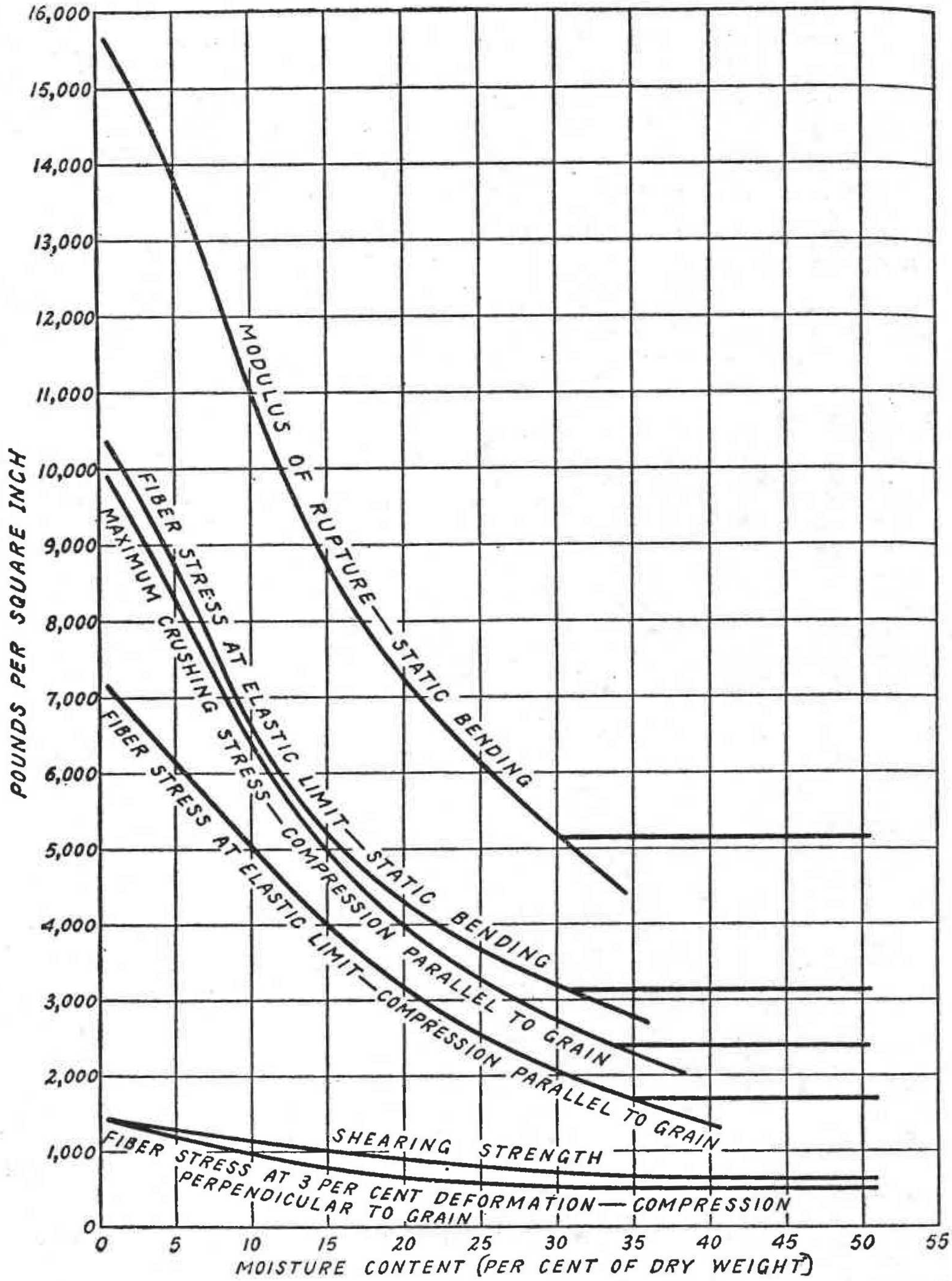

FIGURE 4.—Typical moisture-strength properties curves for red spruce as originally derived from earlier tests

inner part still contains free water. The moisture-strength curve for specimens with moisture nonuniformly distributed may consequently be higher than the correct curve and may be so rounded off from the driest toward the wettest condition as entirely to obscure the fiber-saturation point. Some earlier investigators mistook such curves, an example of which is shown dotted in Figure 5, as true moisture-strength curves. Recent tests (p. 87) have demonstrated that pieces with nonuniformly distributed moisture content do not always have strength values above the true moisture-strength curve.

MOISTURE-ADJUSTMENT FORMULAS

The early Forest Service tests (*12*, *13*) were concerned with relatively few species of wood and with only a few strength properties. They demonstrated that different strength properties, different species, and, to some extent, different pieces of the same species were affected differently by changes in the moisture content of the wood. The results of these tests were summarized in a series of tables presenting average values of reduction factors, or factors by which the strength value at one moisture content should be multiplied to get

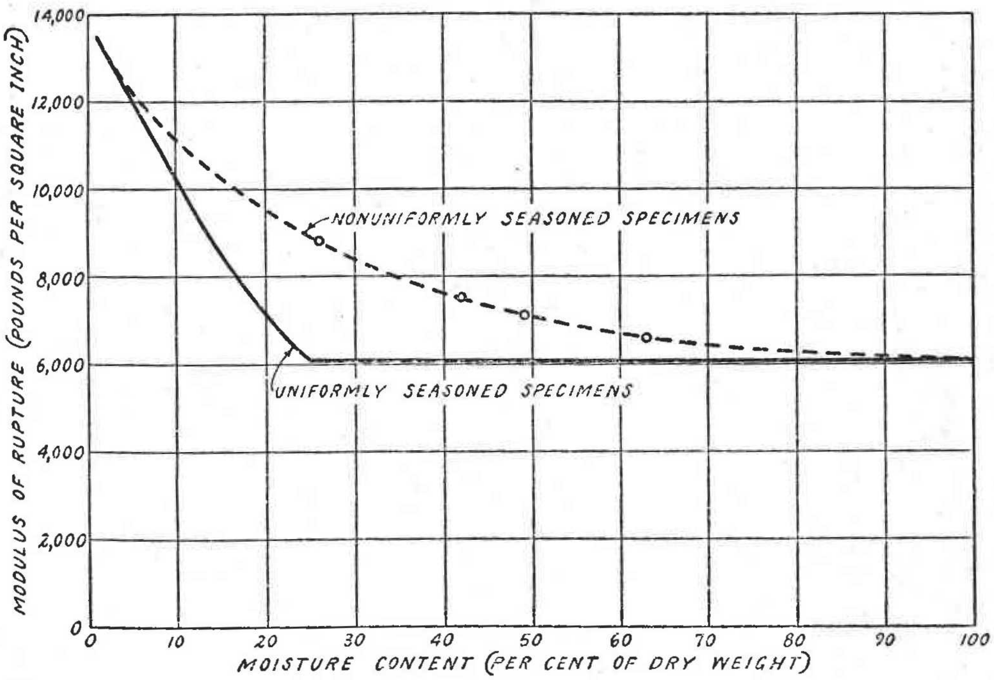

FIGURE 5.—Relation between modulus of rupture and moisture content for chestnut specimens with moisture uniformly and nonuniformly distributed

the strength value at some other moisture content. The reduction factors were taken from curves averaging the relation between moisture content and the respective strength properties as found from tests. The possibility of representing the relation between strength values and moisture content by mathematical formulas was not investigated at that time. Subsequent study of the same and other available data has led to two types of strength-moisture adjustment formulas designated as "straight-line" and "exponential."

STRAIGHT-LINE FORMULAS

The first systematic attempt at representing strength-moisture relations mathematically was the derivation of formulas of a straight-line type. From inspection of such strength-moisture curves as are shown in Figure 6, it is seen that a comparatively short portion of the curve, such as that between 8 and 12 per cent moisture, does not deviate greatly from a straight-line. In devising a straight-line formula for adjusting to 12 per cent moisture, it was assumed that short portions of a moisture-strength curve to the left and right of 12 per cent moisture could be represented by straight lines whose

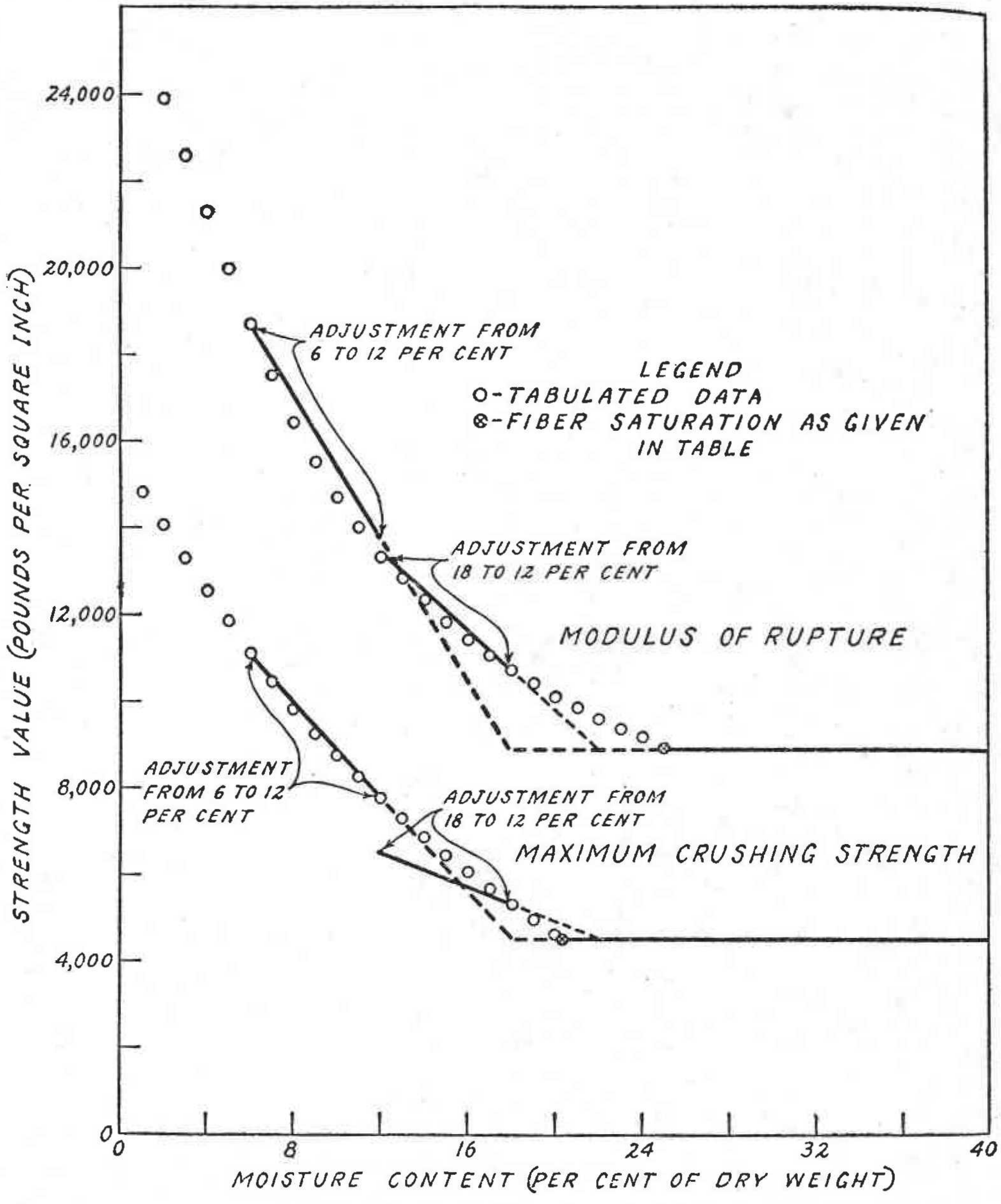

FIGURE 6.—Relation of modulus of rupture and maximum crushing strength of longleaf pine to moisture content and illustration of straight-line formulas. The plotted points are from the curves originally drawn to represent the average strength-moisture relations. Data are from Tables 18 and 19 of Forest Service Bulletin 70 (*12*)

intersections with the horizontal line representing the strength of green wood are at 18 and 22 per cent moisture, respectively. This assumption leads to the following formulas, typical graphs of which are represented by the inclined lines shown in Figure 6:

$$S_{12}=\frac{6(S-G)}{18-M}+G \qquad (3)$$

$$S_{12}=\frac{10(S-G)}{22-M}+G \qquad (4)$$

Where S = strength value as obtained from tests at moisture content of M per cent, G = strength value as obtained from tests of matched material in the green condition, and S_{12} = strength value adjusted to 12 per cent moisture content. Formulas (3) and (4) are for use with values of M below and above 12 per cent, respectively.

Similar straight-line formulas for adjusting strength values to 15 per cent moisture were also devised.

EXPONENTIAL FORMULA

It is obvious from Figure 6 that formulas of the straight-line type can be only roughly approximate and that if their applications are not limited to very small moisture differences comparatively large errors in adjusted values are probable. Need for more accurate adjustments arising in connection with a series of tests made some years ago led to a careful analysis of the data available at that time. These data referred to only a few species of wood and a few strength properties. The principal object of the analysis was to find a type of strength-moisture equation that might be assumed to apply to all species and to all strength properties. In all the sets of strength-moisture data reviewed, it was found that within certain limits the relation between the logarithm of the strength value and the moisture content could be quite accurately represented by a straight line. In Figure 7, the curves [7] from Figure 6 and two additional ones are reproduced with the strength values plotted to a logarithmic scale on the vertical axis and the percentage of moisture content plotted to a uniform, or arithmetic, scale on the horizontal axis.

The general equation of a straight line in such a plot is

$$\text{Log } S=\log S_o-KM, \qquad (5)$$

which is equivalent to

$$S=S_o\cdot 10^{-KM}. \qquad (6)$$

Where S and M are corresponding strength and moisture-content values within the limits of applicability of the equation, S_o is the strength value that will obtain at zero moisture if the equation is valid to that point, and K is an experimentally determined constant, or parameter.

The agreement between the exponential formula and the experimental data is found to be quite good in a large number of instances, and this fact suggests that this type of relation may be a close approximation to the fundamental law of the effect of moisture on strength properties and that the deviations of experimentally obtained values from this law may be largely due to experimental errors. Among the causes of deviation are nonuniform distribution of moisture in test specimens, the disturbing influence of varying amounts of resin or other infiltrated substances in certain species, and particularly the variability of wood and the consequent impossibility of obtaining for

[7] The plotted points in Figures 6 and 7 do not represent actual test results but the curves originally derived from experimental data. As will be shown later, reconsideration of the same data has resulted in different curves to represent the strength-moisture relation.

test at several different moisture-content values specimens that are exactly alike in all particulars except moisture content.

Since moisture content appears in formula (6) as an exponent, the equation is referred to as the exponential strength-moisture formula. Formula (6) is presumed to apply for values of M within part of the range between zero and the intersection of the inclined and horizontal lines in such a diagram as Figure 7. Since as is shown later this intersection does not coincide with the fiber-saturation point as previously

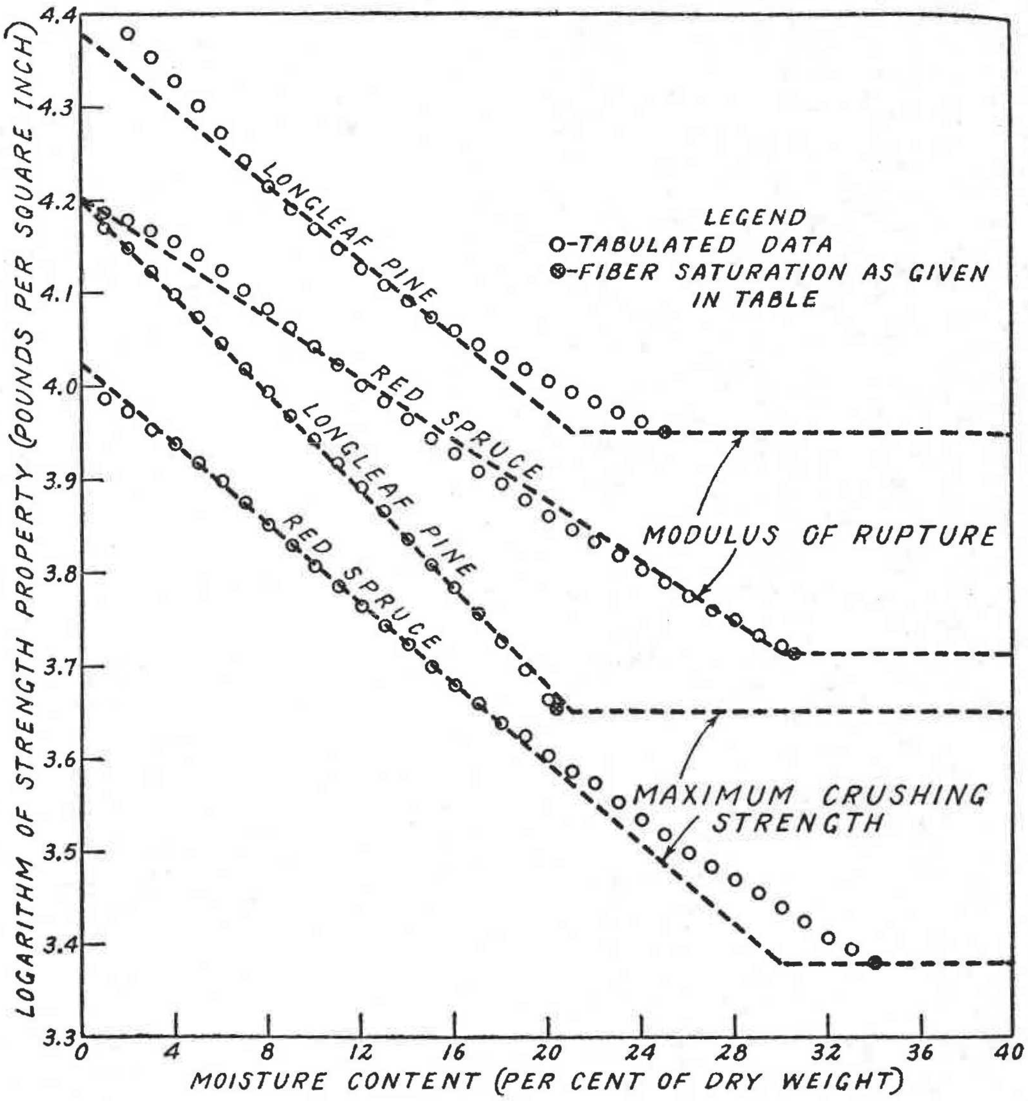

FIGURE 7.—Typical strength-moisture curves plotted semilogarithmically. Data are from Tables 18 and 19 of Forest Service Bulletin 70 (12). The plotted points are from the curves originally drawn to represent the average strength-moisture relations. The data for longleaf pine are the same as those shown plotted to an arithmetic scale in Figure 6

defined, a separate name for it is desirable, and it will be called the "intersection point." M_p will then designate the moisture content at the intersection point and S_p the strength value at that point, that is, the strength value for green wood. Then, since S_p and M_p define a point on the inclined line which is represented by equations (5) and (6),

$$S_p = S_o \cdot 10^{-KM_p}, \tag{7}$$

and dividing (6) by (7),

$$\frac{S}{S_p}=10^{K(M_p-M)} \tag{8}$$

or

$$\text{Log } S=\log S_p+K(M_p-M) \tag{9}$$

The form of equations (5) and (9) shows that if the logarithms of experimentally determined values of S, or of the ratio $\frac{S}{S_p}$, are plotted over the corresponding values of M, the conformity of the resulting points to a straight line will measure the agreement of the experimental data with the exponential formula. Also, if a horizontal line representing the strength of green material and an inclined line averaging the points representing material at lower moisture-content values be drawn the intersection of these lines will determine M_p, and the slope of the inclined line will represent K. The value of K is numerically equal to the slope but of opposite algebraic sign. Thus K is positive and the slope negative for properties that increase with decrease of moisture content.

DATA FROM TESTS OF WOOD AT VARIOUS MOISTURE-CONTENT VALUES

The several series of tests that afford data for study of strength-moisture relations are divided for description and discussion into two groups: (1) The early Forest Service tests previously mentioned (*12*, *13*); (2) tests made more recently at the Forest Products Laboratory on Sitka spruce, Douglas fir, white ash, and yellow birch. The tests of Group 2 were made with the specific object of studying the exponential type of equation as a means of representing strength-moisture relations. Species and properties not previously studied were included.

The data from tests of both groups are presented in diagrams in each of which the strength values to a logarithmic scale are plotted above the corresponding moisture-content values to an arithmetic scale; the strength value for green or soaked control specimens is represented by a horizontal line. In plotting, a different zero of the logarithmic scale is used for each series of points.

GROUP 1. EARLY FOREST SERVICE TESTS

The following quotations from Forest Service Circular 108 (*13*, *p. 6–7*, *10–11*) give pertinent information concerning Group 1 tests:

The selection of test specimens and their proper treatment to secure the desired conditions constituted the chief part of the problem, and required much more time and attention than the tests themselves.

The specimens were carefully cut and placed in series, so that each series consisted of a number of specimens, cut either from the same strip of wood or from adjacent strips in the log or plank, having practically the same straight grain, and free from defects. Each specimen in a series was brought to a different moisture degree in such a manner that the moisture was uniformly distributed. From 7 to 16 of such series of specimens were made for each species of wood and each kind of test.

Tests were made in bending, compression parallel to grain, shearing parallel to grain, and compression at right angles to grain. The sizes of the specimens used were 2 by 2 by 40 inches for bending with a span of 36 inches; 2 by 2 by 5¾ and 2 by 2 by 12 inches for compression parallel to grain and at right angles to grain, respectively; and 2 by 2 by 3 inches for shearing tests in the case of longleaf pine, red spruce, and chestnut. Smaller sizes were used in the subsequent tests upon loblolly pine, red gum, Douglas fir, Norway pine, and tamarack.

The results of the tests were plotted on cross-section paper, and graphically averaged by drawing a separate curve for each series. These series curves were then averaged for the average curve of the species.

The compression tests parallel to grain gave the most uniform and reliable results, and therefore formed the chief subject of the study. Bending tests were made upon the first three species, and also enough upon the next three to establish the fact that the law derived from compression tests applies also to beams. * * *

The moisture was determined by cutting a cross-sectional disk at the point of failure an inch or less in thickness (length) and drying this to constant weight at the boiling point of water. The weight of moisture lost in drying is expressed as a per cent of this dry weight and represents the "moisture per cent" at which the test was made. Other disks were also taken to determine the distribution of moisture. Experiments were made to determine the amount of moisture still remaining in the disk after drying in the manner just described by further drying in vacuum, the average result of which showed that about 0.7 per cent of moisture remained when the disks were dried by the ordinary method. The amount of volatile oils and other matter which escaped in drying the disks was found to be negligible.

* * * * * * *

The best way to determine the fiber-saturation point is by actual tests of the strength of very small specimens. Compression tests similar to the moisture-strength tests were made for this purpose upon series of very small specimens—from 1 to 1½ inches long and from half an inch to 1 square inch in cross section. It is better to use such small pieces for these tests because they may be brought more accurately to the desired moisture condition, and with more uniform distribution of moisture, and also because greater uniformity may thus be obtained in the structure of the specimens of each series.

As shown by the preceding quotations, Group 1 included special tests of small specimens for the determination of the fiber-saturation point and tests of larger specimens for finding the average effect of moisture on strength. Fiber-saturation points also were determined from the latter tests.

Data from tests of 2 by 2 inch specimens are shown in Figures 8 to 11 and Tables 1 to 4 and those from the special compression tests on smaller specimens in Figures 12 and 13 and Tables 5 and 6.

TABLE 1.—*Data pertaining to Figure 8*

Kind of test	Number of specimens tested at each moisture content	Property	Average value [1] for control specimens	Value of *K*
Static bending	5	Modulus of elasticity	1, 896, 000	0. 0062
		Modulus of rupture	8, 890	. 0210
		Fiber stress at elastic limit	4, 920	. 0245
		Work to elastic limit	0. 73	. 0396
Compression parallel to grain	6	Modulus of elasticity	1, 227, 000	. 0109
		Fiber stress at elastic limit	3, 515	. 0228
		Maximum crushing strength	4, 605	. 0257
		Work to elastic limit	5. 16	. 0348
Shear	7	Average of radial and tangential shearing stress.	915	. 0157

[1] Units of inch-pounds per cubic inch for work to elastic limit; pounds per square inch for others.

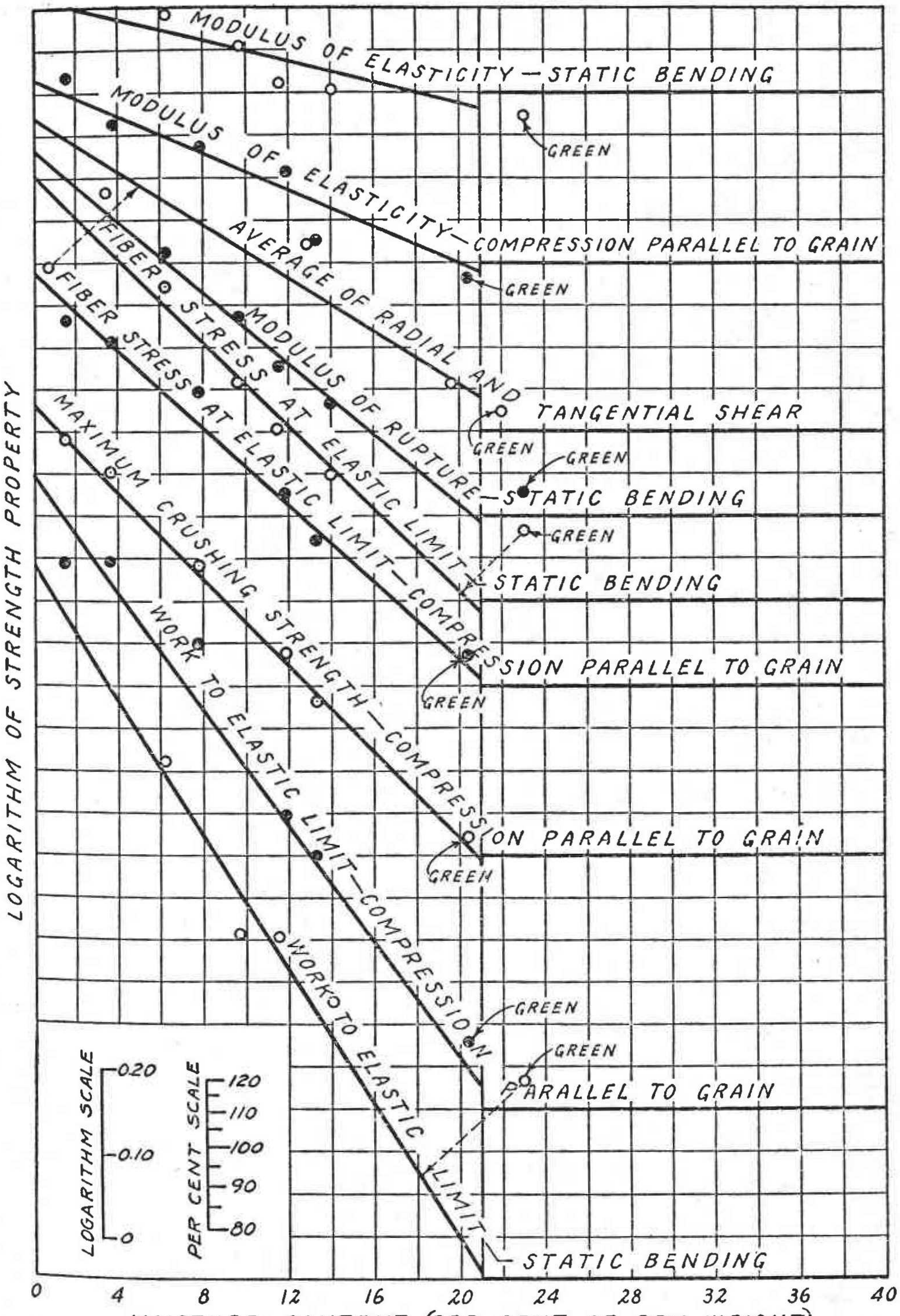

FIGURE 8.—Strength-moisture relations for longleaf pine, specimens 2 by 2 inches. Data are from Tables 1, 5, and 10 of Forest Service Bulletin 70 (12). Control specimens, which are represented by horizontal lines, were soaked to insure a moisture content above the fiber-saturation point. Points labeled "green" represent specimens tested as soon as received. For detailed data see Table 1

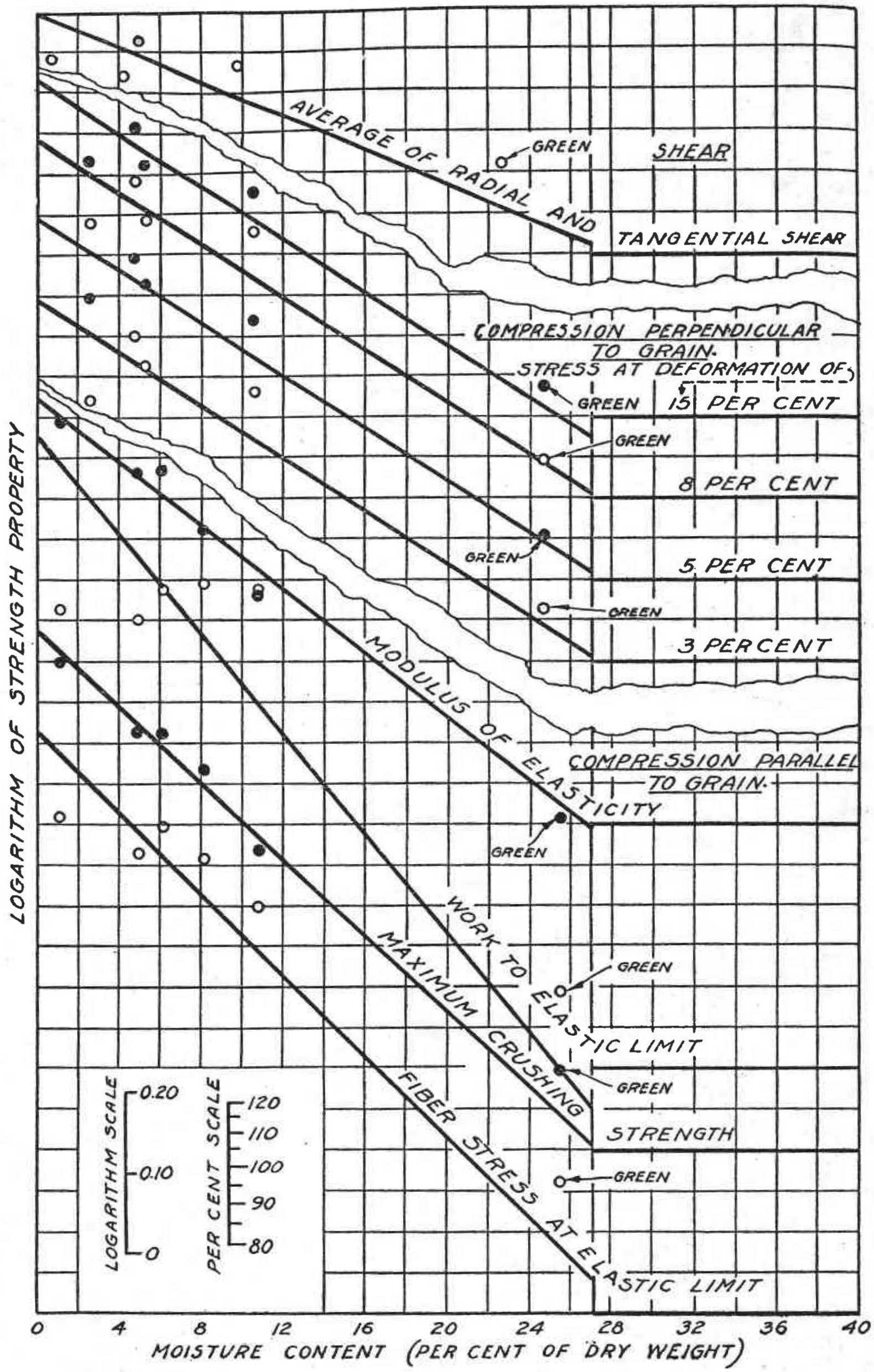

FIGURE 9.—Strength-moisture relations for red spruce, specimens 2 by 2 inches. Data are from Tables 3, 8, and 12 of Forest Service Bulletin 70 (12). Control specimens, which are represented by horizontal lines, were soaked to insure a moisture content above the fiber-saturation point. Points labeled "green" represent specimens kept in damp box outdoors from October to February. For detailed data see Table 2

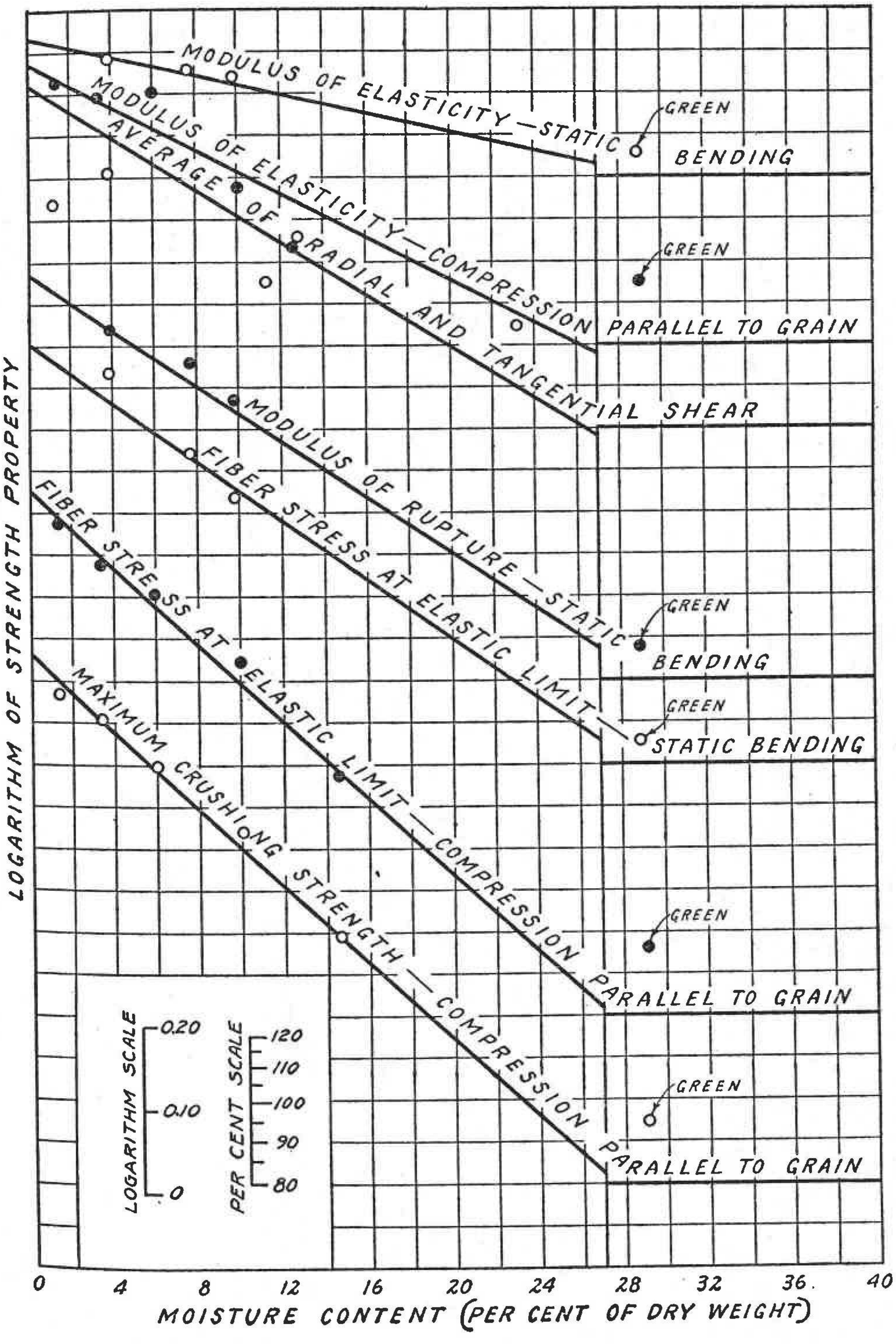

FIGURE 10.—Strength-moisture relations for red spruce, specimens 2 by 2 inches. Data are from Tables 2, 6, and 9 of Forest Service Bulletin 70 (12). Control specimens, which are represented by horizontal lines, were soaked to insure a moisture content above the fiber-saturation point. Points labeled "green" represent specimens stored in damp box from 2 to 14 days before testing. For detailed data see Table 3

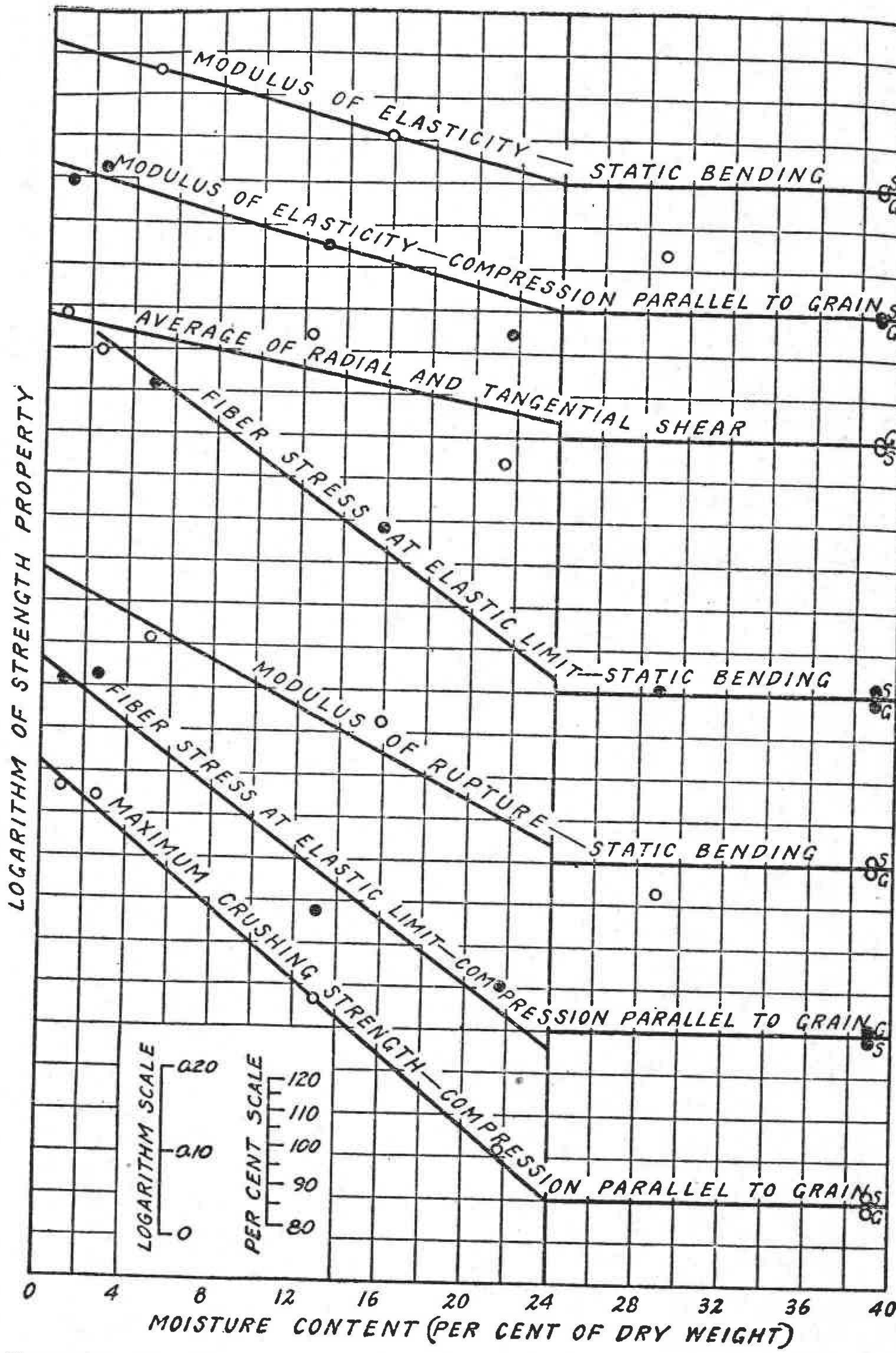

FIGURE 11.—Strength-moisture relations for chestnut, specimens 2 by 2 inches. Data are from Tables 4, 7, and 11 of Forest Service Bulletin 70 (12). Points marked *S* and *G* represent soaked and green specimens, respectively. Moisture content values were as follows: Soaked minimum 113, average 135 per cent; green minimum 100, average 123 per cent. Control values, which are represented by horizontal lines, are the average between soaked and green specimens. For detailed data see Table 4

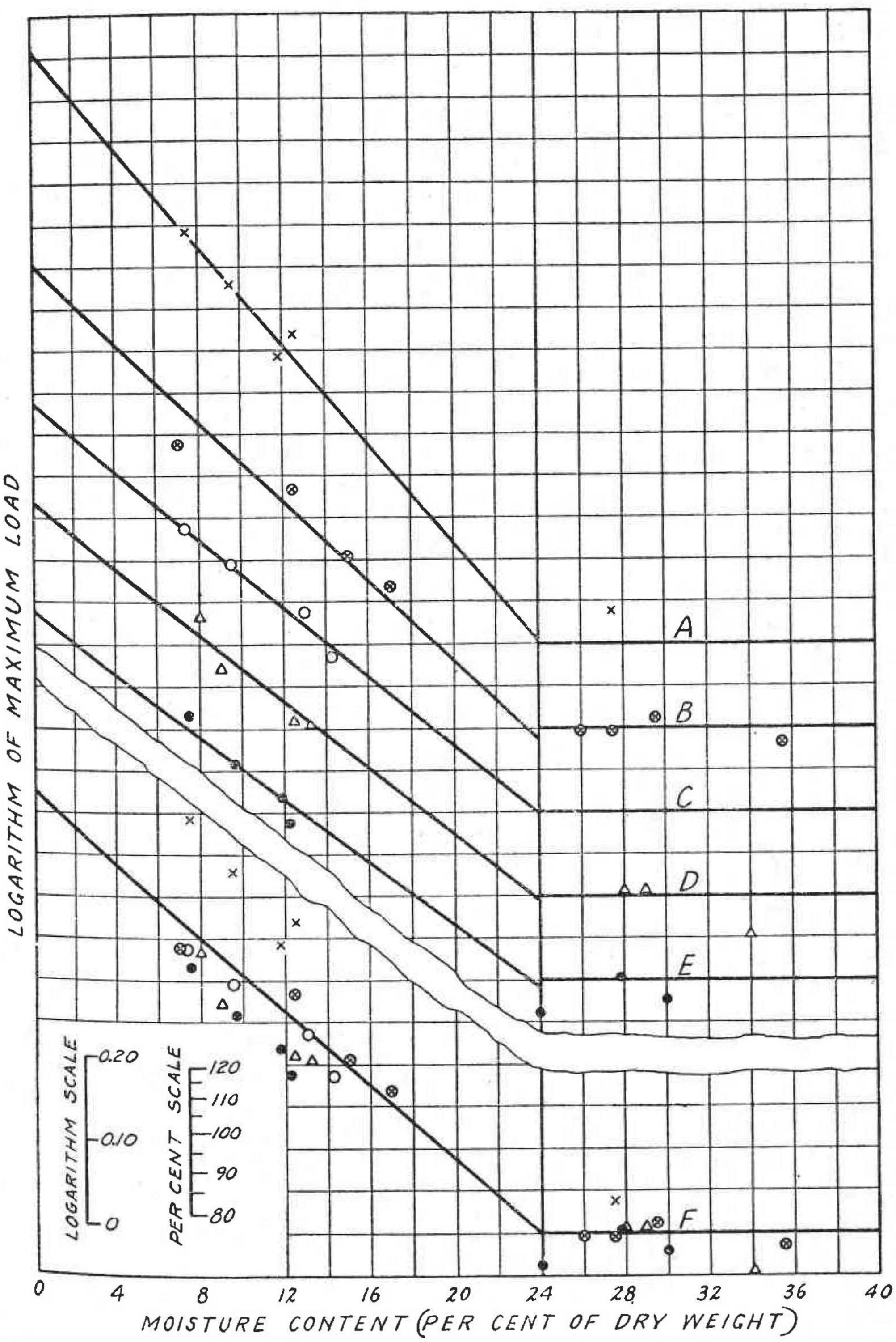

FIGURE 12.—Relation of the maximum load in compression parallel to grain to moisture content for chestnut, specimens 1$\frac{3}{16}$ by 1$\frac{3}{16}$ by 1½ inches. Data are from Figure 18 of Forest Service Bulletin 70 (*12*). Each plotted point represents a single test. Symbols of the same kind represent a series of specimens matched end-to-end. At *F* all individual values are replotted with reference to the same zero. For detailed data see Table 5

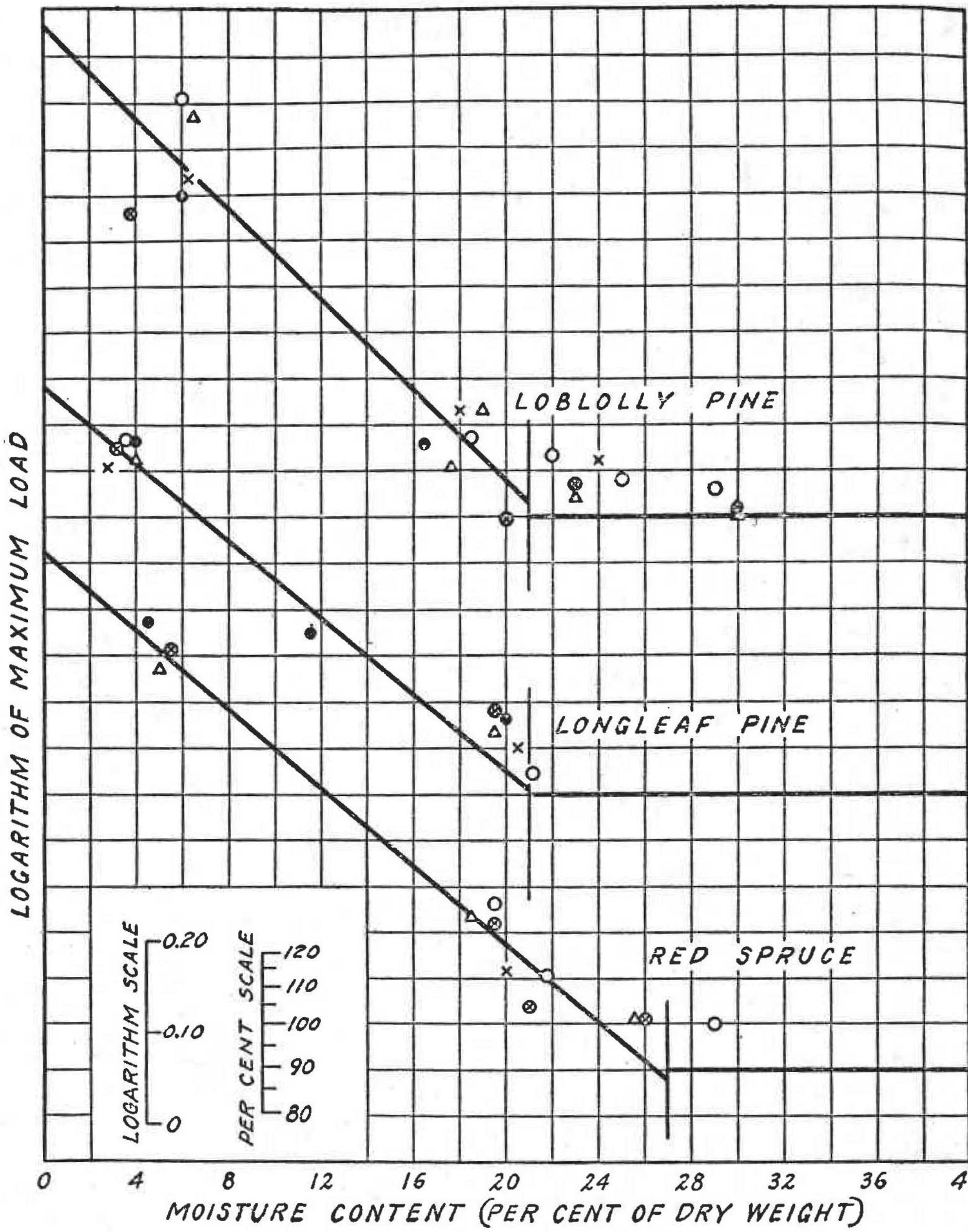

FIGURE 13.—Relation of maximum load in compression parallel to grain to moisture content for small specimens of loblolly pine, longleaf pine, and red spruce. Data are from Figure 18 of Forest Service Bulletin 70 (12). Each point represents a single specimen. Symbols of the same kind represent a series of specimens matched end-to-end. For detailed data see Table 6

TABLE 2.—*Data pertaining to Figure 9*

Kind of test	Number of specimens tested at each moisture content	Property	Average value [1] for control specimens	Value of K
Shear	8	Average of radial and tangential shearing stress.	677	0.0105
Compression perpendicular [2] to grain.	5	Stress at deformation of:		
		15 per cent	688	.0163
		8 per cent	587	.0163
		5 per cent	531	.0163
		3 per cent	481	.0163
Compression parallel to grain	5	Modulus of elasticity	476,000	.0193
		Work to elastic limit	4.30	.0306
		Maximum crushing strength	2,620	.0234
		Fiber stress at elastic limit	1,670	.0250

[1] Units of inch-pounds per cubic inch for work to elastic limit; pounds per square inch for others.
[2] Specimens 12 inches long loaded over the center 4 inches of the length.

TABLE 3.—*Data pertaining to Figure 10*

Kind of test	Number of specimens tested at each moisture content	Property	Average value for control specimens	Value of K
			Pounds per square inch	
Static bending	12	Modulus of elasticity	1,262,000	0.0056
		Modulus of rupture	5,165	.0166
		Fiber stress at elastic limit	3,160	.0176
Compression parallel to grain	11	Modulus of elasticity	651,000	.0129
		Fiber stress at elastic limit	1,765	.0227
		Maximum crushing strength	2,410	.0229
Shear	8	Average of radial and tangential shearing stress.	608	.0155

TABLE 4.—*Data pertaining to Figure 11*

Kind of test	Number of specimens tested at each moisture content	Property	Average value for control specimens	Value of K
			Pounds per square inch	
Static bending	10	Modulus of elasticity	1,068,000	0.0068
		Fiber stress at elastic limit	3,570	.0187
		Modulus of rupture	6,270	.0132
Compression parallel to grain	10	Modulus of elasticity	790,000	.0069
		Fiber stress at elastic limit	2,475	.0179
		Maximum crushing strength	3,070	.0214
Shear	10	Average of radial and tangential shearing stress.	733	.0052

TABLE 5.—*Data pertaining to Figure 12*

Reference letter	Maximum load for green specimen	Value of K	Reference letter	Maximum load for green specimen	Value of K
	Pounds			*Pounds*	
A	1,600	0.0294	D	2,070	.0197
B	1,560	.0236	E	2,960	.0185
C	2,650	.0203	F		.0218

TABLE 6.—*Data pertaining to Figure 13*

Species	Size of specimens	Average maximum load for green specimens	Value of K
		Pounds	
Loblolly pine	1 by 1 by 1½ inches	2,010	0.0247
Longleaf pine	¾ by ¾ by 1½ inches	3,220	.0207
Red spruce	do	1,450	.0217

Points labeled "green" in these figures represent specimens tested at approximately the moisture content they had when first prepared. In numerous instances there was doubt as to whether the moisture content was above the fiber-saturation point in all parts of such specimens, and additional specimens were soaked to insure moisture-content values above this point.

The significance of various features of these graphs and tables is more fully described in connection with the later discussion of the data. (P. 41.)

GROUP 2. TESTS MADE AT THE FOREST PRODUCTS LABORATORY

MATERIAL

All specimens for Group 2 tests were obtained from logs cut for the purpose. Information concerning these logs follows.

Sitka spruce from near Gray's Harbor, Wash.—Two 6-foot logs from each of four trees and three 6-foot logs from a fifth tree were selected. The logs were taken from various positions in the tree, the height varying from 18 to 80 feet. Top diameters were from 22 to 41 inches. The number of annual rings showing on the end of a log was from 245 to 340.

Douglas fir from near Gray's Harbor, Wash.—Two 6-foot logs from each of five trees were selected. One log from each was taken about 30 feet and the other about 75 feet above the stump. Top diameters varied from 29 to 47 inches. The number of annual rings showing on the end of a log was from 475 to 700.

Yellow birch from near Neopit, Wis.—One 12-foot and eight 16-foot logs were cut from seven different trees. Two were butt and the others second logs. Top diameters varied from 15 to 24 inches. The ages of the trees ranged from about 200 to about 260 years.

White ash from near Richland Center, Wis.—One 20-foot, one 12-foot, and two 8-foot butt logs and one 4-foot bolt, the butt of which was 4 feet above the stump, were selected. Trees from which the logs were cut were 125 to 145 years old and from 18 to 24 inches in diameter breast high.

MATCHING OF TEST SPECIMENS

In tests to determine the effect of any one variable, such as moisture, it is obviously desirable that the specimens of a series be carefully matched; that is, that they differ as little as possible with respect to variables other than the single one whose effect is to be determined. In the tests of Group 1 this result was sought through individual matching of specimens, and each series consisted of specimens obtained as nearly as possible from contiguous positions within the same group of annual growth layers.

In preparing the material for the Group 2 tests, each white ash and yellow birch log was cut into 4-foot bolts. These bolts and the 6-foot logs of Douglas fir and Sitka spruce were then sawed into sticks of the proper size from which to prepare test specimens.

Sticks from each bolt or log were assigned to each of eight sets. One of these sets was used for tests in the green condition, and the others were used for tests after drying to approximately 25, 20, 15, 12, 10, 8, 5, and 3 per cent moisture content.

The method of cutting and distributing specimens was such as to make the average quality of the material in the several moisture-content sets approximately the same and hence afforded excellent group matching among the several sets as a whole and reasonably good matching among the subsets derived from any one tree. In other words, a fairly large number of specimens rather than individual matching (as in the Group 1 tests) was depended upon to provide data in which the influence of factors other than the differences in moisture content would be averaged out.

Material from several trees of each species and from different heights in the trees was provided in order to cover some of the variations in the strength properties of wood and some of the expected variations in strength-moisture relations. However, all trees of a species were from the same source.

DRYING AND TESTING

In the Group 2 tests all specimens of a species, except those for test in the green condition, were dried together in a kiln at temperatures that previous experience had indicated would have no injurious effect on the strength properties. The entire charge was first dried to approximately 25 per cent moisture content and so conditioned that in so far as possible the moisture was uniformly distributed in each piece and the stock free from drying or shrinkage stresses. Kiln conditions were then regulated to prevent further change of moisture content and the specimens of one set withdrawn a few at a time, machined to the desired standard size and form, and returned to the kiln where they remained until needed for test when they were again removed from the kiln a few at a time, placed in air-tight containers and cooled to normal temperature, and the tests made. When the testing of one set of specimens had been completed the remainder of the charge was similarly dried and conditioned to the next lower moisture content, when another set of specimens was withdrawn and tested. This was repeated until the last set had been tested. Check determinations showed that no significant change in moisture content or its distribution occurred during the short period required for the final removal from the kiln and the testing.

All specimens were 2 by 2 inches in cross section and tests were made in accordance with standard Forest Service methods (*2*).

Data from the Group 2 tests are shown in Figures 14 to 25 and Tables 7 to 16. These figures and tables are more fully described in the discussion of the data. (P. 38.)

TABLE 7.—*Data pertaining to Figure 14*

Kind of test	Property	Average value [1] for green specimens	K
Impact bending	Maximum drop	24	0.0027
	Fiber stress at elastic limit	7,870	.0090
	Modulus of elasticity	1,365,000	.0079
	Work to elastic limit	2.61	.0101
Static bending	Modulus of elasticity	1,371,000	.0060
	Work to maximum load	5.93	.0099
	Modulus of rupture	6,200	.0147
	Fiber stress at elastic limit	3,755	.0161
	Work to elastic limit	0.61	.0260
Shear	Average of radial and tangential shearing stress.	730	.0072
Compression parallel to grain	Maximum crushing strength	3,070	.0200
Compression perpendicular to grain	Fiber stress at elastic limit	335	.0187

[1] Inches for maximum drop; inch-pounds per cubic inch for work values; pounds per square inch for others.

TABLE 8.—*Detailed data pertaining to Figure 15*

Tree	Reference letter	Specific gravity [1]	Average value	K
			Lbs. per sq. in.	
No. 6	A	0.476	3,735	0.0184
No. 1	B	.439	2,835	.0213
No. 3	C	.461	3,230	.0199
No. 4	D	.405	2,845	.0196
No. 5	E	.416	2,870	.0212
Average	F	.439	3,070	.0200

[1] Average value for all specimens tested. Based on weight and volume when oven dry. The average specific gravity based on weight when oven dry and volume when green was 0.375 for all specimens tested in the green condition.

TABLE 9.—*Data pertaining to Figure 17*

Group	Average values for green specimens		K
	Specific gravity [1]	Maximum crushing strength	
		Lbs. per sq. in.	
A	0.414	3,540	0.0199
B	.385	3,160	.0206
C	.359	2,850	.0200
D	.335	2,710	.0186

[1] Based on volume when green and weight when oven dry.

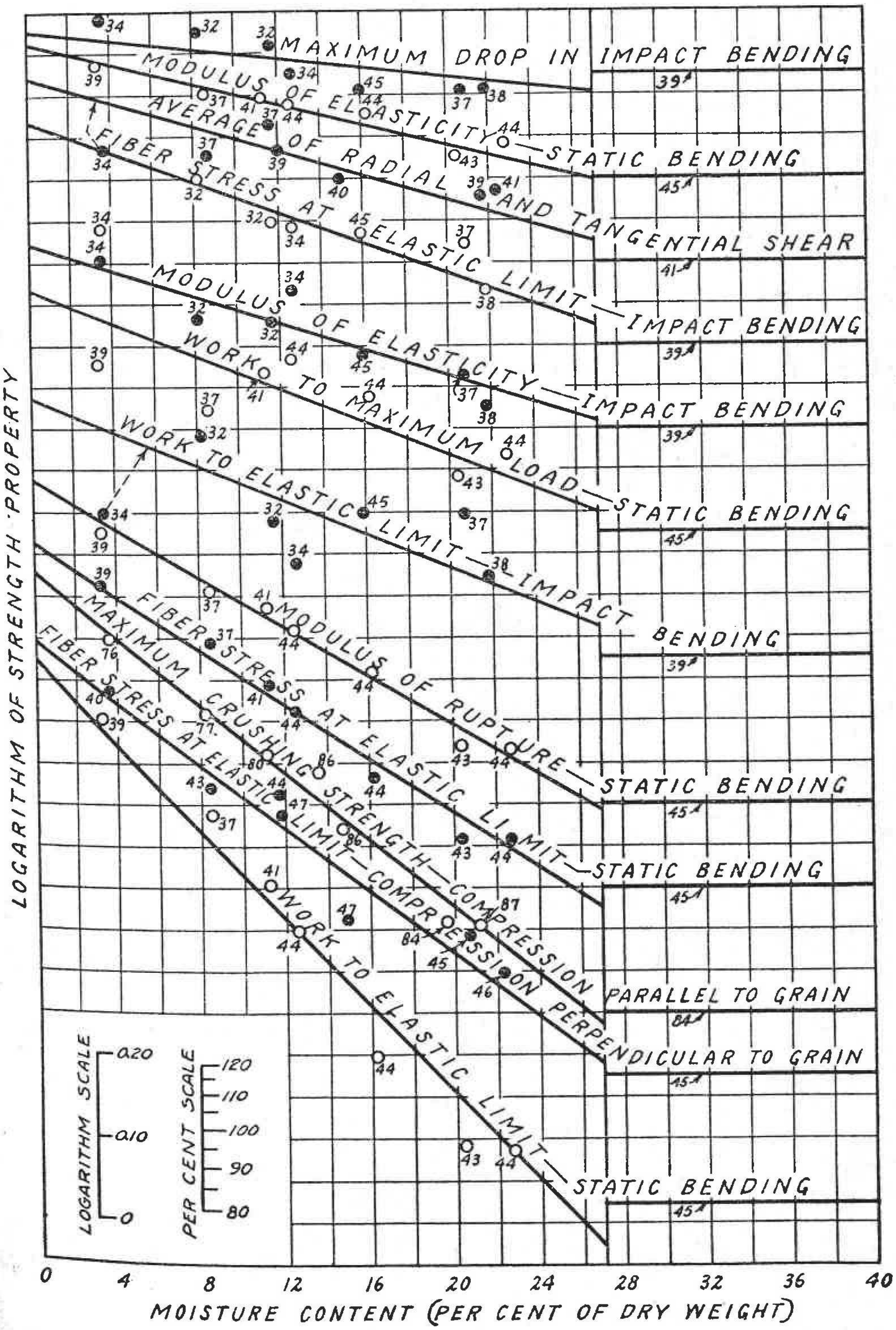

FIGURE 14.—Sitka spruce: Relation of average values of various strength properties to moisture content. Numerals at plotted points and on horizontal lines are numbers of tests averaged. For detailed data see Table 7

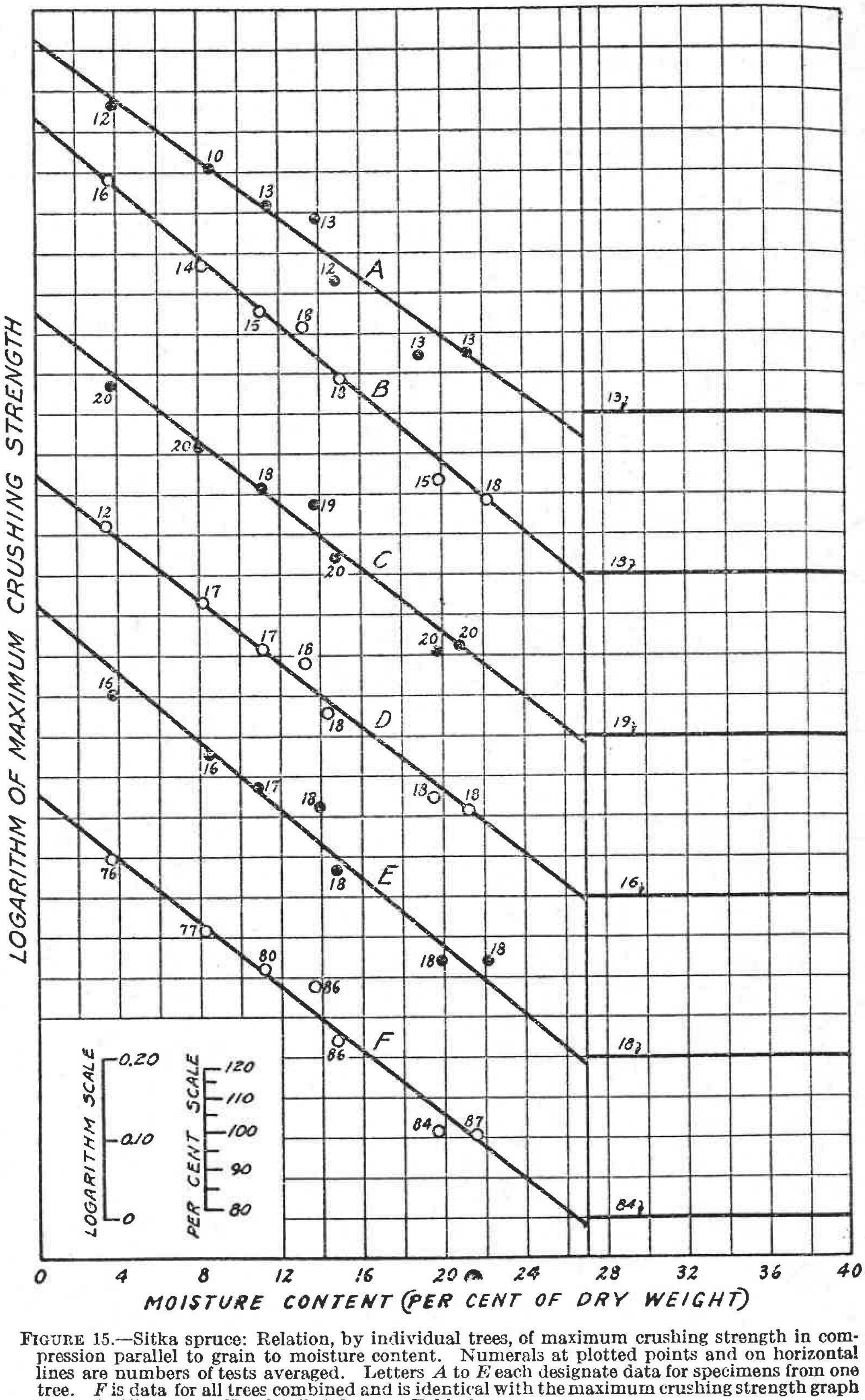

FIGURE 15.—Sitka spruce: Relation, by individual trees, of maximum crushing strength in compression parallel to grain to moisture content. Numerals at plotted points and on horizontal lines are numbers of tests averaged. Letters *A* to *E* each designate data for specimens from one tree. *F* is data for all trees combined and is identical with the maximum crushing strength graph shown in Figure 14. For detailed data see Table 8

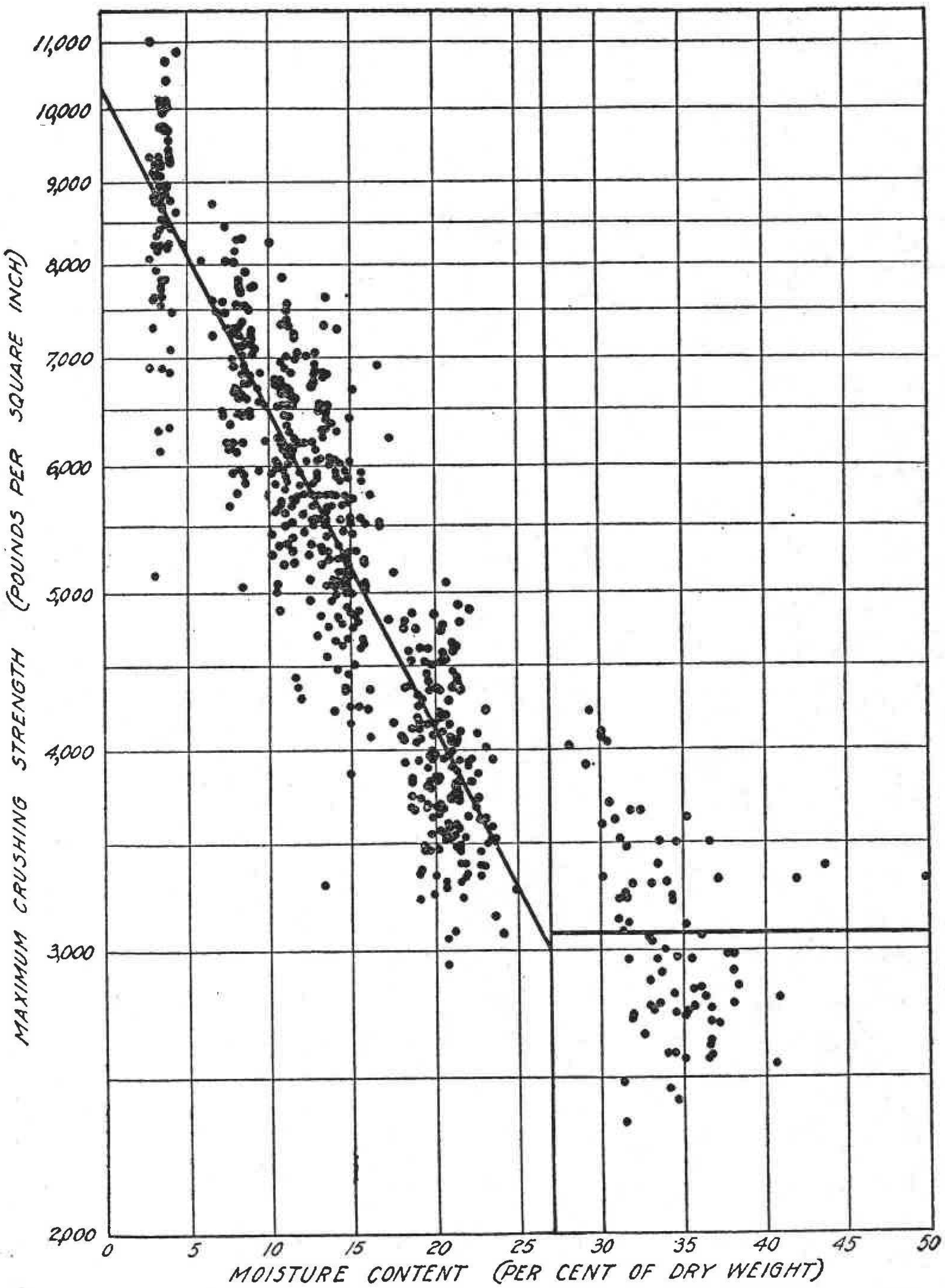

FIGURE 16.—Sitka spruce: Relation, by individual specimens, of maximum crushing strength in compression parallel to grain to moisture content. The inclined and horizontal lines shown are identical with those shown for maximum crushing strength in Figure 14 and at *F* in Figure 15

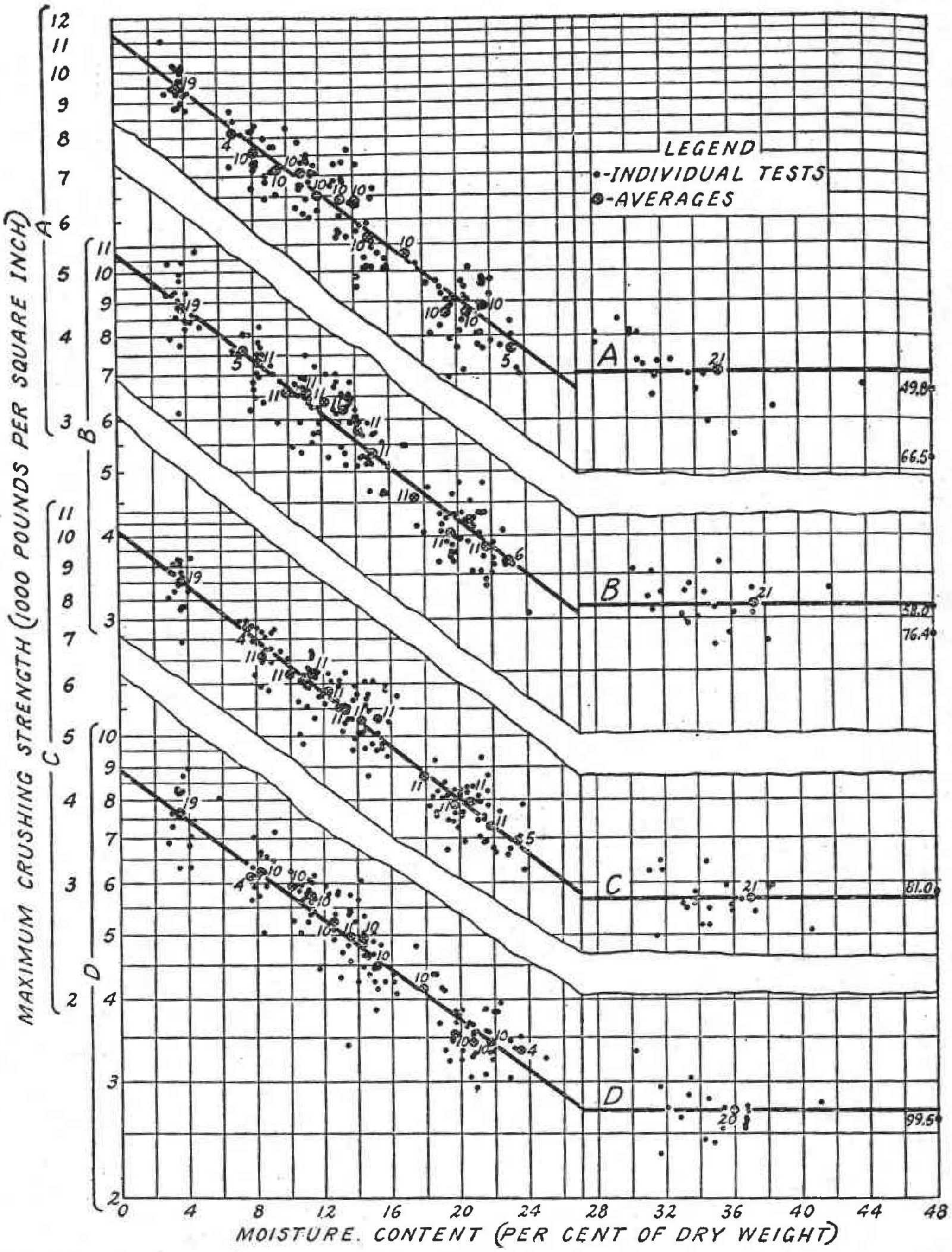

FIGURE 17.—Sitka spruce: Relation of maximum crushing strength in compression parallel to grain to moisture content. Specimens grouped according to specific gravity: *A*, Group of highest specific gravity; *B*, group of next lower specific gravity; *C*, group of next lower specific gravity; *D*, group of lowest specific gravity. Figures near right-hand border are moisture-content values that are not plotted to scale. Numerals at other plotted points and on horizontal lines are numbers of specimens averaged. For detailed data see Table 9

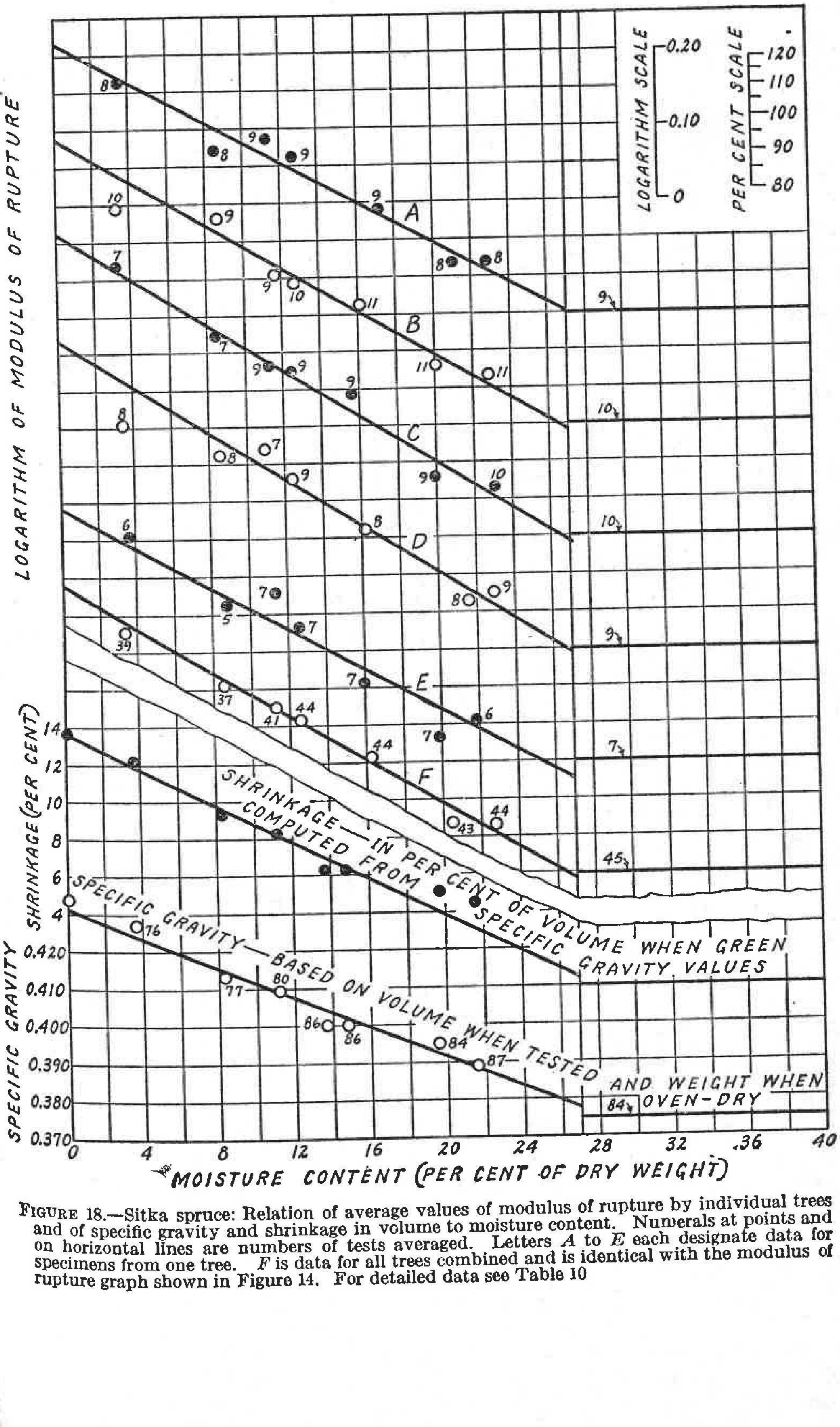

FIGURE 18.—Sitka spruce: Relation of average values of modulus of rupture by individual trees and of specific gravity and shrinkage in volume to moisture content. Numerals at points and on horizontal lines are numbers of tests averaged. Letters *A* to *E* each designate data for specimens from one tree. *F* is data for all trees combined and is identical with the modulus of rupture graph shown in Figure 14. For detailed data see Table 10

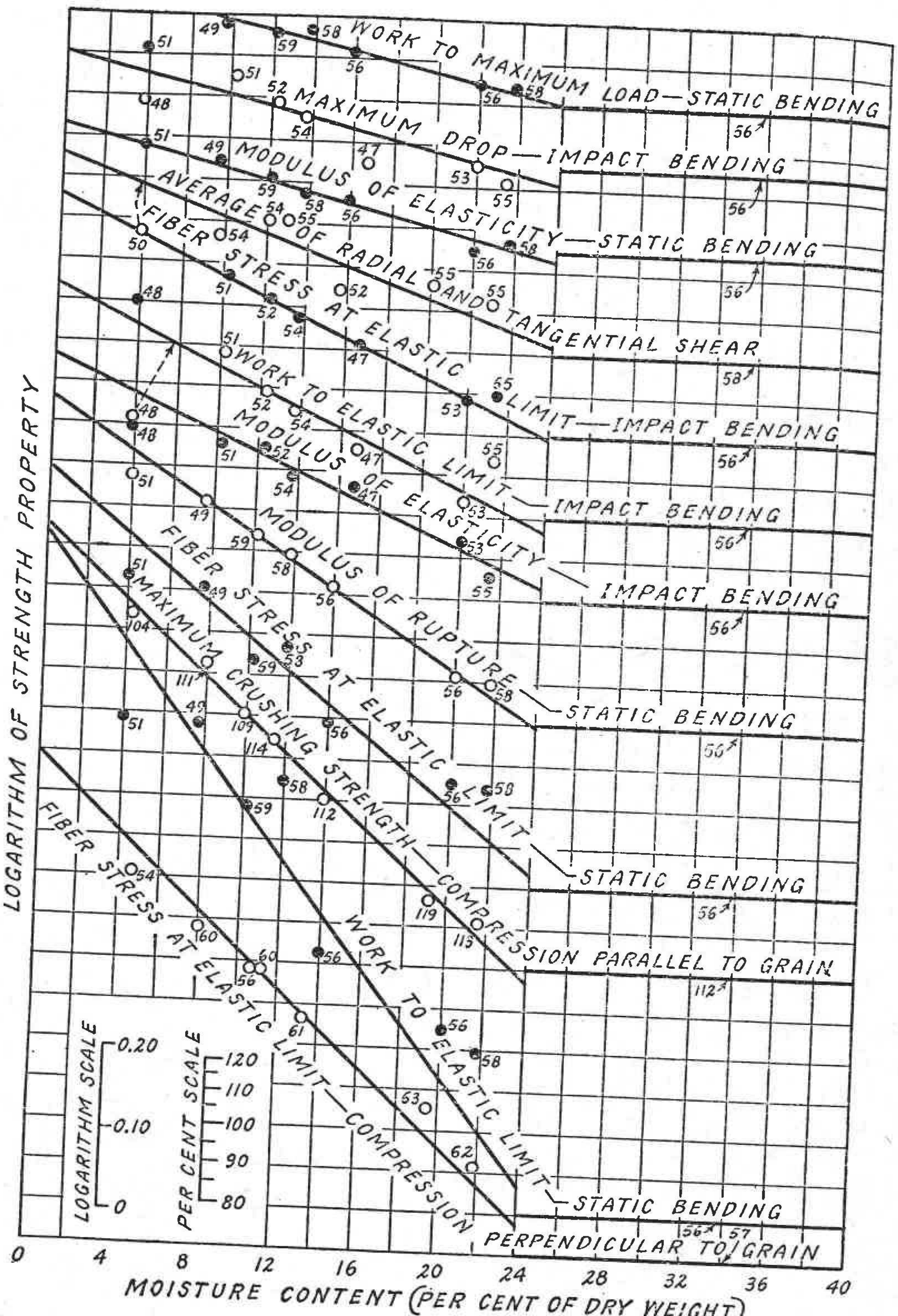

FIGURE 19.—Douglas fir: Relation of average values of various strength properties to moisture content. Numerals at plotted points and on horizontal lines are numbers of tests averaged. For detailed data see Table 11

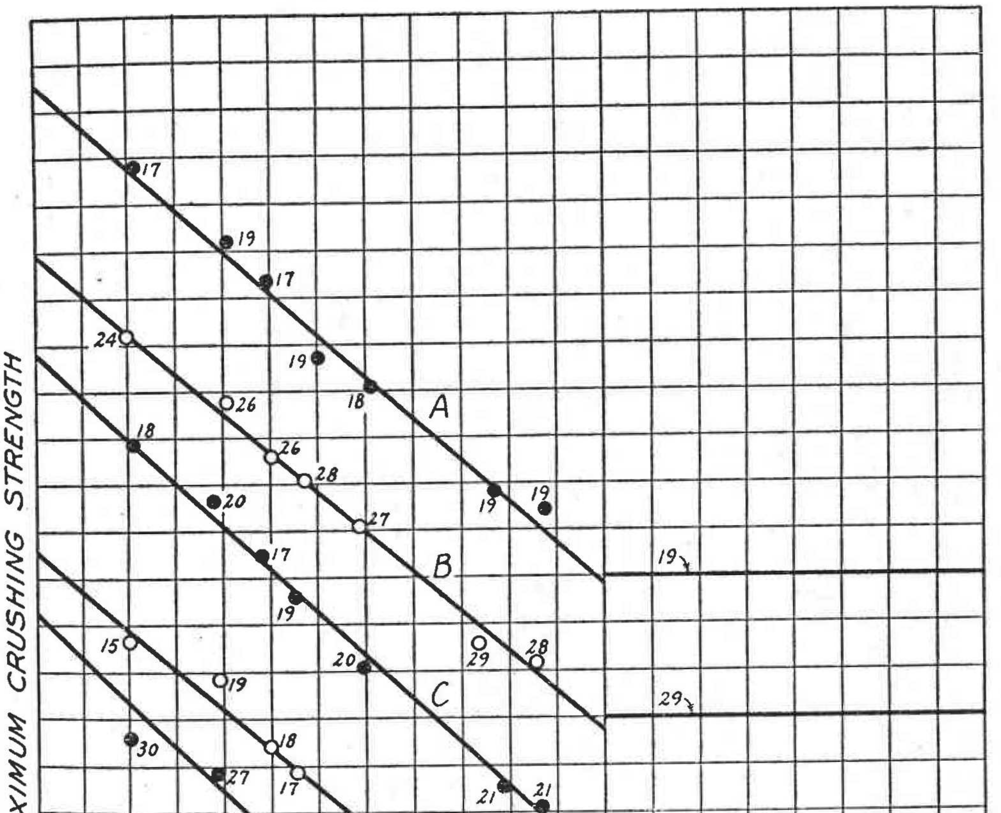

FIGURE 20.—Douglas fir: Relation, by individual trees, of maximum crushing strength in compression parallel to grain to moisture content. Numerals at plotted points and on horizontal lines are numbers of tests averaged. Letters *A* to *E* each designate data for specimens for one tree. *F* is data for all trees combined and is identical with maximum crushing strength shown in Figure 19. For detailed data see Table 12

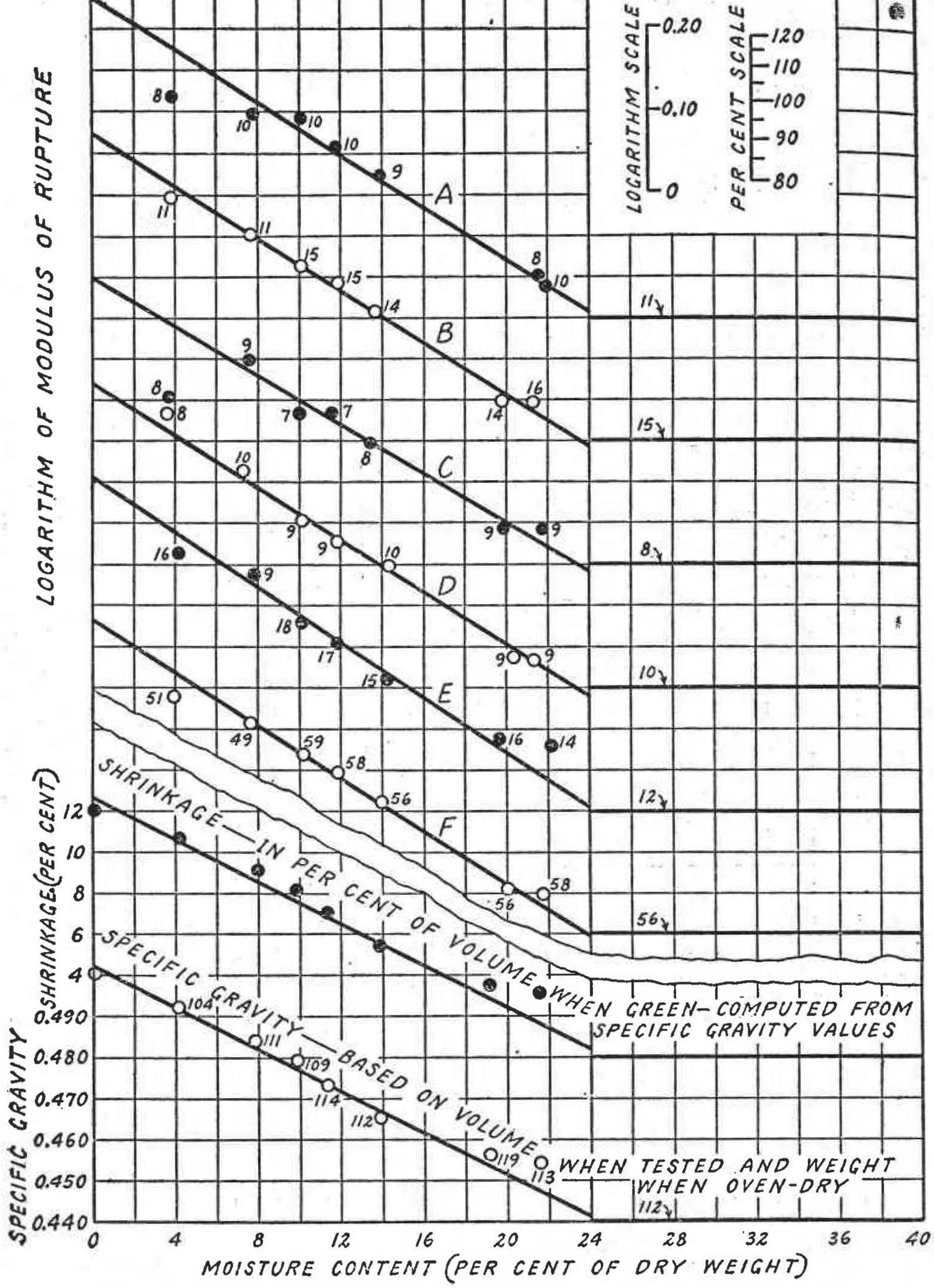

FIGURE 21.—Douglas fir: Relation, by individual trees, of modulus of rupture and of average values of specific gravity and shrinkage in volume to moisture content. Numerals at points and on horizontal lines are numbers of tests averaged. Letters *A* to *E* each designate data for specimens from a single tree. *F* is data for all trees combined and is identical with the modulus of rupture graph shown in Figure 19. For detailed data see Table 13

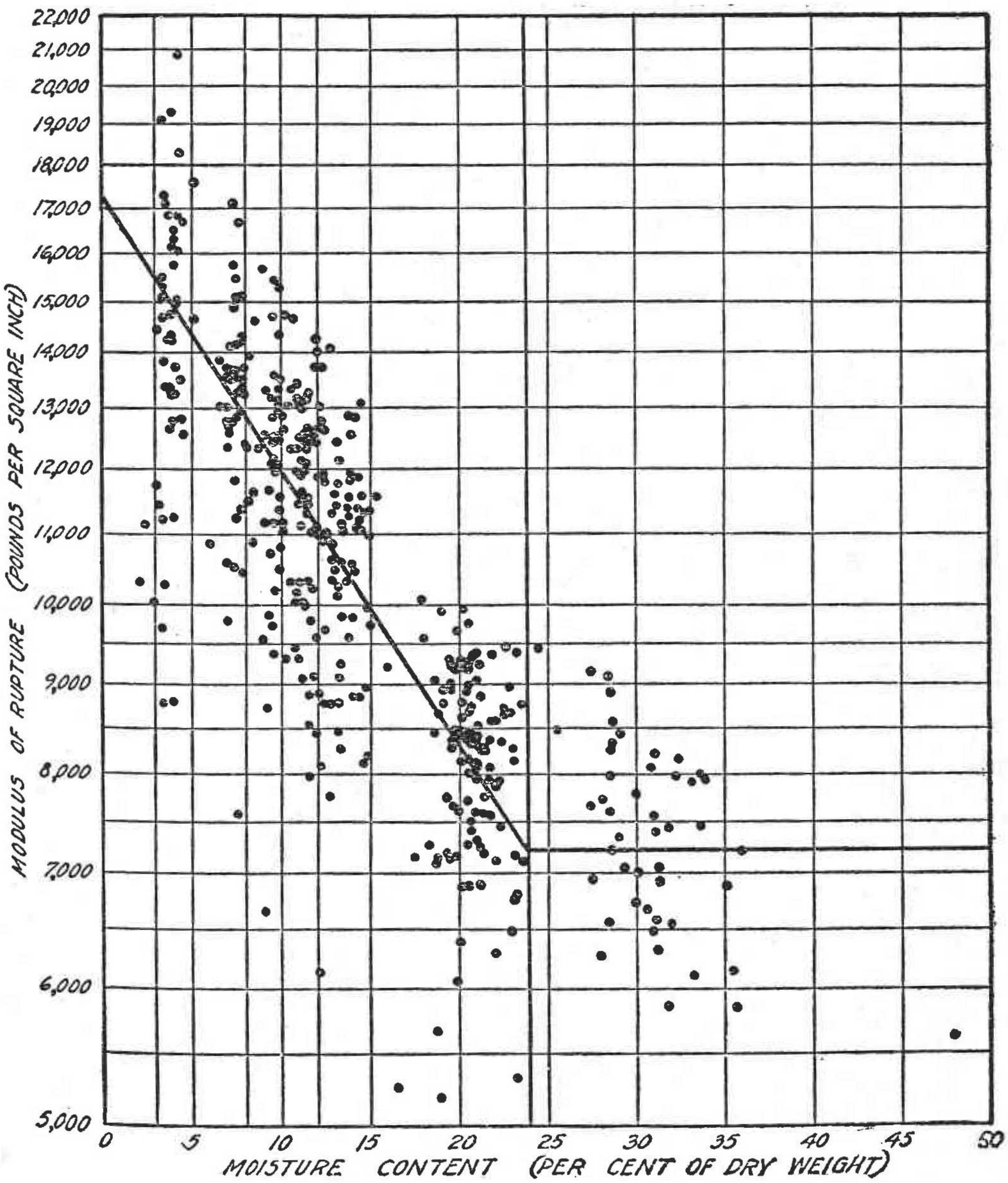

FIGURE 22.—Douglas fir: Relation, by individual specimens, of modulus of rupture to moisture content. The inclined and horizontal lines are identical with those for modulus of rupture shown in Figure 19 and at *F* in Figure 21

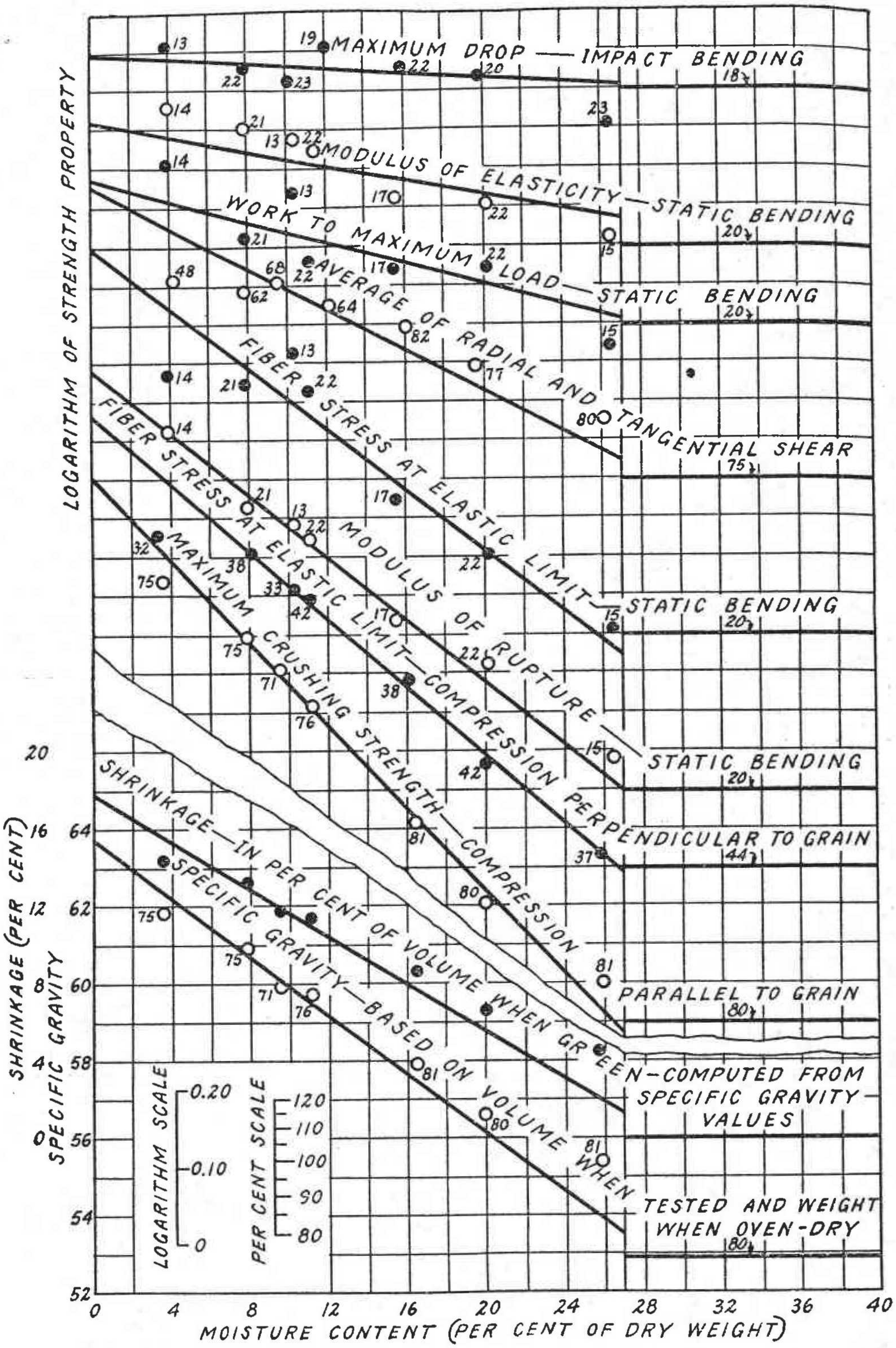

FIGURE 23.—Yellow birch: Relation of average values of various strength properties, specific gravity, and shrinkage to moisture content. Numerals at points and on horizontal lines are numbers of tests averaged. For detailed data see Table 14

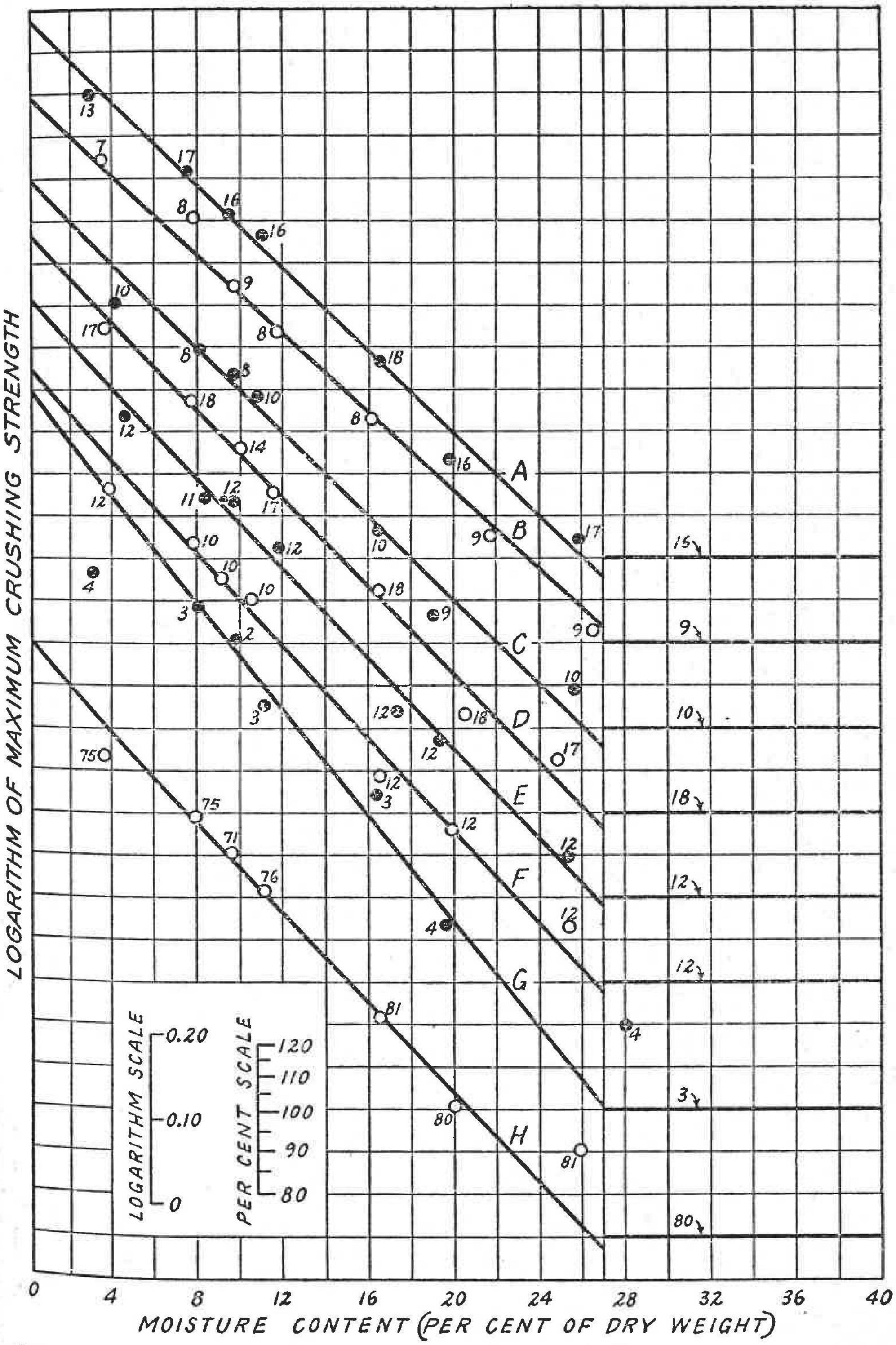

FIGURE 24.—Yellow birch: Relation, by individual trees, of maximum crushing strength in compression parallel to grain to moisture content. Numerals at points and on horizontal lines are numbers of tests averaged. Letters *A* to *G* each designate data for specimens from one tree. *H* is data for all trees combined and is identical with maximum crushing strength shown in Figure 23. For detailed data see Table 15

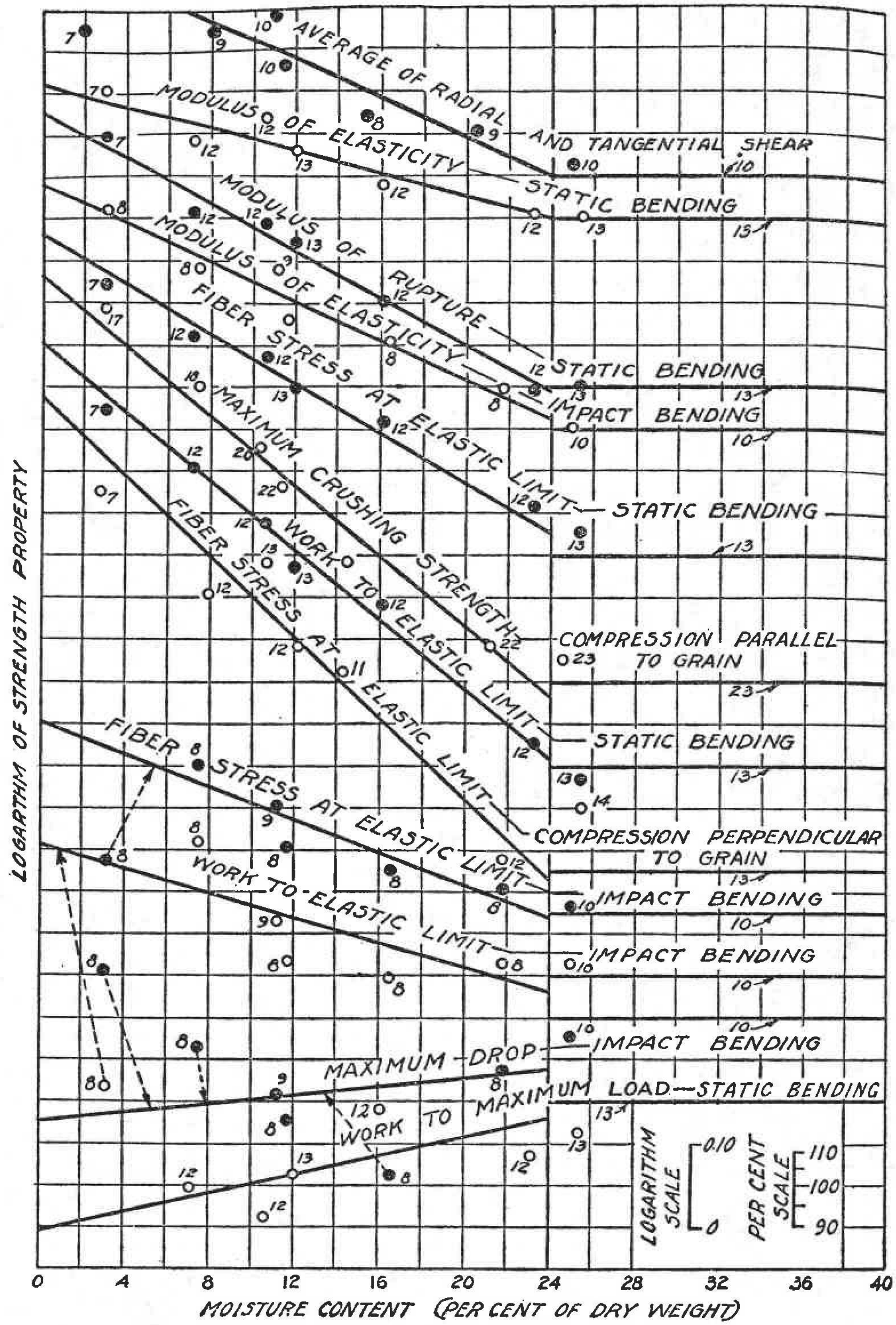

FIGURE 25.—White ash: Relation of average values of various strength properties to moisture content. Numerals at plotted points are numbers of tests averaged. For detailed data see Table 16

TABLE 10.—*Data pertaining to Figure 18* [1]

Tree	Reference letter	Average value	K
		Lbs. per sq. in.	
No. 1	A	5,945	0.0136
No. 3	B	6,355	.0147
No. 4	C	5,700	.0155
No. 5	D	5,780	.0157
No. 6	E	7,570	.0136
Average	F	6,200	.0147

[1] Average specific gravity for each tree is given in Table 8.

TABLE 11.—*Data pertaining to Figure 19*

Kind of test	Property	Average value [1] for green specimens	K
Static bending	Work to maximum load	7.48	0.0058
	Modulus of elasticity	1,477,000	.0063
	Modulus of rupture	7,235	.0160
	Fiber stress at elastic limit	3,840	.0200
	Work to elastic limit	0.61	.0326
Impact bending	Maximum drop	23	.0062
	Fiber stress at elastic limit	9,300	.0117
	Work to elastic limit	3.35	.0120
	Modulus of elasticity	1,456,000	.0112
Shear	Average of radial and tangential shearing stress.	810	.0091
Compression parallel to grain	Maximum crushing strength	3,730	.0225
Compression perpendicular to grain	Fiber stress at elastic limit	470	.0234

[1] Work values in inch-pounds per cubic inch; drop in inches; others in pounds per square inch.

TABLE 12.—*Data pertaining to Figure 20*

Tree	Reference letter	Specific gravity [1]	Average value	K
			Lbs. per sq. in.	
No. 1	A	0.492	3,680	0.0224
No. 2	B	.492	4,000	.0213
No. 3	C	.459	3,330	.0232
No. 4	D	.510	4,150	.0211
No. 5	E	.529	3,480	.0238
Average	F	.500	3,730	.0225

[1] Average value for all specimens tested. Based on weight and volume when oven dry. The average specific gravity based on weight when oven dry and volume when green was 0.442 for all specimens tested in the green condition.

TABLE 13.—*Detailed data pertaining to Figure 21* [1]

Tree	Reference letter	Average value	K
No. 1	A	7,290	0.0159
No. 2	B	7,440	.0159
No. 3	C	6,430	.0150
No. 4	D	7,590	.0158
No. 5	E	7,170	.0167
Average	F	7,235	.0160

[1] Average specific gravity for each tree is given in Table 8.

TABLE 14.—*Data pertaining to Figure 23*

Kind of test	Property	Average value [1] for green specimens	K
Impact bending	Maximum drop	33	0.0015
Static bending	Modulus of elasticity	1,395,000	.0045
	Work to maximum load	11.51	.0065
	Fiber stress at elastic limit	4,380	.0194
	Modulus of rupture	7,400	.0199
Shear	Average of radial and tangential shear	1,042	.0131
Compression perpendicular to grain	Fiber stress at elastic limit	625	.0216
Compression parallel to grain	Maximum crushing strength	2,890	.0265

[1] Drop in inches; work values in inch-pounds per cubic inch; others in pounds per square inch.

TABLE 15.—*Data pertaining to Figure 24*

Tree number	Reference letter	Average value for green specimens	K	Tree number	Reference letter	Average value for green specimens	K
No. 3	A	2,690	0.0244	No. 6	F	2,970	0.0273
No. 2	B	2,800	.0232	No. 4	G	2,340	.0313
No. 8	C	3,500	.0250				
No. 7	D	2,660	.0260	Average	H	2,890	.0265
No. 1	E	3,190	.0266				

TABLE 16.—*Data pertaining to Figure 25*

Kind of test	Property	Average value [1] for green specimens	K
Shear	Average of radial and tangential shearing stress.	1,280	0.0115
Static bending	Modulus of elasticity	1,215,000	.0066
	Modulus of rupture	8,335	.0138
	Fiber stress at elastic limit	4,010	.0148
	Work to elastic limit	0.90	.0206
	Work to maximum load	15.18	−.0057
Impact bending	Modulus of elasticity	1,333,000	.0116
	Fiber stress at elastic limit	9,800	.0096
	Work to elastic limit	4.08	.0073
	Maximum drop	37	−.0026
Compression parallel to grain	Maximum crushing strength	3,320	.0208
Compression perpendicular to grain	Fiber stress at elastic limit	805	.0238

[1] Work values in inch-pounds per cubic inch; maximum drop in inches; others in pounds per square inch.

DISCUSSION OF DATA AND COMPARISON WITH EXPONENTIAL FORMULA

The particular form (p. 13) in which the data are shown in Figures 7 to 25 was chosen because it seems from careful study that the exponential formulas, as previously discussed, represent experimental results more accurately than formulas of any other simple type, and because by such plotting graphs of formulas of the exponential type become straight lines. The data are presented in considerable detail in order to show just how good the representation is.

A vertical percentage scale has been placed on most of the diagrams in addition to the logarithmic scale. This vertical scale applies at any place on the sheet, and the percentage deviation of a plotted point from the line drawn to average the series of points to which it belongs can be estimated by superimposing the 100 per cent point of the scale on the average line. In figures having such vertical scales the points of each series are plotted with respect to a different zero of the vertical scale. The zero for each graph is the average value from tests of green, or in a few instances, soaked, specimens. In other words, the values actually plotted are logarithms of the ratios $\frac{S}{S_p}$, where S and S_p are as defined in connection with equations (5) to (9).

DATA FROM GROUP 2 TESTS

Inasmuch as the tests of Group 2 were made with special reference to comparison with the exponential formula, the data from them will be considered first.

Figure 14 for Sitka spruce shows average values of each property for each of the several moisture-content classes. Reference to the exponential equation in the form of equation (8) or (9) shows that the values of three constants, or parameters, are required to fit this equation to a particular group of test values. One of these is K, the slope of the line that averages the points to the left of its intersection with the line representing the strength of green wood. The other two required parameters are M_p, the moisture content at the intersection point, and S_p, the strength value for green wood. S_p is presumably afforded directly by the test value from green specimens, but, as is shown later, this test value is subject to correction.

Inspection of any of the plots, such as Figure 14, shows that if the inclined lines that average the several series of plotted points are drawn to their intersections with the horizontal lines representing the strength values for green material, the several intersections will be at different values of M. In other words, a variety of values of M_p will be indicated even for properties derived from the same test, such as fiber stress at elastic limit, modulus of rupture, modulus of elasticity, work to elastic limit, and work to maximum load, all of which are determined from static bending tests. Although it is possible that the value of M_p is not the same for all properties, the variety of values of M at the apparent intersection points is explainable on the basis of lack of perfect matching between groups of specimens tested at different moisture-content values, this deficiency of matching probably having a different effect on different strength properties. Had the matching of specimens actually averaged out (p. 23) the effect of all factors other than moisture content and if the assumed exponential law holds true, all the plotted points of a series would lie on a straight line. The fact that the plotted points do not follow a straight line or a smooth curve indicates that the relations between strength values are influenced by factors other than that of differences in the moisture content of the test specimens.

When allowance is made for the lack of perfect matching among the several moisture-content sets, it is possible to derive from the data on each species a value of M_p that is acceptable for all of the strength properties.[8]

Values of M_p for Sitka spruce, Douglas fir, yellow birch, and white ash were determined from the strength data shown in Figures 14, 19, 23, and 25 by a least-squares computation. In making this computation points representing the sets of specimens tested at the lowest moisture content were omitted because the tendency, observed in some instances, for these points to fall below the inclined lines averaging other points of the same series suggested either that drying to

[8] Convenience in the use of formulas for moisture-strength adjustment, as is shown later, makes a single value of M_p for all properties of a species desirable.

so low a moisture content had resulted in injury to the strength properties or that the assumed straight-line relation between percentage of moisture content and the logarithm of the strength property would not hold for very low moisture-content values. Data from the sets of specimens tested at the highest moisture content below the green condition were also omitted because, in spite of the care taken in conditioning specimens, it has not been possible to bring about in this set the desired uniformity of distribution of moisture between parts of the same specimen and between different specimens. These two classes of points represent moisture-content values that are outside the range to which chief interest attaches in connection with moisture-strength adjustments. The M_p vertical and the several inclined lines in Figure 14 were so located as to make the sum (for the entire figure) of the squares of the vertical deviations of the plotted points, exclusive of those omitted for reasons just stated, and of the points at the intersections of the horizontal lines with the M_p vertical a minimum except that location of M_p at fractional values of moisture-content percentages was not considered. The same procedure was followed in locating the M_p verticals and fitting the inclined lines to the data on strength properties in Figures 19, 23, and 25.

In Figures 15, 18, 20, 21, and 24 are presented data on maximum crushing strength for individual trees of Douglas fir, Sitka spruce, and yellow birch, and on modulus of rupture for individual trees of Douglas fir and Sitka spruce. Similar diagrams are not shown for other properties and species because the number of tests from individual trees is not sufficient to afford reliable averages.

The inclined lines in these diagrams (figs. 15, 18, 20, 21, and 24) were located by least-squares methods, the strength values for green material being assumed to obtain at the value of M_p previously found for the respective species.

In Figures 16 and 22 are plotted individual test values for maximum crushing strength of Sitka spruce and modulus of rupture of Douglas fir, respectively. Each of these figures shows a comparatively large variation in strength values for green specimens and a somewhat larger variation for specimens at moisture-content values below M_p. This indicates that the major portion of the variation in strength at any moisture content value below M_p is due to variation in the inherent strength of the wood, the remainder being the result of variations in the effect of drying.

It has been shown (*8*) that there is a reasonably good correlation between specific gravity and strength properties of wood. Consequently, it is to be expected that the variations in strength values exhibited by Figures 16 and 22 would be reduced if the range in specific gravity of specimens were reduced. In Figure 17 the result of classifying the data of Figure 16 into four groups according to the specific gravity of the specimens is shown.

In assembling the data for this figure the seasoned specimens were first divided into groups within each of which there was only a comparatively small range of moisture-content values. The specimens of each of these groups were then arranged in order of their specific-gravity values and were divided into four subgroups *A*, *B*, *C*, and *D*, each of which comprised an approximately equal number of tests, subgroup *A* including the specimens of highest specific gravity. The subgroup averages for maximum crushing strength and moisture content, as well as the individual test values are plotted in Figure 17.

The inclined lines shown in this figure have been fitted to the subgroup averages by least-squares computations, assuming the green values to obtain at 27 per cent moisture, which is the value of M_p previously determined for Sitka spruce.

All the data for specimens below 25 per cent moisture content were used because in this instance there is little or no evidence that the material near the upper limit of moisture content has been influenced by unequal moisture distribution or that that near the lower limit has been adversely affected by drying to so low a moisture content.

The variability of maximum crushing strength for green specimens or for specimens at any moisture content below the M_p value is readily seen to be considerably less in each section of Figure 17 than in Figure 16, showing that the classification of specimens according to their specific gravity has reduced the variability in the strength value. It remains true of each part of Figure 17, however, as of Figure 16, that the variation of strength at moisture-content values below M_p is greater than the variation in strength of green material, indicating that part of the variability at moisture-content values below M_p is due to variability in the effect of drying.

DATA FROM GROUP 1 TESTS

The data from Group 1 tests are shown in Figures 8 to 13. The M_p vertical and the inclined lines in Figure 8 (longleaf pine) were located by the method described in connection with Figure 14. This was considered better than to rely on the tests on small specimens for determination of the interesection point as advocated in the previously quoted excerpts (p. 13) because Figure 8 (2 by 2 inch specimens) includes data for a variety of moisture-content values between zero and the intersection point, whereas the smaller specimens (fig. 13) were tested only at values near the fiber-saturation point and at comparatively low moisture-content values.

Data on loblolly pine are available only for the small specimens. (Fig. 13.) These were tested at moisture-content values near the fiber-saturation point and at low moisture-content values. Taking only those points representing a moisture content below 20 per cent, the least-squares computation indicates a value of nearly 22 per cent for M_p. However, the points just below 20 per cent may be raised slightly by nonuniform drying of specimens, and this would tend to increase the computed value of M_p. Furthermore, it might be expected that loblolly pine would be quite similar to longleaf pine with respect to moisture content at the intersection point, and since Figure 8 indicates 21 per cent as the best value for longleaf, this value is taken for loblolly pine also. Information from shrinkage tests presented later is further evidence of the similarity of longleaf and loblolly pines with respect to moisture content at the intersection point.

In determining a value of M_p for red spruce, principal reliance was placed on the data on maximum crushing strength (figs. 9, 10, and 13) and on fiber stress at elastic limit in compression parallel to grain. (Figs. 9 and 10.) These data indicate a value of 27 per cent for M_p—the same value as found for Sitka spruce, to which red spruce is very similar in many other properties. (A value of 30 per cent for M_p of red spruce is indicated by Figure 7. This figure, however, shows points taken from the curves originally drawn to represent the data, whereas the value of 27 per cent has been determined from a study of the actual test data as plotted in Figures 9, 10, and 13.)

The data on maximum crushing strength (fig. 11 for 2 by 2 inch specimens and fig. 12 for smaller specimens) were used in determining M_p for chestnut, and a value of 24 per cent was found.

ADDITIONAL DATA

Tests, additional to those of Groups 1 and 2, are presented in Figures 26 and 27. Figure 26 is data on maximum crushing strength in

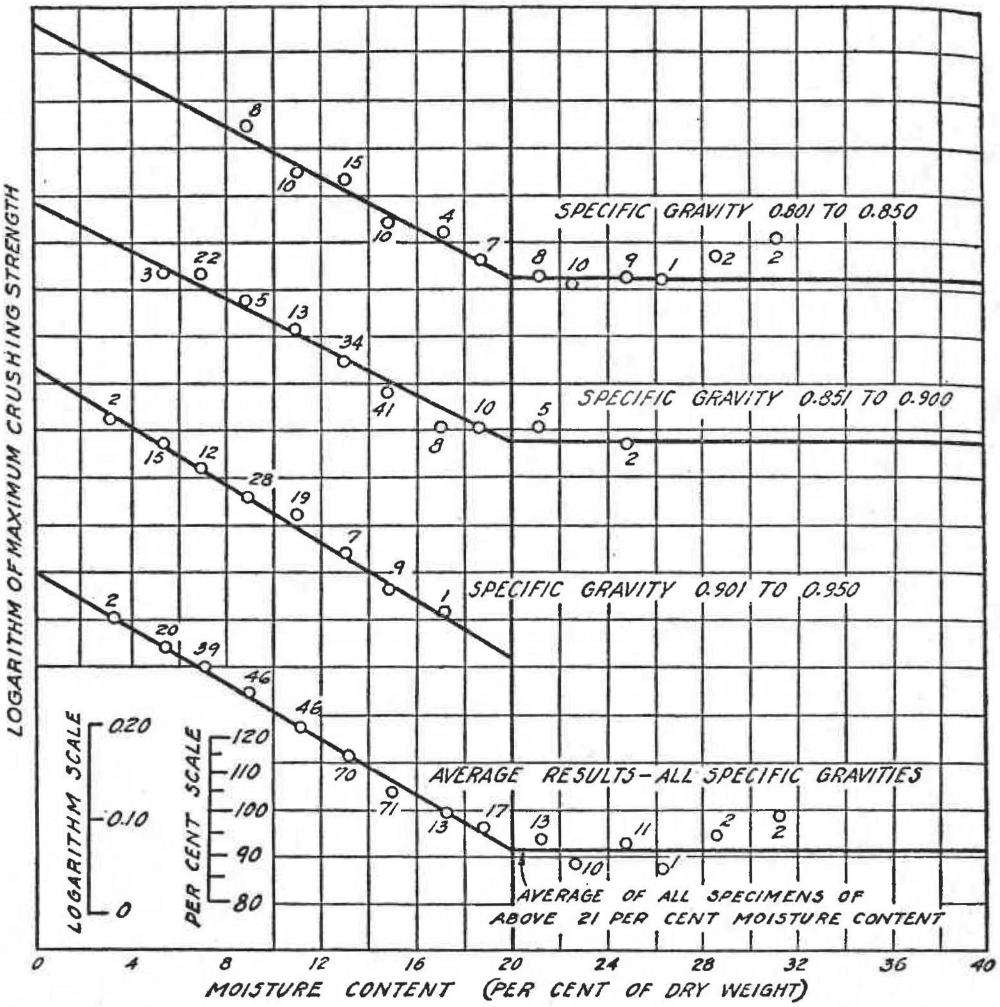

FIGURE 26.—Greenheart: Relation of maximum crushing strength in compression parallel to grain to moisture content. Specimens were 1 by 1 by 2¾ inches. Numerals at points are numbers of tests averaged. The average results curve includes data from specimens with specific gravity values below 0.801 and above 0.950.

compression parallel to the grain derived from tests on 1 by 1 by 2¾ inch specimens of greenheart (*Nectandra rodioei*). These data show exceptionally good conformity to a straight-line relation. Figure 27 exhibits moisture relations for modulus of rigidity, shear stress at elastic limit, and ultimate shear stress as found from torsion tests of Sitka spruce (*14*).

SUMMARY OF DATA AND DISCUSSION

The relation of moisture content to mechanical properties of wood has been pictured in Figures 8 to 27 and compared to the exponential formula for all series of tests for which original data are available. Data on 22 mechanical properties and 9 species of wood are included.

In general, it may be said that the agreement of experimental data with the exponential formula is sufficiently good to justify the belief that with the proper values of K and M_p this formula will represent the relation between moisture content, over a considerable part of the range between zero and the fiber-saturation-point value and any mechanical property for any species of wood very accurately.[9]

It is evident from the data presented that both K and M_p vary, and before discussing the use of the exponential formula in adjusting test results, it will be well to consider the variations in these parameters and to compare values of M_p with fiber-saturation-point moisture-content and similar values as derived from other experimental data.

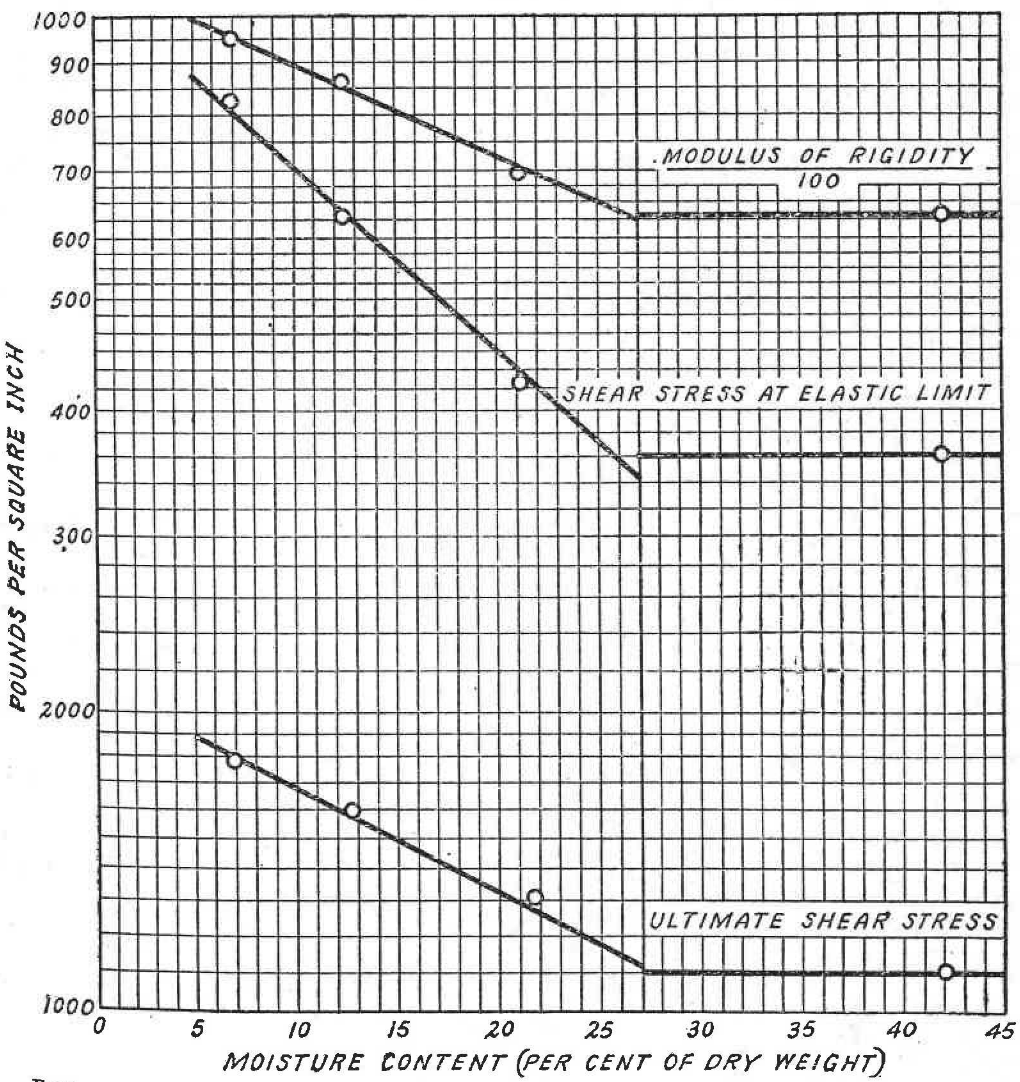

FIGURE 27.—Sitka spruce: Relation of properties obtained from torsion tests to moisture content. Each plotted point represents three tests. Values of K for modulus of rigidity, shear stress at elastic limit, and ultimate shear stress are 0.0092, 0.0184, and 0.0105, respectively

Values of M_p for the species included in Figures 8 to 27 and of K for several properties of these species are assembeled in Table 17.[10] M_p is seen to vary with the species, the range shown being from 20 to 27 per cent moisture. As accurate adjustment of test results for differences in moisture content (p. 66) requires accurate values for M_p, some method by which such values can be found without an elaborate series of mechanical tests is obviously very desirable.

[9] It is interesting to note in this connection that for moisture content values below the fiber-saturation point the specific electrical conductance of wood conforms to a similar law. (P. 57.)

[10] Table 17 includes information on four species additional to those previously discussed. The values listed for these four species were derived from data taken from average curves constructed by the original investigators, the original test data not being available (4, 5, 13).

TABLE 17.—*Results of tests of the effect of*

Species	Figure	[1] M_p	Tree No.	Specific gravity of specimens—based on weight when oven-dry and volume when— Green	Specific gravity … Oven-dry	Compression parallel to grain (maximum crushing strength): Value for green specimens	Compression: K	Static bending, Fiber stress at elastic limit: Value for green specimens	Fiber stress: K	Static bending, Modulus of rupture: Value for green specimens	Modulus of rupture: K
		Per cent moisture				*Lbs. per sq. in.*		*Lbs. per sq. in.*		*Lbs. per sq. in.*	
White ash	25	24	(2)	0.490	0.575	3,320	0.0208	4,010	0.0148	8,335	0.0138
Yellow birch	23	27	(2)	.529		2,890	.0265	4,380	.0194	7,400	.0199
			1	.543		3,190	.0266				
			2	.511		2,800	.0232				
			3	.519		2,690	.0244				
Do	24		4	.497		2,340	.0313				
			6	.552		2,970	.0273				
			7	.535		2,660	.0260				
			8	.545		3,500	.0250				
Chestnut	11	24	(2)	.43		3,070	.0214	3,570	.0187	6,270	.0132
							.0218				
						2,420	.0294				
Do	12					2,360	.0236				
						4,015	.0203				
						3,135	.0197				
						4,480	.0185				
Douglas fir	19	24	(2)	.440	.500	3,730	.0225	3,840	.0200	7,235	.0160
			1		.492	3,680	.0224			7,290	.0159
			2		.492	4,000	.0213			7,440	.0155
Do	20, 21		3		.459	3,330	.0232			6,430	.0150
			4		.510	4,150	.0211			7,590	.0158
			5		.529	3,480	.0238			7,170	.0167
Greenheart	26	20	(2)		.875	10,130	.0149				
Loblolly pine	13	21	(2)			2,010	.0247				
Longleaf pine	8	21		.56		4,605	.0257	4,920	.0245	8,890	.0210
	13					5,720	.0207				
	9	27		.36		2,620	.0234				
Red spruce	10			.38		2,410	.0229	3,160	.0176	5,165	.0166
	13					2,580	.0217				
Sitka spruce	14	27	(2)	.375	.439	3,070	.0200	3,755	.0161	6,200	.0147
			1		.439	2,835	.0213			5,945	.0136
			3		.461	3,230	.0199			6,355	.0147
Do	15, 18		4		.405	2,845	.0196			5,700	.0155
			5		.416	2,870	.0212			5,780	.0157
			6		.476	3,735	.0184			7,570	.0136
Western hemlock		28				3,250	.0192			7,200	.0139
Western larch		28				3,900	.0190			7,600	.0143
Norway pine		24				1,800	.0260				
Tamarack		24				3,200	.0246				

[1] Some recently available data on the relation of strength properties of redwood to its moisture content indicate a value of M_p of about 21 per cent.

[2] Average

moisture on the strength properties of wood

Static bending						Compression perpendicular to grain (fiber stress at elastic limit)		Shear parallel to grain (average of radial and tangential shear)		Impact bending (drop required to cause failure 50-pound hammer)	
Modulus of elasticity		Work to elastic limit		Work to maximum load							
Value for green specimens	*K*	Value for green specimens	*K*	Value for green specimens	*K*	Value for green specimens	*K*	Value for green specimens	*K*	Value for green specimens	*K*
1,000 lbs. per sq. in.		*In.-lbs. per cu.in.*		*In.-lbs. per cu.in.*		*Lbs. per sq. in.*		*Lbs. per sq. in.*		*Inches*	
1,215	0.0066	0.90	0.0206	15.18	−0.0057	805	0.0238	1,280	0.0115	37	−0.0026
1,395	.0045	----	----	11.51	.0065	625	.0216	1,042	.0131	33	.0015
----	----	----	----	----	----	----	----	----	----	----	----
1,068	.0068	----	----	----	----	----	----	733	.0057	----	----
----	----	----	----	----	----	----	----	----	----	----	----
1,477	.0063	.61	.0326	7.48	.0058	470	.0234	810	.0091	23	.0062
----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----
1,896	.0062	.73	.0396	----	----	----	----	915	.0157	----	----
----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	677	.0105	----	----
1,262	.0056	----	----	----	----	----	----	603	.0155	----	----
1,371	.0060	.61	.0260	5.93	.0099	335	.0187	730	.0072	24	.0027
----	----	----	----	----	----	----	----	----	----	----	----
1,375	.0066	----	----	----	----	----	----	----	----	----	----
1,350	.0070	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----
----	----	----	----	----	----	----	----	----	----	----	----

METHODS OF FINDING M_p

Methods that may be considered for finding or estimating M_p are: (1) Estimation from other properties and characteristics of the species; (2) simple mechanical tests; (3) physical measurements, such as shrinkage, electrical conductivity, and equilibrium moisture content.

ESTIMATION OF M_p FROM SPECIES CHARACTERISTICS AND FROM MECHANICAL TESTS

Inspection of Table 17 indicates that M_p is not definitely correlated with other tabulated characteristics of the species or of different series of specimens of the same species. For instance, no systematic relation to specific gravity or to the strength of the wood is apparent. Neither is there any indication that coniferous woods have value of M_p differing from those of the hardwood species. (The range of values shown is from 20 to 27 per cent for hardwoods.) Hence, it is quite improbable that an accurate estimate of the value of M_p can be had from a consideration of other characteristics of a species.

However, listing the species from Table 17 according to decreasing values of moisture content at the intersection point brings out some interesting relationships. The list is as follows:

Species	M_p	Species	M_p
Western larch	28	White ash	24
Western hemlock	28	Chestnut	24
Sitka spruce	27	Douglas fir	24
Red spruce	27	Norway pine	24
Yellow birch	27	Tamarack	24
		Loblolly pine	21
		Longleaf pine	21
		Greenheart	20

Except western larch, the species in the first column have no well developed summer wood. Larch, moreover, is usually very fine ringed, which tends to give the wood a uniform structure. The species in the second column, except greenheart, have well-developed summer wood which differs from the spring wood in many respects. The suggestion from this listing is that wood structure of different types, even within a single species, may have different fiber-saturation points or intersection points.

The data on maximum crushing strength of Sitka spruce have been studied to determine whether they indicate a relation between M_p and the specific gravity of the wood.

As previously stated (p. 41) the inclined lines in each section of Figure 17 were fitted to the plotted points by a least-square computation, assuming the green values to obtain at 27 per cent moisture content, that is, assuming $M_p=27$ per cent. If no assumption is made as to the value of M_p and straight lines are fitted to the subgroup averages for moisture-content values below 24 per cent, these lines intersect the horizontals representing the strength of green wood as follows: A at 25.3 per cent; B at 26.0 per cent; C at 27.4 per cent; and D at 27.4 per cent moisture content. These data afford a slight indication that M_p is lower for wood of high specific gravity. Similar analyses of the maximum crushing strength data for Douglas fir and yellow birch fail to disclose any relation between M_p and specific gravity.

As has been mentioned, the principal difficulty in getting accurate information on moisture-strength phenomena is that of obtaining close matching between specimens or groups of specimens for test at different moisture-content values. This makes necessary the testing of a considerable number of specimens in order to obtain reliable averages. A test or determination that would not damage or change the specimen would be advantageous in this connection, since it could be applied to a specimen in the green condition and to the same specimen following its conditioning to successively lower moisture-content values, thus eliminating the matching problem and reducing the number of specimens required. Mechanical properties that can be determined without damage to the specimen are modulus of elasticity and modulus of rigidity. A few determinations of modulus of elasticity were made on the same specimens at various moisture-content values in connection with the other tests of the Group 2 series. Six specimens of Douglas fir and one each of white ash and Sitka spruce were used. Unfortunately, determinations were not made on these specimens while they were green. Consequently, it is not possible from the results to find values of M_p to be compared with those derived from other tests so as to evaluate modulus of elasticity determinations as a means of locating the intersection point. Experience with the tests made indicates that more than ordinary care in the selection, preparation, and conditioning of the specimens, and more than ordinary accuracy in measuring deflections and the dimensions of specimens will be required to get satisfactory results from a few specimens. Modulus of elasticity determinations made on the same specimens in the green condition and again after drying the specimens to successively lower moisture-content values are apparently worthy of further investigation as a means of locating the intersection point. However, since M_p may vary with different pieces of the same species, it would be unsafe to rely on tests of a single specimen or of a few specimens.

If dependence is to be put on tests of a single mechanical property for determining the intersection point, maximum crushing strength in compression parallel to grain would be the first choice because it is most affected by changes of moisture content and consequently the effect of differences in moisture is less likely to be obscured by other uncontrolled factors. It should be noted, however, that maximum crushing strength taken alone would have fixed the intersection points for each of the four species included in Group 2 at slightly lower moisture-content values than are indicated by all the properties taken together. Specimens for this test can be of small size, and hence good matching can be obtained. In any such tests a considerable number of specimens for test at each of several degrees of moisture content are necessary. A number of series of specimens should be so selected as to cover reasonably well the range in the quality of the wood of the species.

ESTIMATION OF M_p FROM SHRINKAGE MEASUREMENTS

In connection with the tests of Group 2 very careful measurements were made of the shrinkage of specimens taken from the same logs as those for mechanical tests. These specimens were each weighed and measured in the green condition and then placed in a room in which a relative humidity of about 90 per cent was maintained, where they were weighed and measured at frequent intervals until equilibrium was attained. Weights and measurements were similarly made after successive transfers to 60 per cent and to 30 per cent humidity rooms. Finally the specimens were weighed and measured after they had been dried to constant weight at 100° C. The specimens were 1 inch thick by 4 inches wide by 1 inch along the grain, the width being radial or tangential according to the direction of the shrinkage to be measured. Both radial and tangential measurements were made on an additional series of specimens of yellow birch 2 by 2 inches in cross section and one-fourth inch along the grain. The computed shrinkage and moisture-content values are shown in Figures 28 to 31, inclusive. These graphs show that in most instances measurable shrinkage occurred at a moisture content greater than the intersection-point value. In locating the inclined lines in these figures, only points representing decreasing moisture content have been considered; that is, points such as those numbered 10 in Figure 28, which represent moisture-content and shrinkage determinations made when the specimens had regained moisture after having been dried to a lower moisture content, have been disregarded. Except the one at zero moisture content, points representing decreasing moisture-content values below 16 per cent are very close to a straight line. Each inclined line in Figures 28 to 31 was located to pass through the point representing the lowest moisture content above zero and through the average of two points near 12 per cent moisture content. The validity of basing the location of these lines on the three points selected might be questioned. However, the effort has been to locate lines that will represent the shrinkage-moisture relation within the range of about 4 to 16 per cent moisture content. The points selected are the only ones available for this purpose, the two near 12 per cent moisture are in most instances almost exactly in line with that representing the lowest moisture content above zero, and the three points taken together quite definitely fix the position of the line representing the desired range. The percentages of moisture at the intersections of the inclined lines in Figures 28 to 31 with the horizontal lines representing zero shrinkage are taken as the intersection-point values.[11] (No question of lack of matching as previously considered in connection with the strength tests is involved because identical specimens were measured at different moisture-content values.) The intersection points as determined from the several sets of shrinkage-moisture data vary over a fairly wide range for each species. Heartwood and sapwood appear to differ, but neither consistently indicates higher intersection points. Hence, these data afford no basis for a generalization as to a comparison between heartwood and sapwood with respect to moisture content at the intersection point. On the contrary, tangential shrinkage measurements consistently indicate

[11] It has been demonstrated that the change in dimensions of wood of some hardwood species in drying from the green state to a low moisture content is greatly influenced by the relative humidity to which the wood is subjected. For example, twice as much decrease in cross-sectional area occurred in oak specimens dried at high relative humidities as in matched specimens dried to the same moisture content at practically the same temperature but at much lower humidities. Similar results have been observed in the drying of some other hardwoods. Apparently, the shrinkage of most softwood, or coniferous, species is influenced but little by the conditions under which drying takes place. What effect the humidity maintained during drying has on the intersection points in plots of shrinkage-moisture data has not been investigated.

higher values than do radial. This might be supposed to be due to the fact that measurements of shrinkage in the two directions were made on different specimens.[12] However, as shown by *C* and *D* of Figure 30, the same comparison obtains for tangential and radial measurements made on identical specimens of yellow birch. In additional series of shrinkage measurements (p. 54) it was quite consistently true that tangential shrinkage measurements indicated higher values than did radial.

Table 18 lists the values of moisture content at intersection points as found from the shrinkage data in Figures 28 to 31 and for comparison the average values found from mechanical tests. The value from mechanical tests of Sitka spruce is higher than that from shrinkage, whereas the reverse is true for the other three species. The conclusion from this comparison is that the value of moisture content at the intersection point in such plots of shrinkage-moisture data as are shown in Figures 28 to 31 does not coincide with the value of M_p obtained from mechanical-test data, but may in the absence of determinations of the latter kind be considered sufficiently reliable to be taken as a guide in estimating values of M_p for use in dealing with data on mechanical properties of species for which M_p has not been determined.

TABLE 18.—*Values of M_p from mechanical tests and percentage of moisture at intersection point from shrinkage measurements on the same species*

Species	Average value for M_p from mechanical tests	Percentage of moisture at intersection point—from shrinkage measurements: Tangential shrinkage			Radial shrinkage			Tangential and radial shrinkage (All specimens)
		Specimens of heartwood	Specimens of sapwood	All specimens	Specimens of heartwood	Specimens of mixed heartwood and sapwood	All specimens	
Sitka spruce	27	26.2	25.9	26.0	24.6	23.6	24.1	25.3
Douglas fir	24	25.6	27.3	26.2	26.0	25.4	26.0	25.8
Yellow birch	27			30.8			27.0	28.9
White ash	24	26.9	28.6	28.0	24.4	25.5	25.0	26.7

Table 19 lists intersection point-moisture content values obtained from other shrinkage-moisture data. Each species is represented in this table by shrinkage and moisture measurements on specimens 1 by 4 by 1 inches in dimension. Although these shrinkage determinations were carried out with less care and refinement than those represented in Table 18, the values given are believed to be reasonably reliable as determinations of the intersection point moisture from shrinkage data. Values in Tables 18 and 19 for species common to the two tables agree quite well, the greatest difference being about 3 per cent for white ash.

[12] In order to get the width more nearly tangential, the tangential specimens must ordinarily be taken further from the pith of the tree than the radial.

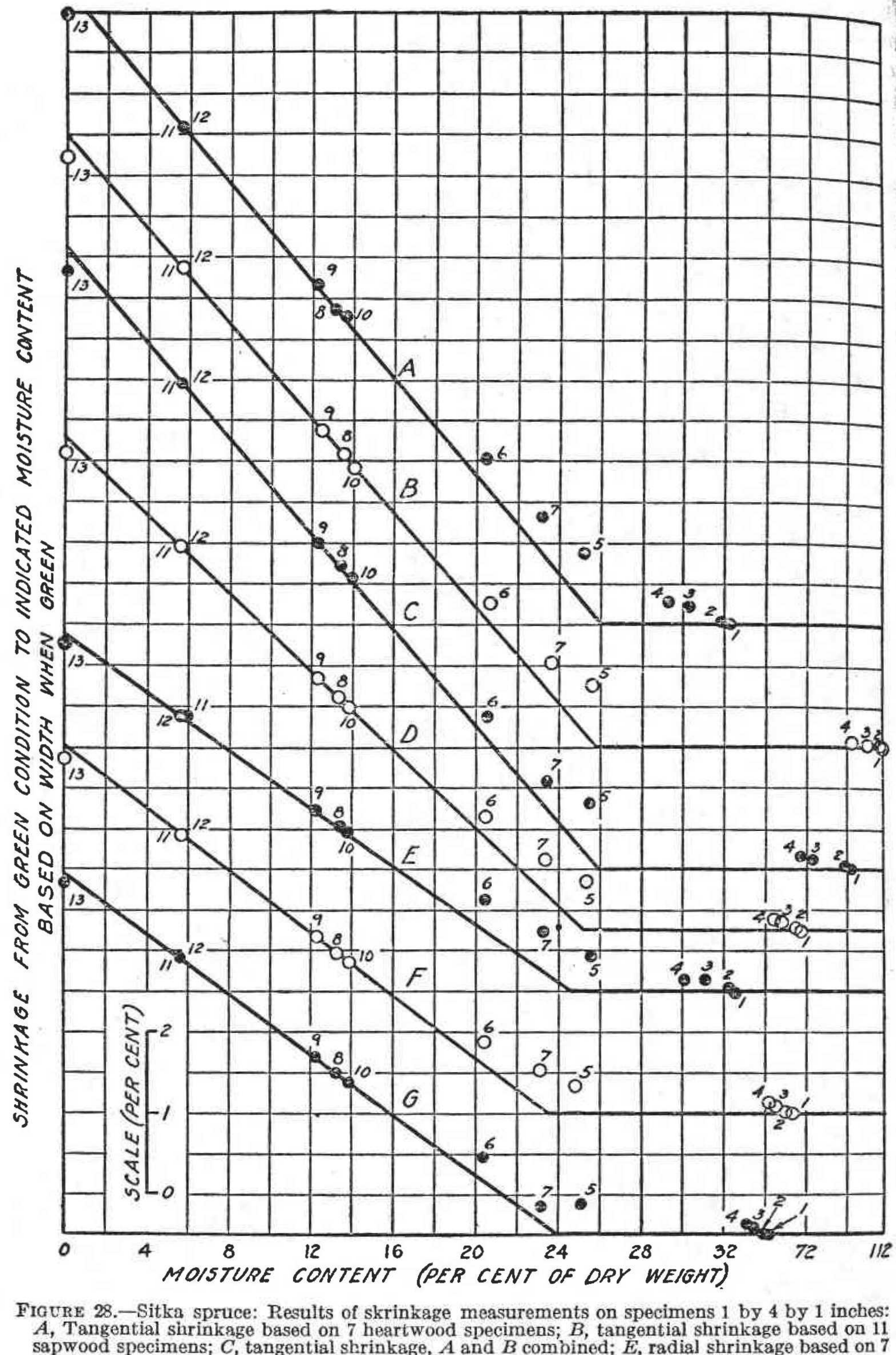

FIGURE 28.—Sitka spruce: Results of skrinkage measurements on specimens 1 by 4 by 1 inches: *A*, Tangential shrinkage based on 7 heartwood specimens; *B*, tangential shrinkage based on 11 sapwood specimens; *C*, tangential shrinkage, *A* and *B* combined; *E*, radial shrinkage based on 7 heartwood specimens *F*, radial shrinkage based on 11 specimens of mixed heartwood and sapwood averaging about 30 per cent sapwood; *G*, radial shrinkage, *E* and *F* combined; *D*, *C*, and *G* combined. Points are numbered in the order in which measurements were taken

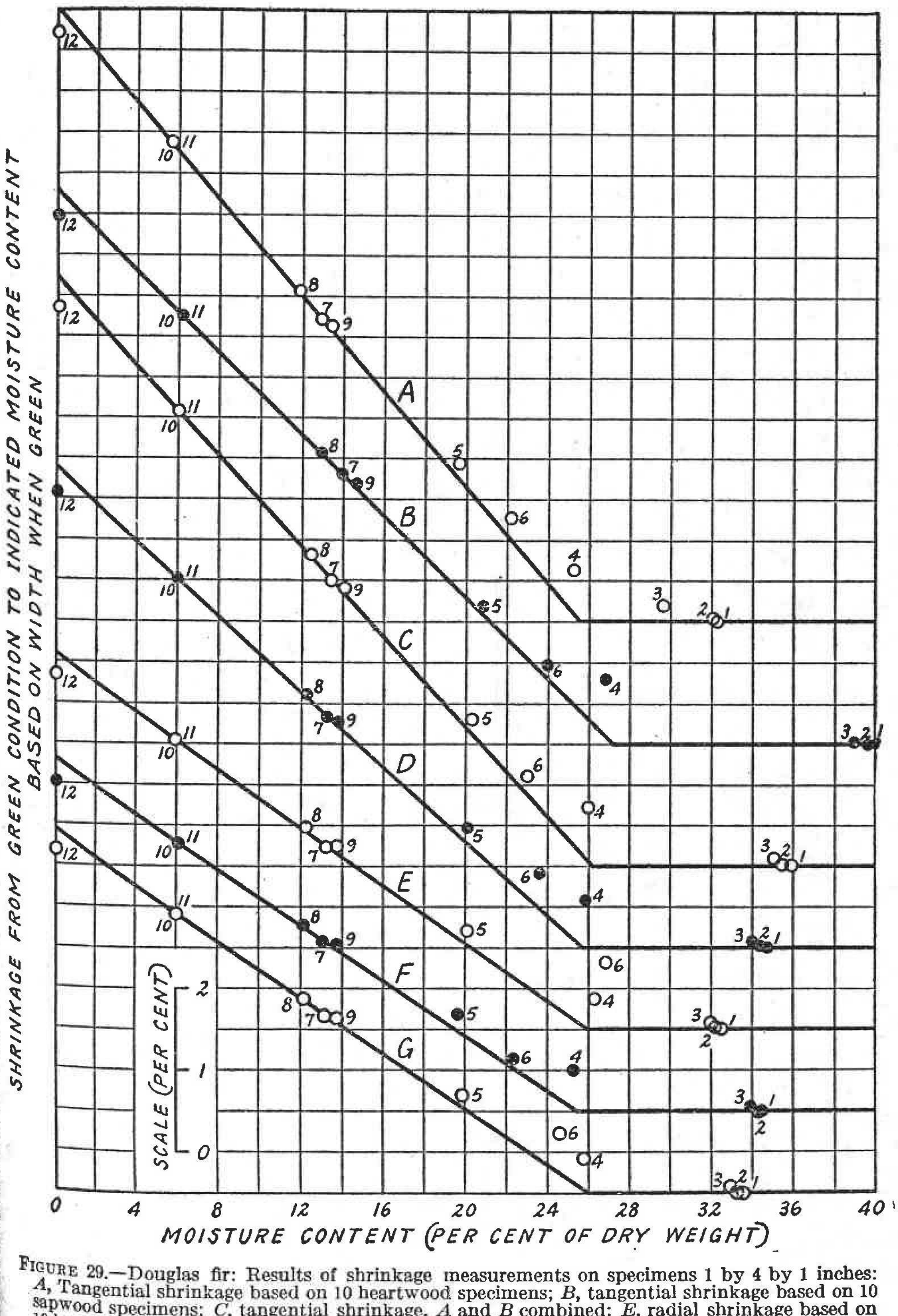

FIGURE 29.—Douglas fir: Results of shrinkage measurements on specimens 1 by 4 by 1 inches: *A*, Tangential shrinkage based on 10 heartwood specimens; *B*, tangential shrinkage based on 10 sapwood specimens; *C*, tangential shrinkage, *A* and *B* combined; *E*, radial shrinkage based on 10 heartwood specimens; *F*, radial shrinkage based on 9 specimens of mixed heartwood and sapwood averaging about 50 per cent sapwood; *G*, radial shrinkage, *E* and *F* combined; *D*, *C*, and *G* combined. Points are numbered in the order in which measurements were taken

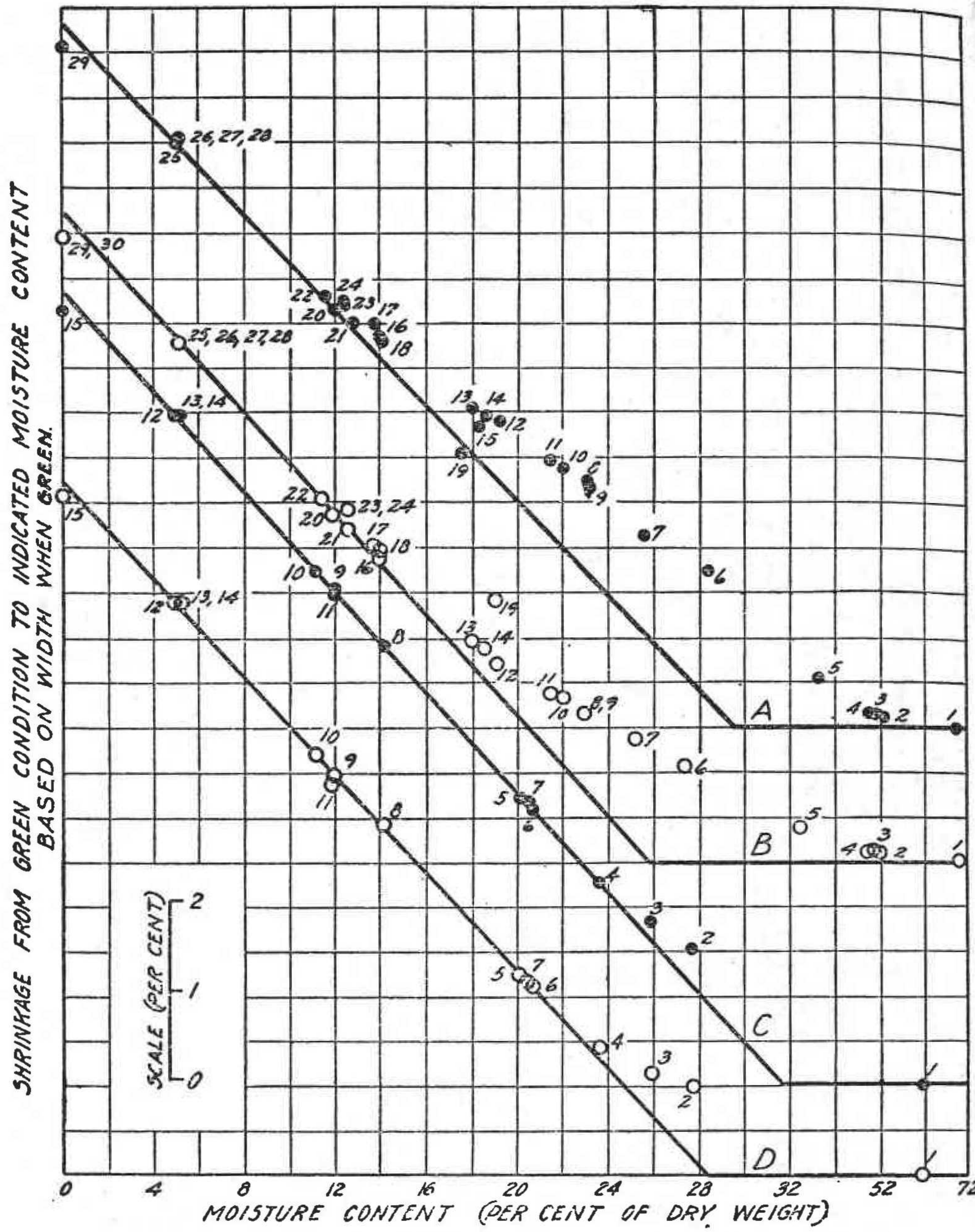

FIGURE 30.—Yellow birch: Results of shrinkage measurements: *A* and *B*, Tangential and radial shrinkages, respectively, each based on 5 specimens 1 by 4 by 1 inches; *C*, tangential shrinkage, based on 12 specimens 2 by 2 by ¼ inches; *D*, radial shrinkage, based on the same 12 specimens as at *C*. Points are numbered in the order in which measurements were taken

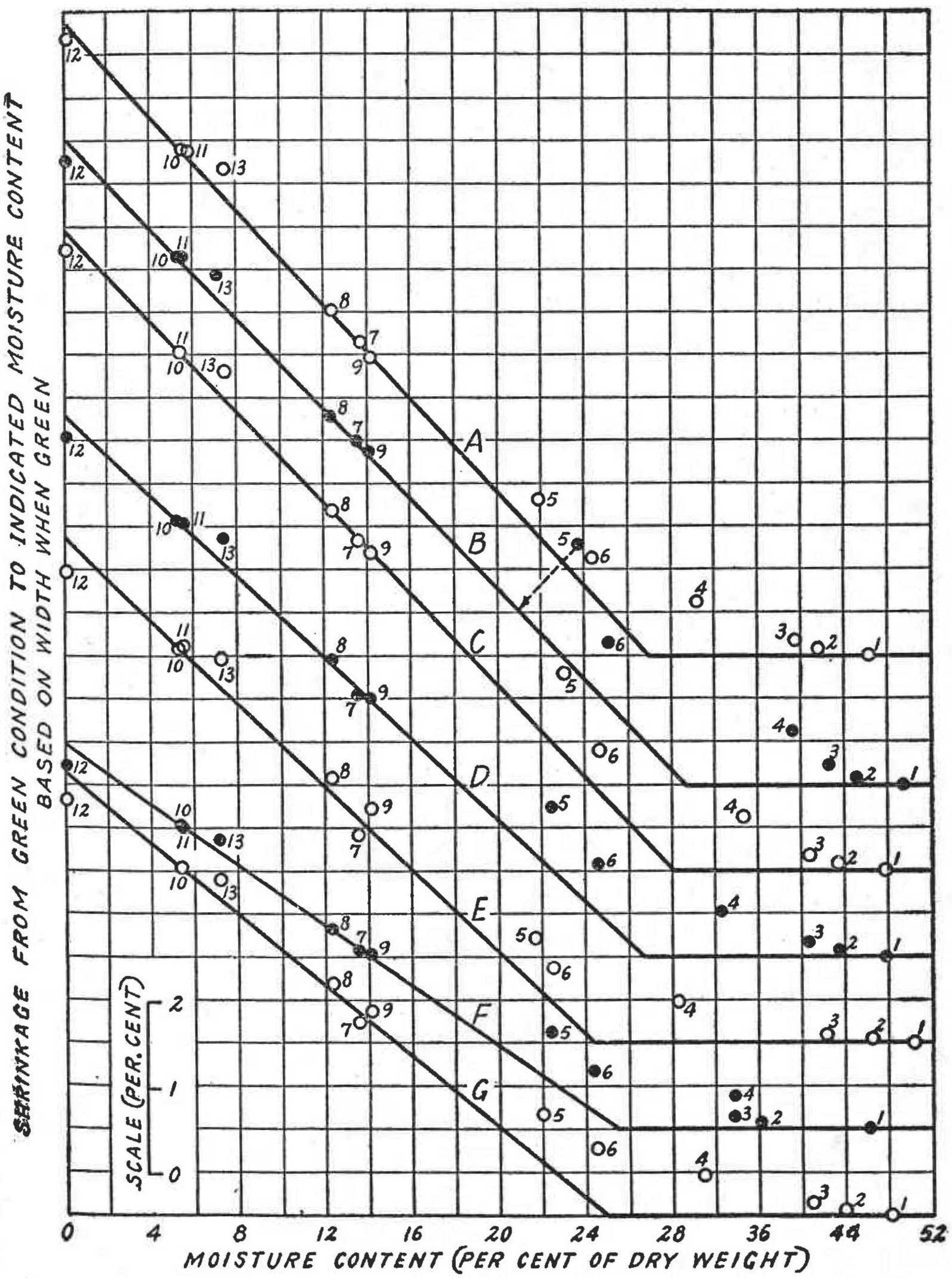

FIGURE 31.—White ash: Results of shrinkage measurements on specimens 1 by 4 by 1 inches: *A*, Tangential shrinkage based on 6 heartwood specimens; *B*, tangential shrinkage based on 6 sapwood specimens; *C*, tangential shrinkage, *A* and *B* combined; *E*, radial shrinkage based on 6 heartwood specimens; *F*, radial shrinkage based on 6 specimens of mixed heartwood and sapwood averaging about 50 per cent sapwood; *G*, radial shrinkage, *E* and *F* combined; *D*, *C*, and *G* combined. Points are numbered in the order in which measurements were taken

TABLE 19.—*Per cent moisture at intersection point as found from shrinkage measurements on specimens 1 by 4 by 1 inches*

(Averages of values found from radial and tangential shrinkages)

Common and botanical names of species	Specimens	Moisture content at intersection point
	Number	*Per cent*
Apple (Malus sp.)	31	32
Ash, white (Fraxinus americana)	23	25
Birch, yellow (Betula lutea)	9	29
Blackwood (Avicennia nitida)	4	24
Bustic (Dipholis salicifolia)	2	25
Buttonwood (Conocarpus erecta)	4	28
Cedar, red (Juniperus sp.)	4	28
Cypress, southern (Taxodium distichum)	16	27
Douglas fir, (Pseudotsuga taxifolia)	16	26
Fig, golden (Ficus aurea)	2	25
Fir:		
Noble (Abies nobilis)	16	27
California red (Abies magnifica)	12	24
Gumbo limbo (Bursera simarouba)	4	25
Gum, red (Liquidambar styraciflua)	18	32
Hemlock, western (Tsuga heterophylla)	24	23
Inkwood (Exothea paniculata)	4	32
Ironwood, black (Krugiodendron ferreum)	4	26
Khaya (Khaya sp.)	8	26
Mahogany, Central American (Swietenia sp.)	10	21
Mangrove (Rhizophora mangle)	4	25
Maple sugar (Acer saccharum)	12	28
Mastic (Sideroxylon foetidissimum)	4	22
Oak:		
Live (Quercus virginiana)	3	24
Red group (Quercus sp.)	14	33
Paradise tree (Simarouba glauca)	4	27
Pine:		
Norway (Pinus resinosa)	4	24
Sand (Pinus clausa)	4	26
Slash (Pinus caribaea)	4	25
Western white (Pinus monticola)	24	20
Northern white (Pinus strobus)	24	22
Plum, pigeon (Coccolobis laurifolia)	4	27
Poisonwood (Metopium toxiferum)	2	28
Poplar, yellow (Liriodendron tulipifera)	28	27
Spruce, Sitka (Picea sitchensis)	26	25
Redwood (Sequoia sempervirens)	10	20
Walnut, black (Juglans nigra)	21	23
Stopper, red (Eugenia confusa)	2	25

Additional values of intersection-point moisture content from shrinkage-moisture data on several coniferous species are listed in Table 20. These data are from specimens of each species selected at several sawmills located in various parts of each producing region. The specimens were seven-eighths inch thick, 5½ inches wide, and 8 inches long. They were measured and weighed before any shrinkage occurred and were then dried at 90° F. and 60 to 65 per cent relative humidity until practically constant weight and dimension were attained. The relative humidity was then reduced to about 30 per cent and the specimens dried to equilibrium, after which they were dried at a temperature of 210° and a relative humidity approaching zero. Weights and measurements were taken periodically during each of the first two stages of the drying and at the end of each of the three stages. Although the work was not done with the specific object of determining the intersection point, study of the data has indicated that they afford reasonably reliable estimates of this point. Because of the larger number of specimens involved, the values given in Table 20 are probably more accurate as averages than are those of Table 19. It may be further noted, however, that there are no very great discrepancies among Tables 18, 19, and 20 with respect to species that are common to two or to all three tables.

TABLE 20.—*Percentage of moisture at intersection point as found from shrinkage measurements on specimens ⅞ by 5½ by 8 inches*

(Averages of values found from radial and tangential shrinkages)

Common and botanical names of species	Specimens	Moisture content at intersection point
	Number	*Per cent moisture*
Cypress, southern (Taxodium distichum)	104	25
Douglas fir (Pseudotsuga taxifolia)	202	23
Fir, white (Abies concolor)	24	22
Hemlock, western (Tsuga heterophylla)	138	24
Larch, western (Larix occidentalis)	38	25
Pine:		
Loblolly [1]	100	22
Longleaf [1]	100	21
Shortleaf [1]	100	22
Sugar (Pinus lambertiana)	44	23
Western white (Pinus monticola)	80	22
Western yellow (Pinus ponderosa)	108	24
Spruce, Sitka (Picea sitchensis)	146	24
Redwood (Sequoia sempervirens)	146	21

[1] The grouping of southern yellow pine specimens into loblolly, longleaf, and shortleaf was done on the basis of the general appearance of the wood as no definite identification was possible.

FIBER-SATURATION POINTS FROM ELECTRICAL CONDUCTIVITY AND MOISTURE EQUILIBRIUM MEASUREMENTS

Physical properties and relations other than shrinkage that have been used in determining the moisture content at which a change of relation takes place include studies of electrical conductivity and studies of the moisture content of the wood in equilibrium with 100 per cent relative humidity.

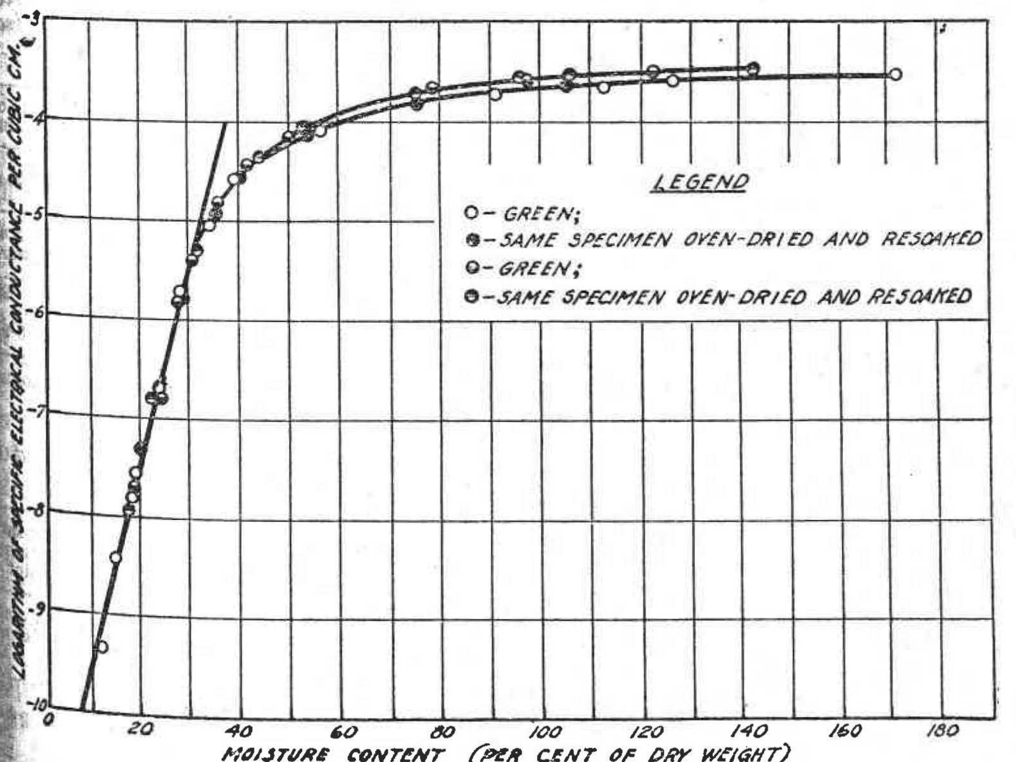

FIGURE 32.—Relation between the moisture content of redwood and its specific electrical conductance

Figure 32 exhibits the relation found between the moisture content of redwood and its specific electrical conductance (*10*). The point of departure of the data from the straight-line relation shown for low values of moisture content is assumed to be the fiber-saturation point (about 29.5 per cent in this instance).

The moisture content of wood in equilibrium with 100 per cent relative humidity has never been accurately determined because of the tremendous effect of slight changes in temperature but from the extrapolation of data taken at lower relative humidities, the equilibrium moisture content at 100 per cent can be estimated as has been done for Sitka spruce in Figure 1. Values obtained in this way are found to agree quite closely with fiber-saturation points obtained from electrical-conductivity experiments. The available fiber-saturation-point values for different species as given by the equilibrium moisture-content and electrical-conductivity methods are included in Tables 21 and 22 and are seen to be consistently higher and to spread over a much smaller range than the intersection-point values indicated by data on shrinkage and mechanical properties. The greatest difference is in redwood, for which the electrical-conductivity method gives a value for the fiber-saturation point of about 30 per cent, whereas the intersection-point values obtained from two series of shrinkage measurements are, as shown by Tables 19 and 20, 20 and 21 per cent. Some recently available data on the relation of strength properties of redwood to its moisture content indicate a value of M_p of about 21 per cent. Also the electrical conductivity method gave 30½ per cent for Douglas fir, whereas the mechanical tests indicate a value of 24 per cent for M_p of this species.

TABLE 21.—*Fiber-saturation points of Sitka spruce and redwood at room temperature as determined by relative humidity-moisture equilibrium and specific electrical conductance-moisture content relations and intersection point as determined from moisture-strength and moisture-shrinkage relations*

Method	Fiber-saturation or intersection point	
	Sitka spruce	Redwood
	Per cent moisture	*Per cent moisture*
Relative humidity-moisture content equilibrium	30.5	
Electrical conductivity	29.0	29.5
Strength tests	27.0	(1)
Shrinkage measurements	25.3	20.0-21.0

[1] Some recently available data on the relation of strength properties of redwood to its moist urecontent indicate a value of M_p of about 21 per cent.

TABLE 22.—*Fiber-saturation points of wood at 24° to 27° C. as determined by electrical conductivity*

Species of wood (heartwood specimens)	Original condition of wood	Fiber-saturation point
		Per cent moisture
Redwood	Green	29.5
Do	Resoaked after drying	29.5
Do	Hot-water extracted	31.0
Do	Alcohol extracted	31.0
Sitka spruce	Resoaked after drying	29.0
Alaska cedar	do	28.5
Western red cedar	do	30.0
Western hemlock	do	30.5
Western yellow pine	do	30.0
California red fir	do	30.0
Douglas fir	do	30.5
Yellow poplar	do	31.5

These comparisons suggest that the intersection points in such plots of moisture-strength and moisture-shrinkage data as are shown herein are not true fiber-saturation points of the respective species. However, it has been shown that a straight-line relation exists between percentage moisture, within a range somewhat below the intersection point or the fiber-saturation point, and the logarithm of the strength property. Failure of the intersection point to coincide with the true fiber-saturation point does not vitiate this relation nor render invalid its application in adjusting strength values for differences in moisture content.

SOME FURTHER CONSIDERATIONS PERTAINING TO STRENGTH-MOISTURE RELATIONS

Throughout the preceding discussion, the hypothesis that variations in moisture content have no effect on strength properties so long as the moisture content is above its fiber-saturation-point value has been tacitly accepted. The truth of this hypothesis, as far as the strength of the cell walls or other elements of the structure are concerned, follows from the definition of fiber-saturation point as stated on page 6. It has been suggested, however, that changes in moisture content above the fiber-saturation-point value may produce surface tension of the water in partially filled cell cavities sufficiently great to affect the strength properties of the wood.

Evidence exists that a different effect obtains when wood is thoroughly saturated and the cell cavities are completely filled with water. Deformation produced by the application of external forces may then cause sufficient hydraulic pressure within the cavities to stress and possibly disrupt the cell structure. No tests have been made with the specific object of studying this effect. Evidence that it operates to weaken wood with respect to strength in compression at right angles to grain is afforded by the observation that in static-bending tests more severe crushing occurs at load and support points when the wood has a very high moisture content than when its moisture content is lower but above the fiber-saturation-point value. Similar effects have been observed in the testing of wood heavily impregnated with creosote. Observation that buckling failures in the steam bending of wood are more common when the moisture content is very great affords further evidence of the action of hydraulic pressure within the cell cavities. Since, as is indicated by Figure 1, the fiber-saturation-point moisture content decreases as the temperature increases, the heating of the wood to near the boiling-point temperature, as is ordinarily done in steam bending, may cause some of the water that is "imbibed" or "bound" at lower temperatures to be released and to be added to the previously existing "free" water within the cavities. Also the bending operation causes comparatively large deformations; frequently as much as 10 or 12 per cent and in extreme cases as much as 25 per cent or more. Consequently, hydraulic pressure may be set up within the cell cavities even when these cavities are not filled with water at the beginning of the operation.

Increase in the strength of wood with decrease in moisture content may be considered to be the resultant of two factors: (1) Actual strengthening and stiffening of the elements of the wood structure; (2) increase in the compactness of the wood structure because of the shrinkage that accompanies loss of moisture. The effects of these two factors are combined in the data considered herein. No satisfactory method of separating these effects has been found.

Experiments have indicated that the specific gravity of wood substance, that is, the material of which the cell walls are composed, varies but little among several species of wood (*3*, *9*). Consequently, differences in specific gravity of wood substance would be expected to have but little effect on the amount of moisture at the fiber-saturation point and would probably have no effect on the percentage of moisture at that point or on the increase in strength brought about by loss of moisture. Furthermore, as far as is known, the differences among species with respect to chemical composition are apparently not sufficient to account for any very wide variations in percentage of moisture at the fiber-saturation point or in the increase in strength produced in drying.

The data of Tables 21 and 22 indicate that there are no wide variations in fiber-saturation-point moisture content as determined by electrical-conductivity and moisture-equilibrium methods. Discrepancies between fiber-saturation-point values as determined by these two methods and the intersection-point values from strength tests are possibly due to the effect of the size and arrangement of elements of the wood structure on the intersection point. An indication of a relation between structure and intersection-point moisture content has been discussed on page 46. Table 23, which is based on data from Table 17, affords an indication of relation between the structure of the wood and the computed ratio of strength at zero moisture content to strength in the green condition. The species are arranged in order of decreasing ratio for maximum crushing strength, which it will be noted is closely paralleled by the ratio for modulus of rupture. Yellow birch, a diffuse porous hardwood heads the list. Next come five coniferous species, followed by two ring-porous hardwoods. Greenheart, an exotic species of very high specific gravity, is last. Except for red spruce, there is but little variation among the coniferous species with respect to the ratios listed, in spite of the fact that longleaf pine, loblolly pine, and Douglas fir, which have very distinct summer wood, and Sitka spruce, which has much less distinct summer wood, are included. In general, it may be said that there are distinct differences among the species as grouped in Table 23 with respect to the ratios shown in the last two columns.

TABLE 23.—*Computed ratios of strength at zero moisture content to strength in the green conditions*

Species	Ratio of strength at zero moisture content to strength in the green condition	
	Maximum crushing strength	Modulus of rupture
Group I: Yellow birch	5.20	3.45
Group II:		
Red spruce	4.19	----------
Longleaf pine	3.47	2.77
Douglas fir	3.47	2.70
Sitka spruce	3.47	2.49
Loblolly pine	3.31	----------
Group III:		
Chestnut	3.26	2.08
White ash	3.16	2.14
Group IV: Greenheart	1.99	----------

VARIABILITY OF K AND TABLE OF ADDITIONAL VALUES

Inspection of Table 17 suggests that K is less variable than the strength values. For example, considering data from compression-parallel-to-grain tests on individual trees of Douglas fir, the highest and lowest values of maximum crushing strength of green material are 4,150 and 3,330 pounds per square inch, respectively, giving a ratio of highest to lowest of 1.25 to 1, whereas highest and lowest values of K for this property are 0.0238 and 0.0211, giving a ratio of 1.13 to 1. Also consideration of the values of maximum crushing strength and corresponding values of K among the several species represented in Table 17 shows that the tabulated values of K are considerably less variable than the strength property. It is quite probable that among averages for different species, the value of K for any strength property is less variable than the strength property itself. Other data indicate, however, that a similar situation may not obtain with respect to different lots of material of the same species. At any rate, it has been found that strength properties of a species vary over a considerable range, their values being different in different trees and in different parts of the same trees. Accordingly, it is to be expected that the value of K for any property of any species will likewise be subject to variation, and consequently, in attempting to set up average values of K, it is desirable that all available data be considered.

Figure 17, in which moisture-strength data are presented for different specific-gravity classes of wood of the same species, affords little indication of correlation between specific gravity and K. Values of K as found from the data of this figure are given in Table 9.

A similar study shows (1) that approximately the same value of K applies to the three higher specific-gravity classes of Douglas fir, whereas that for the lowest specific-gravity class of this species is distinctly lower and (2) that practically the same value of K applies to the four specific-gravity classes of yellow birch.

The Sitka spruce individual-tree values of specific gravity and of K for maximum crushing strength and for modulus of rupture as shown in Table 17 afford an indication that K increases as specific gravity decreases. Values given in the same table for Douglas fir and yellow birch indicate that K for modulus of rupture increases as the specific gravity increases, whereas no correlation between K for maximum crushing strength of Douglas fir and its specific gravity is indicated. In none of these instances, however, is the change in K with change in specific gravity consistent, and no close correlation is indicated.

Additional data for the determinations of values of K are afforded by results of a standard series of strength tests on American species that have been made at the Forest Products Laboratory (*6*, *7*). In this series tests were made on green and seasoned specimens from similar locations in the same trees. From these tests, values of K can be derived for those species for which M_p has been determined. Such values are listed in Table 24 for several properties of several species.

TABLE 24.—*Compilation of values of K*

Species	*Mp*	Weighting factor [1]	Specimens [2]	Moisture content of seasoned material	Values of *K*: Compression parallel to grain: Fiber stress at elastic limit	Compression parallel to grain: Maximum crushing strength	Static bending: Fiber stress at elastic limit	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Work to elastic limit	Static bending: Work to maximum load	Impact bending: Fiber stress at elastic limit	Impact bending: Work to elastic limit	Impact bending: Maximum drop	Compression perpendicular to grain (fiber stress at elastic limit)	Hardness: End	Hardness: Side	Shear (average of radial and tangential)
			Number	*Per cent*														
Ash:																		
Biltmore white	[3] 24		71	5.4		0.0223	0.0186	0.0122	0.0066	0.0297	0.0002	0.0118	0.0174	0.0102	0.0198	0.0185	0.0107	0.0113
Blue	[3] 24		48	9.6		.0185	.0129	.0129	.0042	.0216	-.0009	.0180	.0219	-.0009	.0205	.0149	.0082	.0100
Green	[3] 24		53	11.2		.0201	.0239	.0149	.0069	.0406	.0057	.0102	.0097	.0000	.0163	.0225	.0149	.0131
			43	9.6		.0177	.0146	.0143	.0052	.0242	.0034	.0155	.0211	-.0059	.0241	.0164	.0089	.0169
White	24		27	10.5		.0201	.0234	.0186	.0103	.0362	.0074	.0079	.0092	.0013	.0127	.0198	.0109	.0153
			26	9.5		.0213	.0217	.0160	.0058	.0378	.0011	.0159	.0223	-.0006	.0276	.0189	.0121	.0127
			48	6.9		.0232	.0187	.0167	.0069	.0304	-.0005	.0121	.0188	-.0005	.0233	.0189	.0113	.0130
			14	12.2		.0264	.0170	.0186	.0076	.0270	-.0022	-.0218	-.0276	-.0030	.0167	.0222	.0117	.0063
			10	11.6		.0219	.0174	.0163	.0046	.0294	.0046	.0121	.0173	.0240	.0181	.0173	.0097	.0142
		5				.0208	.0148	.0138	.0066	.0206	-.0057			-.0026	.0238			.0155
Average						.0217	.0172	.0155	.0068	.0264	-.0018	.0052	.0080	.0008	.0217	.0194	.0111	.0139
Average [3] (biltmore white, blue, green, and white)						.0211	.0173	.0150	.0065	.0271	-.0007	.0091	.0122	.0008	.0213	.0188	.0109	.0136
Birch, yellow	27		34	10.3	0.0273	.0268	.0303	.0219	.0106	.0496	.0060	.0131	.0199	.0100	.0293	.0158	.0136	.0054
			43	9.0	.0242	.0250	.0202	.0180	.0074	.0322	.0043	.0167	.0201	.0087	.0273	.0175	.0150	.0179
			24	11.1	.0181	.0250	.0308	.0216	.0063	.0526	.0198	.0079	.0068	-.0032	.0164	.0204	.0129	.0171
			22	11.1		.0250	.0241	.0194	.0051	.0420	.0003	.0061	.0060	-.0020	.0141	.0209	.0181	.0193
			8	11.2	.0256	.0245	.0248	.0185	.0073	.0421	.0067	.0028	-.0040	-.0037	.0190	.0135	.0071	.0196
			29	11.3	.0243	.0270	.0243	.0252	.0143	.0338	.0146	.0084	.0036	.0005	.0176	.0198	.0150	.0244
			16	11.1	.0237	.0223	.0232	.0174	.0032	.0427	.0081	.0035	.0005	-.0032	.0219	.0170	.0132	.0159
		8				.0265	.0194	.0199	.0045		.0065			.0015	.0216			.0131
Average					.0239	.0258	.0222	.0201	.0060	.0421	.0075	.0084	.0076	.0013	.0212	.0178	.0136	.0150
Chestnut	24		7	7.4	.0247	.0234	.0226	.0173	.0109	.0343	-.0031				.0217			.0159
			8	8.0	.0236	.0232	.0260	.0199	.0090	.0427	.0067	.0098	.0170	.0000	.0268	.0155	.0127	.0077
			8	9.2	.0296	.0223	.0219	.0133	.0121	.0319	-.0176	.0089	.0087	-.0131	.0232	.0128	.0052	.0101
			7	10.1	.0220	.0253	.0193	.0166	.0154	.0195	-.0072	.0153	.0210	-.0019				.0096

			52	9.0	.0252	.0309	.0259	.0184	.0097	.0415	.0023	.0168	.0283	−.0104	.0279	.0179	.0108	.0155
			77	8.3	.0213	.0290	.0253	.0146	.0091	.0416	−.0061	.0063	.0102	−.0026	.0170	.0075	.0062	.0123
			21	9.4	.0149	.0237	.0206	.0139	.0090	.0314	−.0006	.0139	.0228	−.0047	.0242	.0055	.0073	.0067
			22	8.2	.0233	.0275	.0287	.0160	.0085	.0488	−.0048	.0066	.0196	−.0098	.0247	.0117	.0098	.0101
			24	8.4	.0189	.0255	.0287	.0144	.0105	.0446	−.0056	.0102	.0134	.0030	.0302	.0107	.0097	.0074
			23	8.9	.0209	.0278	.0211	.0139	.0132	.0304	−.0070	.0102	.0168	−.0060	.0310	.0093	.0097	.0079
			22	8.1	.0290	.0257	.0271	.0152	.0139	.0403	.0005	.0076	.0111	−.0185	.0260	.0065	.0091	.0096
			21	8.6	.0274	.0290	.0263	.0194	.0109	.0408	.0019	.0129	.0154	.0000	.0251	.0076	.0080	.0131
			22	9.9	.0275	.0280	.0246	.0177	.0082	.0417	.0006	.0046	.0035	−.0023	.0158	.0049	.0062	.0112
			23	9.2	.0252	.0271	.0194	.0104	.0088	.0311	.0009	.0090	.0129	.0025	.0232	.0155	.0102	.0096
			24	10.2	.0161	.0261	.0243	.0157	.0088	.0409	−.0022	.0131	.0242	.0038	.0228	.0127	.0082	.0074
			23	8.0	.0272	.0287	.0296	.0205	.0118	.0476	.0013	.0073	.0157	−.0182	.0310	.0167	.0127	.0101
		10				.0214	.0187	.0132	.0068									
		5				.0218												
Average					.0236	.0241	.0222	.0150	.0091	.0381	−.0025	.0102	.0160	−.0052	.0247	.0111	.0090	.0103
Douglas fir	24		82	6.5		.0256	.0218	.0181	.0086	.0348	.0112	.0132	.0205	.0123	.0268	.0173	.0131	.0095
			38	6.8		.0282	.0197	.0163	.0110	.0286	.0047	.0117	.0160	.0057	.0053	.0133	.0158	.0096
			80	6.0		.0246	.0215	.0168	.0066	.0366	.0071	.0126	.0161	.0102	.0204	.0121	.0098	.0085
			70	5.9		.0228	.0195	.0153	.0063	.0326	.0061	.0125	.0218	.0110	.0230	.0125	.0098	.0059
			79	6.8		.0248	.0215	.0170	.0070	.0362	.0123	.0087	.0101	.0126	.0137	.0133	.0110	.0091
			105	11.6		.0230	.0208	.0182	.0055	.0353	.0144	.0125	.0154	.0120	.0273	.0096	.0091	.0142
			81	11.4		.0241	.0232	.0193	.0065	.0384	.0178	.0072	.0086	.0049	.0298	.0137	.0100	.0145
			72	11.1		.0188	.0155	.0174	.0057	.0251	.0128	.0072	.0092	.0000	.0240	.0108	.0082	.0071
			27	12.1		.0208	.0145	.0166	.0090	.0182	.0105	.0046	.0000	.0078	.0284	.0176	.0159	−.0052
			55	11.4		.0207	.0209	.0200	.0063	.0326	.0186	.0138	.0090	.0087	.0384	.0234	.0127	.0000
			55	12.2		.0164	.0194	.0171	.0059	.0320	.0098	.0052	−.0084	.0068	.0260	.0184	.0125	.0021
			25	11.8		.0135	.0119	.0155	.0051	.0190	.0102	.0007	−.0069	−.0004	.0147	.0151	.0099	−.0004
			59	6.2		.0246	.0189	.0167	.0075	.0304	.0143	.0095	.0167	.0079	.0231	.0129	.0090	.0096
		5				.0225	.0200	.0160	.0063	.0326	.0058			.0062	.0234			.0091
			44	9.8		.0259	.0282	.0197	.0045	.0518	.0080	.0082	.0156	.0055	.0223	.0137	.0133	.0133
			41	9.3		.0256	.0238	.0190	.0079	.0395	.0160	.0091	.0124	.0117	.0169	.0095	.0120	.0112
			40	9.9		.0281	.0224	.0198	.0067	.0382	.0142	.0108	.0160	.0073	.0310	.0103	.0105	.0152
			39	9.9		.0263	.0270	.0205	.0070	.0462	.0082	.0137	.0220	.0050	.0162	.0158	.0119	.0098
			40	9.9		.0248	.0247	.0160	.0059	.0429	.0006	.0136	.0206	.0062	.0224	.0096	.0075	.0074
			49	9.9		.0255	.0279	.0156	.0065	.0485	−.0026	.0095	.0121	.0066	.0259	.0101	.0083	.0096
			43	9.6		.0276	.0277	.0214	.0084	.0465	.0104	.0114	.0205	.0112	.0248	.0112	.0125	.0121
			19	12.9		.0265	.0198	.0150	.0081	.0328	−.0040				.0219	.0210	.0144	.0184
			50	6.8		.0244	.0188	.0144	.0079	.0280	.0007	.0118	.0198	.0088	.0223	.0120	.0142	.0021
Average						.0235	.0211	.0172	.0069	.0347	.0085	.0099	.0127	.0074	.0230	.0138	.0114	.0085

[1] Numerals in this column are on lines giving values of K derived from data presented in Figures 8 to 25 and indicate the number of trees or series of specimens. Each such line of values was weighted according to this number in averaging. Each other line of values is based on tests from a single tree and was given unit weight in averaging.

[2] Number of specimens in each of the two conditions, green and seasoned, on which determinations of maximum crushing strength were made. The number of static bending specimens is about one-half and that for fiber stress at elastic limit, compression perpendicular to grain, end hardness, and side hardness each one-fourth as great. The number of impact bending and shear specimens varies, being usually at least four for impact bending and three each for radial and tangential shear.

[3] As Biltmore white, blue, green, and white ashes are very similar botanically and in many strength properties, the value of Mp determined from tests of white ash has been assumed to apply to each of the other three species, and values of K have been combined to form averages for this group of species.

TABLE 24.—*Compilation of values of K*—Continued

Species	*Mp*	Weighting factor	Specimens	Moisture content of seasoned material	Values of *K*: Compression parallel to grain: Fiber stress at elastic limit	Compression parallel to grain: Maximum crushing strength	Static bending: Fiber stress at elastic limit	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Work to elastic limit	Static bending: Work to maximum load	Impact bending: Fiber stress at elastic limit	Impact bending: Work to elastic limit	Impact bending: Maximum drop	Compression perpendicular to grain (fiber stress at elastic limit)	Hardness: End	Hardness: Side	Shear (average of radial and tangential)
			Number	*Per cent*														
Pine, loblolly	21		31	7.1	0.0360	0.0351	0.0314	0.0237	0.0088	0.0530	0.0091	0.0197	0.0290	0.0022	0.0337	0.0322	0.0189	0.0215
			41	7.8	.0336	.0360	.0314	.0239	.0125	.0486	.0057	.0124	.0175	-.0134	.0373	.0293	.0190	.0210
			23	5.5	.0241	.0325	.0280	.0224	.0166	.0391	-.0009	.0101	.0151	-.0135	.0326	.0302	.0202	.0167
			23	5.7	.0292	.0323	.0256	.0205	.0113	.0398	.0025	.0124	.0162	-.0027	.0296	.0235	.0167	.0178
			24	11.2	.0335	.0362	.0320	.0299	.0095	.0542	.0164	.0168	.0206	-.0087	.0289	.0204	.0201	.0195
			24	11.4	.0365	.0331	.0397	.0267	.0077	.0718	.0099	.0165	.0168	.0039	.0271	.0292	.0306	.0241
			19	11.5	.0173	.0383	.0316	.0259	.0107	.0519	.0068	.0202	.0224	.0078	.0297	.0210	.0288	.0190
			22	11.3	.0232	.0342	.0351	.0298	.0113	.0564	.0170	.0221	.0243	.0033	.0324	.0205	.0248	.0146
			24	11.1	.0461	.0339	.0371	.0287	.0092	.0634	.0096	.0221	.0298	.0055	.0321	.0259	.0261	.0217
			29	11.2	.0373	.0352	.0377	.0300	.0136	.0595	.0126	.0203	.0235	.0058	.0346	.0358	.0181	.0201
			19	11.2	.0351	.0333	.0322	.0264	.0152	.0479	.0035	.0109	.0091	-.0012	.0511	.0234	.0188	.0238
			24	11.1	.0416	.0351	.0357	.0296	.0089	.0632	.0169	.0191	.0216	.0116	.0280	.0312	.0176	.0229
			18	11.0	.0223	.0289	.0383	.0310	.0185	.0562	.0111	.0123	.0133	.0048	.0292	.0132	.0069	.0179
			24	10.7	.0142	.0315	.0315	.0259	.0135	.0590	.0169	.0077	-.0026	.0200	.0356	.0196	.0116	.0145
			33	11.9	.0233	.0355	.0413	.0307	.0144	.0681	.0144	.0156	.0130	.0073	.0528	.0331	.0232	.0230
			26	12.2	.0334	.0378	.0384	.0322	.0125	.0566	.0193	.0236	.0347	.0000	.0422	.0250	.0250	.0219
			29	11.8	.0415	.0375	.0359	.0310	.0138	.0578	.0207	.0154	.0174	.0009	.0424	.0344	.0231	.0256
			28	12.0	.0291	.0370	.0317	.0257	.0100	.0530	.0100	.0152	.0118	-.0005	.0417	.0357	.0239	.0185
			24	12.2	.0572	.0326	.0311	.0220	.0138	.0458	-.0026	.0144	.0109	-.0053	.0607	.0365	.0170	.0174
			25	12.1	.0328	.0337	.0423	.0272	.0095	.0736	.0114	.0125	.0083	.0029	.0470	.0239	.0185	.0168
			24	12.0	.0358	.0338	.0419	.0282	.0082	.0738	.0060	.0194	.0200	.0015	.0521	.0272	.0199	.0242
			30	12.5	.0259	.0339	.0421	.0314	.0097	.0728	.0175	.0123	.0107	.0103	.0293	.0265	.0302	.0164
			28	12.2	.0347	.0327	.0405	.0278	.0067	.0710	.0080	.0163	.0188	-.0005	.0365	.0333	.0223	.0182
			38	12.3	.0310	.0339	.0454	.0310	.0096	.0806	.0163	.0189	.0220	-.0032	.0512	.0342	.0268	.0137
			34	13.2	.0268	.0413	.0235	.0307	.0167	.0300	.0137	.0150	.0137	-.0023	.0176	.0221	.0233	.0255
			32	12.7	.0398	.0361	.0186	.0266	.0130	.0238	.0094	.0030	-.0033	.0050	.0022	.0183	.0190	.0200
			38	12.0	.0309	.0334	.0313	.0286	.0148	.0480	.0166	.0152	.0141	-.0056	.0110	.0256	.0232	.0218
			38	12.2	.0284	.0371	.0316	.0293	.0133	.0493	.0208	.0176	.0176	.0035	.0120	.0271	.0274	.0252
			40	12.1	.0200	.0326	.0277	.0296	.0153	.0395	.0112	.0111	.0054	-.0016	.0345	.0235	.0168	.0239
			31	12.0	.0239	.0297	.0278	.0288	.0182	.0380	.0139	.0150	.0134	-.0037	.0259	.0224	.0169	.0229
		5				.0247												
Average					.0315	.0331	.0339	.0278	.0122	.0549	.0114	.0156	.0162	.0011	.0341	.0268	.0212	.0203

Pine, longleaf	21		54	12.0	.0270	.0309	.0317	.0236	.0093	.0594	.0199	.0221	.0349	-.0056	.0505	.0220	.0205	.0235
			44	7.4	.0255	.0338	.0279	.0221	.0115	.0441	.0117	.0143	.0196	-.0025	.0316	.0298	.0212	.0112
			41	6.2	.0215	.0313	.0276	.0227	.0119	.0431	.0115	.0185	.0284	.0009	.0341	.0293	.0219	.0163
			37	6.7	.0294	.0321	.0281	.0254	.0123	.0439	.0150	.0156	.0210	.0038	.0423	.0257	.0196	.0225
			37	7.4	.0304	.0356	.0280	.0244	.0136	.0427	.0162	.0179	.0244	.0000	.0400	.0262	.0238	.0168
			28	6.8	.0321	.0341	.0290	.0231	.0128	.0450	.0072	.0105	.0166	-.0045	.0277	.0221	.0137	.0139
			26	7.6	.0311	.0319	.0287	.0224	.0097	.0477	.0104	.0099	.0142	-.0015	.0248	.0198	.0118	.0061
			24	12.8	.0159	.0307	.0227	.0298	.0193	.0241	.0189	.0436	.0741	.0078	.0118	.0208	.0223	.0182
			24	12.7	.0091	.0329	.0284	.0316	.0128	.0438	.0238	.0334	.0525	.0016	.0383	.0117	.0227	.0167
			14	12.7	.0424	.0307	.0248	.0283	.0144	.0347	.0144	.0181	.0193	.0136		.0146	.0163	.0110
			15	12.5	.0234	.0321	.0223	.0258	.0077	.0373	.0136	.0136	.0058	-.0115	.0458	.0189	.0242	.0269
			8	13.0	.0411	.0352	.0339	.0282	.0061	.0596	.0117	.0373	.0639	.0131	.0585	.0178	.0143	.0248
			20	14.0	.0385	.0357	.0313	.0278	.0115	.0510	.0144	.0289	.0434	.0048	.0394	.0230	.0255	.0288
			16	13.8	.0228	.0345	.0358	.0312	.0117	.0592	.0172	.0268	.0392	-.0062	.0572	.0297	.0191	.0236
			8	13.1	.0362	.0299	.0167	.0270	.0130	.0202	.0163	.0342	.0586	-.0087	.0296			.0255
			24	13.9	.0295	.0341	.0265	.0300	.0118	.0412	.0233	.0330	.0552	.0084	.0275	.0247	.0228	.0136
			28	13.5	.0350	.0315	.0189	.0279	.0131	.0234	.0126	.0307	.0491	-.0048	.0176	.0245	.0196	.0183
			26	11.0	.0318	.0318	.0283	.0308	.0308	.0455	.0265	.0248	.0365	.0004	.0238	.0183	.0209	.0264
			24	11.1	.0431	.0315	.0271	.0270	.0125	.0410	-.0027	.0253	.0369	-.0053	.0085	.0287	.0205	.0290
			23	12.9	.0309	.0338	.0274	.0258	.0081	.0465	.0005	.0226	.0344	-.0172	.0254	.0210	.0161	.0283
			23	12.3	.0318	.0355	.0376	.0320	.0157	.0588	.0154	.0276	.0439	-.0015	.0303	.0259	.0249	.0324
			23	12.3	.0467	.0362	.0348	.0326	.0117	.0569	.0250	.0239	.0390	.0009	.0516	.0253	.0231	.0250
			22	11.8	.0234	.0302	.0250	.0287	.0087	.0382	.0271	.0268	.0412	-.0042	.0297	.0261	.0214	.0292
			11	12.6	.0326	.0337	.0215	.0265	.0043	.0394	.0109	.0225	.0367	.0039	.0425	.0175	.0094	.0243
			16	11.4	.0355	.0339	.0234	.0294	.0122	.0336	.0234	.0272	.0327	.0049	.0294	.0178	.0155	.0288
			8	11.4	.0311	.0337	.0217	.0180	.0024	.0411	-.0127	.0236	.0286	.0024	.0446	.0152	.0082	.0233
			14	11.2	.0365	.0323	.0253	.0262	.0120	.0383	.0174	.0274	.0368	-.0021	.0233	.0340	.0218	.0141
		6				.0257	.0245	.0210	.0062	.0396								.0157
		5				.0207												
Average					.0309	.0302	.0267	.0259	.0103	.0422	.0144	.0244	.0366	-.0003	.0341	.0227	.0193	.0204
Spruce, Sitka	27		116	8.9		.0192	.0208	.0171	.0073	.0334	-.0115	.0133	.0175	-.0031	.0266	.0087	.0098	.0098
			281	12.7		.0228	.0238	.0167	.0087	.0257	.0118	.0073	.0055	-.0019	.0317	.0193	.0146	.0174
			115	12.2		.0235	.0180	.0152	.0053	.0291	.0108	.0090	.0092	.0047	.0232	.0175	.0113	.0173
			161	12.6		.0217	.0200	.0155	.0062	.0389	.0079	.0041	.0030	.0033	.0305	.0239	.0140	.0179
			183	13.1		.0210	.0170	.0162	.0067	.0271	.0070	.0083	.0085	-.0019	.0247	.0185	.0130	.0168
			23	11.3		.0256	.0232	.0216	.0128	.0339	.0132	.0088	.0071	-.0030	.0125	.0136	.0122	.0126
			34	11.3		.0236	.0177	.0173	.0080	.0267	.0105	.0070	.0048	-.0008	.0162	.0147	.0140	.0094
			144	10.0		.0205	.0205	.0165	.0059	.0346	.0095	.0057	.0035	.0097	.0176	.0140	.0068	.0098
			120	10.0		.0228	.0224	.0182	.0058	.0380	.0151	.0058	.0032	.0043	.0204	.0273	.0156	.0084
		5				.0200	.0161	.0147	.0060	.0260	.0099			.0027	.0187			.0072
Average						.0215	.0188	.0163	.0069	.0298	.0105	.0077	.0069	.0020	.0212	.0175	.0124	.0111
Spruce, red	27		57	7.5		.0237	.0209	.0163	.0058	.0357	.0078	.0175	.0248	.0112	.0163	.0126	.0095	.0102
			40	8.0		.0230	.0194	.0158	.0042	.0333	.0062	.0118	.0161	.0066	.0149	.0073	.0086	.0041
		5				.0234												
		11				.0229												
		5				.0217												
Average						.0228	.0202	.0160	.0050	.0345	.0070	.0146	.0204	.0089	.0156	.0100	.0090	.0072

The method of computing the values of K listed in Table 24 will be evident from examples presented later. (Examples 1–A and 1–B, p. 69.) The computed values are shown in detail rather than by averages alone in order to afford further information on the variability of K. It appears from inspection that K for any one species and property varies through a considerable range. Two causes of the variation exhibited are: (1) K actually varies for different trees and different lots of material; (2) specimens tested in the seasoned condition did not exactly match the green specimens. It is impossible to determine how much of the variation in computed values is due to each of these causes. In Table 24 the kinds of tests are arranged approximately in the order of the number of specimens. The largest number of specimens were tested in compression parallel to grain, about one-half as many in static bending, about one-fourth as many in compression perpendicular to grain and hardness, and, on an average, a yet smaller number in impact bending and shear. Inspection indicates that the tabulated values of K are less variable for those properties represented by the larger number of tests and that the variability increases as the number of tests decreases. This suggests that if green and seasoned specimens were in all cases perfectly matched the variability in values of K would be considerably reduced. The lack of perfect matching is a compensating factor probably causing the values to be too high as often as too low so that its effect on average values is probably quite small.

USE OF THE EXPONENTIAL FORMULA IN THE ADJUSTMENT OF STRENGTH VALUES

The following methods of adjusting strength values for differences in moisture content are based on the exponential formula which implies a straight-line relation between the percentage moisture content and the logarithm of the strength property. All problems of adjustment are covered by two cases as follows:

CASE 1.—Strength values derived from matched specimens tested at two different moisture-content values are known, and the value at some third moisture-content value is desired.

CASE 2.—The strength value at only one moisture-content value is known, and that at a second is desired.

Formulas for use in either of these cases can readily be derived from equations already given (9) and the adjusted values computed by the use of a slide rule or a table of logarithms. The computations, however, can be handled very easily by graphical methods on semilogarithmic paper [13] or specially prepared diagrams. The use of graphical methods and of the corresponding formulas can best be explained by examples under each case.

EXAMPLES OF CASE 1

EXAMPLE 1–A

United States Department of Agriculture Bulletin 556 (7) gives the maximum crushing strength of Sitka spruce in compression parallel

[13] Semilogarithmic paper has a series of vertical lines uniformly spaced and a series of horizontal lines spaced according to the logarithms of numbers.

to grain as 2,600 and 5,770 pounds per square inch in the green condition and at 8.9 per cent moisture, respectively. What would have been the maximum crushing strength if tests had been made at 12 per cent moisture? The solution is shown in the lower part of Figure 33, where 5,770 is plotted at 8.9 per cent moisture and 2,600 at 27 per cent, which as shown by Table 17, is the value of M_p for Sitka spruce. The line connecting these points crosses the vertical representing 12 per cent moisture at 5,020, which is the value of maximum crushing strength adjusted to 12 per cent.

This procedure is the graphical solution of the following formula:

$$\text{Log } S_3 = \log S_1 + \frac{M_1 - M_3}{M_1 - M_2} (\log S_2 - \log S_1) \qquad (10)$$

Where S_1 and M_1 are one pair of corresponding strength and moisture-

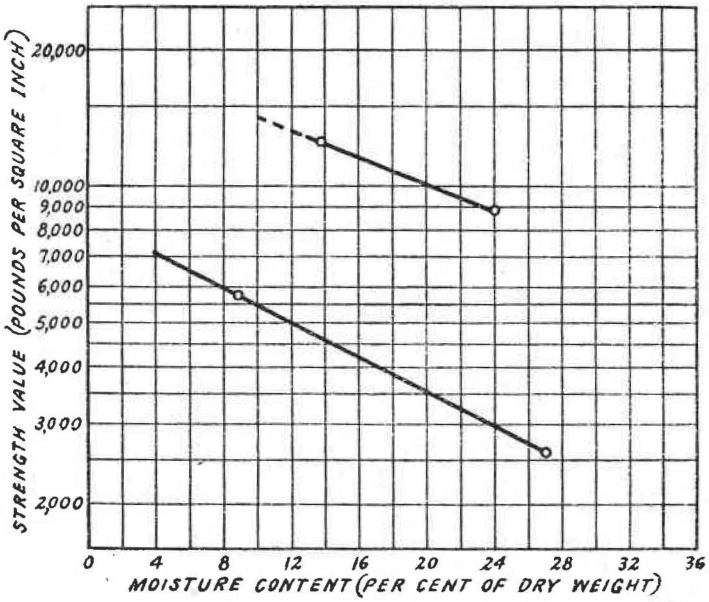

FIGURE 33.—Graphical solution of Examples 1-A and 1-B

content values as found from test, S_2 and M_2 are another pair, and S_3 is the strength value adjusted to moisture content M_3. In this example $S_1 = 2{,}600$, $M_1 = 27$, $S_2 = 5{,}770$, $M_2 = 8.9$, $M_3 = 12.0$, and the solution gives $S_3 = 5{,}030$ pounds per square inch.

Formula (10) is derived as follows. Equation 9 may by permutation of subscripts be written:

$$\text{Log } S_2 = \log S_p + K (M_p - M_2) \qquad (a)$$
$$\text{Log } S_1 = \log S_p + K (M_p - M_1) \qquad (b)$$
$$\text{Log } S_3 = \log S_1 + K (M_1 - M_3) \qquad (c)$$

Subtracting (*b*) from (*a*) and solving—

$$K = \frac{\log S_2 - \log S_1}{M_1 - M_2}$$

and equation (10) results when this value of K is substituted in (c).

The numerical computation by formula (10) is as follows:

Log 5,770 =	3.7612
Log 2,600 =	3.4150
Log 5,770 − log 2,600 =	0.3462
0.3462 ÷ (27.0 − 8.9)	0.0191
Log 2,600 =	3.4150
0.0191 × (27.0 − 12.0) =	0.2865
Log 2,600 + 0.0191 × 15.0 =	3.7015 = log 5030

and 5,030 pounds per square inch is the adjusted value, which does not differ significantly from the 5,020 read from the graph.

EXAMPLE 1–B

Tests of matched groups of white ash specimens gave the following values for modulus of rupture: 8,880 pounds per square inch in the green condition (by Table 17 $M_p = 24$ per cent) and 12,500 pounds per square inch at 13.8 per cent moisture.

What is the corresponding value of modulus of rupture at 10 per cent moisture content? The solution is shown by the upper pair of points and line in Figure 33 and is similar to that of example 1–A, except that in the present example adjustment is to be made to a moisture content lower than that at which the seasoned specimens were tested and the line joining the points must be extended in order to meet the vertical representing 10 per cent moisture; also the value of M_p is 24 instead of 27 per cent as in example 1–A. The value shown at this intersection is about 14,300 pounds per square inch. The numerical computation by formula (10) is as follows:

Log 12,500 =	4.0969
Log 8,880 =	3.9484
Log 12,500 − log 8,880 =	0.1485
0.1485 ÷ (24.0 − 13.8) =	0.0146
Log 8,880 =	3.9484
0.0146 × (24.0 − 10.0) =	0.2044
Log 8,880 + 0.0146 × 14.0 =	4.1528 = log 14,220

and 14,220 pounds per square inch is the value adjusted to 10 per cent moisture content.

EXAMPLE OF CASE 2

EXAMPLE 2

A specimen of longleaf pine at 9.8 per cent moisture content was found from test to have a modulus of rupture of 13,500 pounds per square inch. What would have been the modulus of rupture if the test had been made at 12 per cent moisture? In this case no tests of matched green specimens are available, and in order to make the adjustment a value of K is required. The average value of K for modulus of rupture of longleaf pine of 0.0259 as given in Table 24 will be used. The graphical solution is as follows: 13,500 is plotted at 9.8 per cent moisture in Figure 34. The next step is to draw through this point a line whose inclination to the horizontal is equal to the value of K. Data for doing this is afforded by Figure 35, in which are shown for various values of K, values of Z, a multiplying factor corresponding to a horizontal distance equal to 30 per cent on the scale of moisture content. For a value of K of 0.0259, the graph of Figure 35 gives a value of 6.0 for Z. Then in Figure 34, 1,000 is plotted at 30 per cent and 6,000, which is equal to six times 1,000, is plotted at 0 per cent moisture. The line connecting these two points has the desired inclination. A line is drawn parallel to this line and through the point first plotted in Figure 34. From this line the modulus of rupture adjusted to any moisture content below the intersection point can be read. The reading for 12 per cent moisture is about 11,800 pounds per square inch.

This procedure is a graphical solution of the following formula:

$$\text{Log } S_2 = \log S_1 - K\ (M_2 - M_1) \qquad (11)$$

Where S_1 and M_1 are the pair of corresponding strength and moisture content values as found from test and S_2 is the strength value adjusted

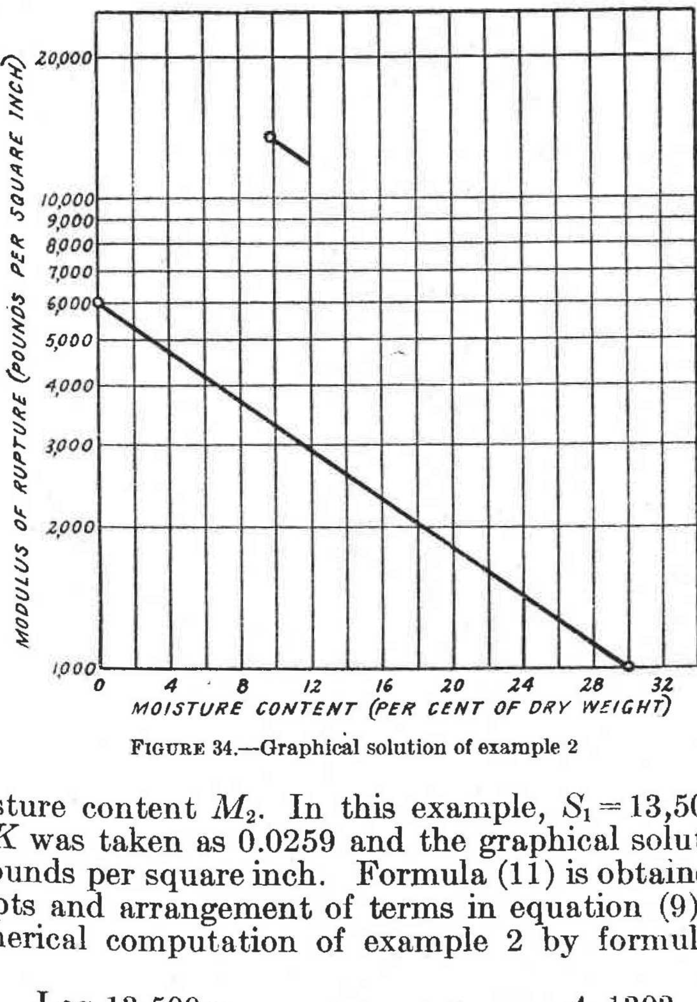

FIGURE 34.—Graphical solution of example 2

to the moisture content M_2. In this example, $S_1 = 13{,}500$, $M_1 = 9.8$, $M_2 = 12.0$, K was taken as 0.0259 and the graphical solution gives $S_2 = 11{,}830$ pounds per square inch. Formula (11) is obtained by changing subscripts and arrangement of terms in equation (9).

The numerical computation of example 2 by formula (11) is as follows:

Log 13,500 =	4.1303
$0.0259 \times (12.0 - 9.8) =$	.0570
Log $13{,}500 - 2.2 \times 0.0259 =$	4.0733 = log 11,840

and 11,840 pounds per square inch is the adjusted value.

The principle of the graphical solution of case 1 is to plot the two known strength values over their corresponding moisture-content values on semilogarithmic paper, and from the line connecting these points read the strength value corresponding to a third moisture content. When one of the moisture-content values is above the intersection-point value, the corresponding strength value is to be plotted at the intersection point.

In case 2 the principle is to plot the one known strength value at the corresponding moisture content and through this point to draw a line with the inclination defined by an assumed or estimated value of K. Then the strength value for a second moisture content is read from this line.

It is now evident that the principal difference between the two cases is that in case 1 the slope of the line, which is the value [14] of K, is determined from the data of the problem itself, whereas in case 2 the appropriate value of K has to be estimated from other data.

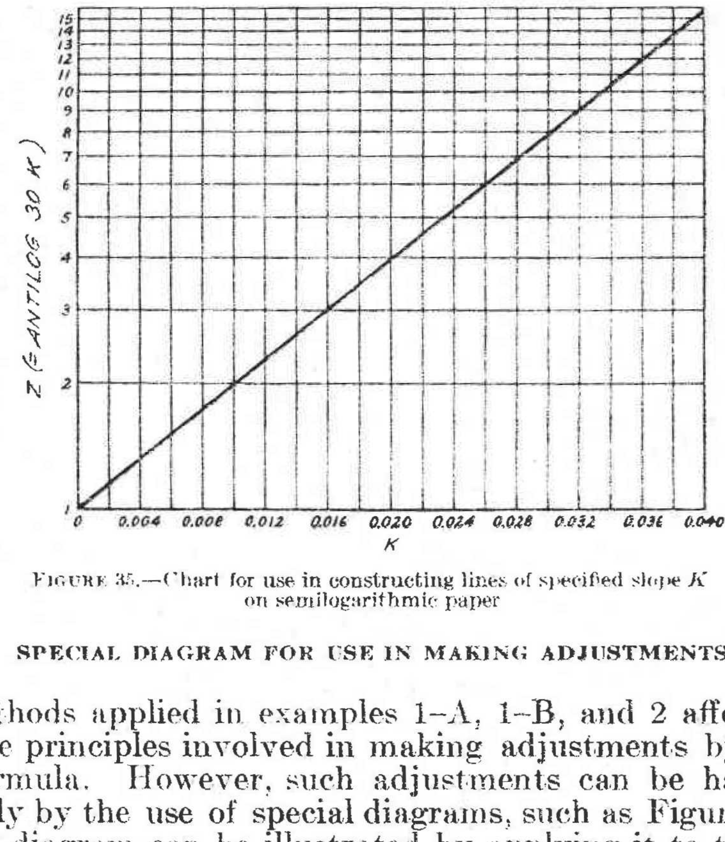

FIGURE 35.—Chart for use in constructing lines of specified slope K on semilogarithmic paper

SPECIAL DIAGRAM FOR USE IN MAKING ADJUSTMENTS

The methods applied in examples 1–A, 1–B, and 2 afford illustrations of the principles involved in making adjustments by the exponential formula. However, such adjustments can be handled even more simply by the use of special diagrams, such as Figure 36. The use of this diagram can be illustrated by applying it to the previous examples.

EXAMPLES OF THE USE OF FIGURE 36

EXAMPLE 1–A

Tests of Sitka spruce in the green condition and at 8.9 per cent moisture content gave values for maximum crushing strength of 2,600 and 5,770 pounds per square inch, respectively. The intersection-point moisture-content value M_p for Sitka spruce is 27 per cent. What would have been the strength value if tests had been made at 12 per cent moisture?

[14] The figures underscored in the computations of examples 1-A and 1-B (p. 66) are values of K.

The ratio R of the known strength values is 2.21, which equals $\frac{5,770}{2,600}$. The difference between the moisture-content values given is 18.1, which equals 27.0–8.9, and the higher moisture content

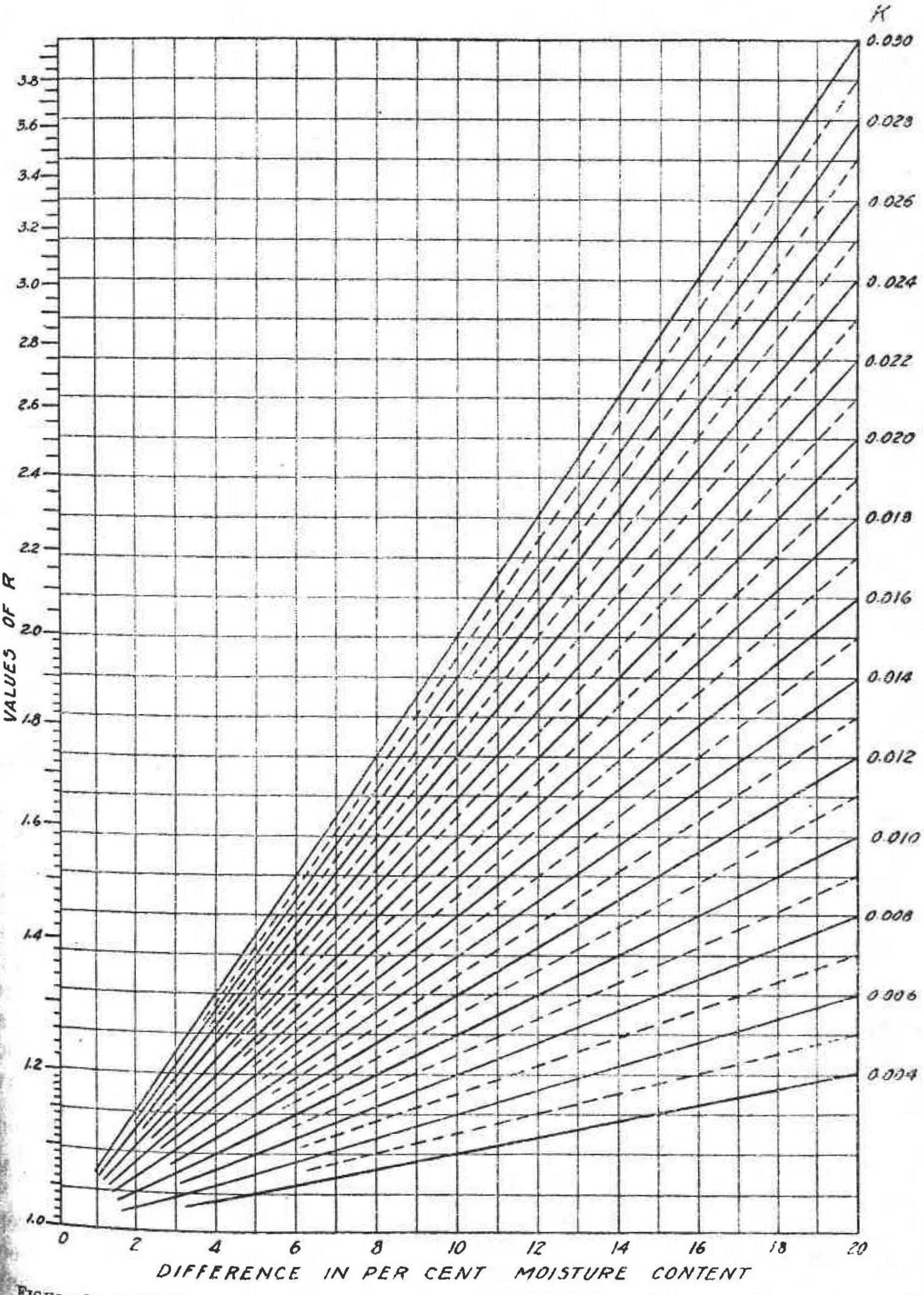

FIGURE 36.—Chart for use in making strength-moisture adjustments. (For examples see pp. 68 to 70)

(27 per cent) minus that to which adjustment is to be made (12 per cent) is 15 per cent. The R of 2.21 applies then to a moisture difference of 18.1, and the value of R for a moisture difference of 15 is to be found:

Starting with 2.21 at the left-hand margin of Figure 36 and following horizontally to the vertical representing 18.1 per cent moisture difference, the value of K (0.019) is found on one of the converging lines. Following this line to its intersection with the vertical through 15 per cent and thence horizontally to the left-hand margin, an adjusted R of 1.93 is read and $1.93 \times 2,600 = 5,020$ pounds per square inch, which is the strength value adjusted to 12 per cent moisture.

EXAMPLE 1-B

Tests of matched groups of white ash specimens in the green condition and at 13.8 per cent moisture gave values of modulus of rupture of 8,880 and 12,500 pounds per square inch, respectively. The value of M_p for white ash is 24 per cent. What is the value of modulus of rupture corresponding to a moisture content of 10 per cent?

The ratio R of the known strength values is 1.41, which equals $\frac{12,500}{8,880}$, and applies to a moisture difference of 10.2 per cent (24–13.8). The difference between the M_p value and the moisture content to which adjustment is to be made is 14 per cent (24–10). Following horizontally from 1.41 at the left-hand margin to the vertical through 10.2 per cent, thence in the direction of the converging lines to the vertical through 14 per cent, and then horizontally to the left margin the value of R for a moisture difference of 14 is read as about 1.61. Then $1.61 \times 8,880 = 14,300$, which is the strength value in pounds per square inch adjusted to 10 per cent moisture.

EXAMPLE 2

A specimen of longleaf pine tested at 9.8 per cent moisture content had a modulus of rupture of 13,500 pounds per square inch. If the value of K is estimated as 0.026, what is the value of modulus of rupture of this specimen adjusted to 12 per cent moisture content?

Adjustment is to be made from 9.8 per cent to 12 per cent; that is, for a moisture difference of 2.2 per cent. Starting with 2.2 per cent at the bottom of Figure 36 and following upward to the line representing $K = 0.026$, then horizontally to the left-hand margin, a value of 1.14 is found for R. Since the adjustment is to a higher moisture content, the adjusted value will be lower than the original. Consequently, the original strength value must be divided by R, and $13,500 \div 1.14 = 11,840$, the value in pounds per square inch of modulus of rupture adjusted to 12 per cent moisture. If adjustment had been to a moisture content lower by 2.2 per cent than that at which the test was made, as from 14.2 to 12.0, the ratio of 1.14 would have been used as a multiplier.

EFFECT ON ADJUSTED VALUES OF ERRORS IN ESTIMATING K AND M_p

Adjustment of strength values for differences in moisture content requires values of K or M_p. As values of these parameters have been found for only a few species, it is necessary in many cases to estimate the value of one or the other of them. Also K, and probably M_p, varies for different specimens of a species, and the known values of these parameters may not be exactly correct for the test values to be adjusted. Consequently, a consideration of the effect of errors in estimates of K and M_p on the accuracy of the adjusted strength values is pertinent.

EFFECT OF ERROR IN K

It can be shown that the effect of an error in estimating the value of K to be used in case 2 problems increases in the manner indicated by Figure 37 with the error and with the difference between the moisture-content values from and to which adjustment is to be made.

For example, the effect of an error of 0.01 in the value of K to be used in adjusting for a difference of 5 per cent in moisture content is found as follows: Starting with 0.01 at the bottom (fig. 37), follow upward to the inclined line representing a difference of 5 per cent in

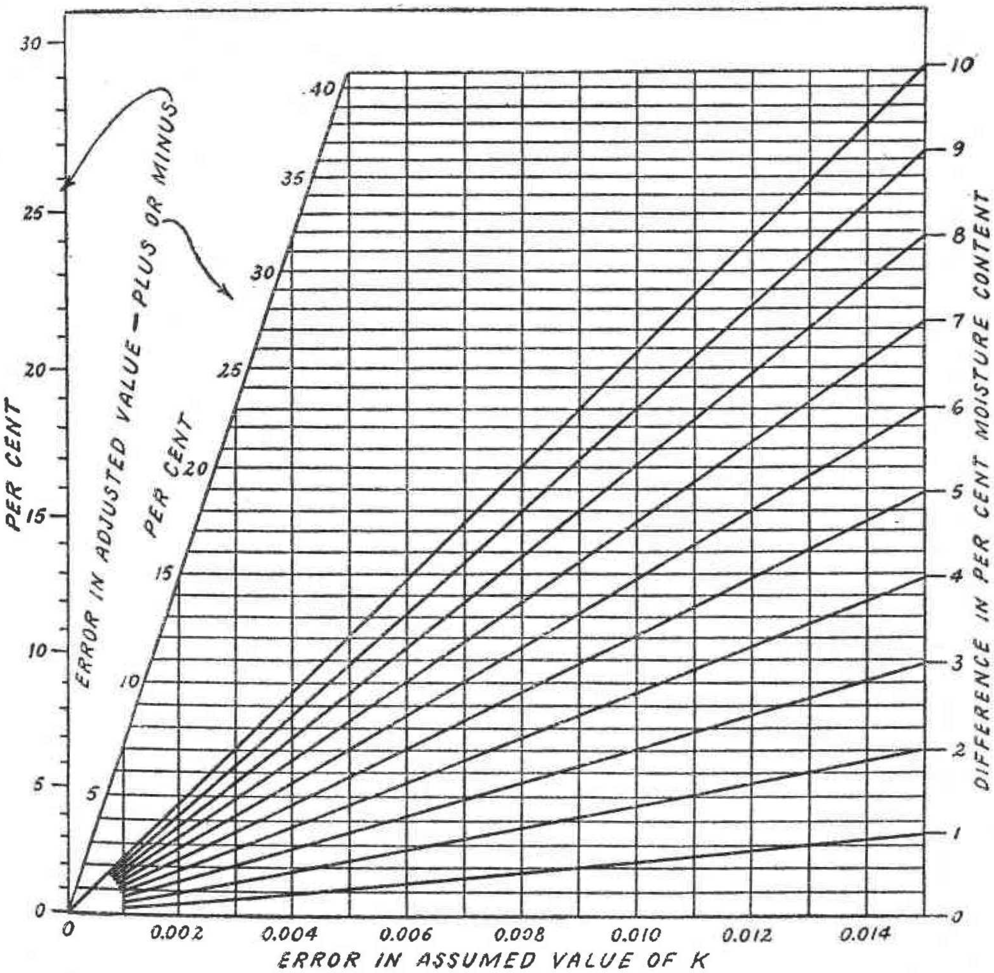

FIGURE 37.—Relation of error in adjusted strength value to error in assumed value of K

moisture content, then horizontally to the left, where values of about +12 and −11 per cent are read. This means that the error of 0.01 in the assumed value of K would cause a strength value obtained by adjusting for a moisture-content difference of 5 per cent to be about 12 per cent higher or 11 per cent lower than the true value. Whether the adjusted is higher or lower than the true value depends on whether adjustment is made to a higher or to a lower moisture content and on whether the assumed value of K is too large or too small according to the following scheme:

Error in assumed value of K	Adjustment made to—	Error in adjusted value
+	Higher moisture content	−
+	Lower moisture content	+
−	Higher moisture content	+
−	Lower moisture content	−

Obviously, the error in an assumed value of K is never known. It is often possible, however, to estimate how much the assumed value may be in error, and Figure 37 affords a means of computing the effect of the estimated error.

EFFECT OF ERROR IN M_p

The effect of an error in estimating the value of M_p to be used in case 1 problems can not be pictured so simply because it depends on several factors. It can, however, be expressed by an equation which indicates how the error and these several other factors affect the result. This equation is developed as follows:

Let S_1 = a strength value as found from tests at moisture content M_1.
S_p = the strength value for matched green material.
M_p = the true value of the per cent moisture at the intersection point.
M_q = estimate of M_p.

S_2 the strength value corresponding to some moisture content M_2 less than M_p is to be found.

Changing subscripts in equation (10) and substituting for $(\log S_1 - \log S_p)$ its equivalent, $\log \frac{S_1}{S_p}$:

$$\text{Computed value of } \log S_2 = \log S_p + \frac{M_q - M_2}{M_q - M_1} \log \frac{S_1}{S_p};$$

similarly,

$$\text{true value of } \log S_2 = \log S_p + \frac{M_p - M_2}{M_p - M_1} \log \frac{S_1}{S_p}.$$

Then

$$\text{Computed value of } \log S_2 - \text{true value of } \log S_2$$

$$= \log \frac{\text{computed value of } S_2}{\text{true value of } S_2}$$

$$= \left(\frac{M_q - M_2}{M_q - M_1} - \frac{M_p - M_2}{M_p - M_1}\right) \log \frac{S_1}{S_p}$$

$$= \frac{(M_2 - M_1)\ (M_q - M_p)}{(M_p - M_1)\ (M_q - M_1)} \log \frac{S_1}{S_p} \tag{12}$$

or

$$\log \frac{\text{computed value of } S_2}{\text{true value of } S_2} = \text{A} \log \frac{S_1}{S_p}, \tag{13}$$

where $\text{A} = \frac{(M_2 - M_1)\ (M_q - M_p)}{(M_q - M_1)\ (M_q - M_1)}$.

Equation (12) shows that the error in the computed value of log S_2, and hence the percentage error in the adjusted value S_2, is greater:

(1) The greater is $M_q - M_p$, the error in the assumed value of moisture content at the intersection point.

(2) The greater is $M_2 - M_1$, the difference in moisture content for which adjustment is made.

(3) The greater is $\frac{S_1}{S_p}$, the increase in the strength value produced by drying to the moisture content M_1.

(4) The less is M_p, the moisture content at the intersection point.

(5) The less is $M_p - M_1$; that is, the closer the moisture content M_1 is to the intersection-point value.

Frequently 12 per cent moisture is taken as a standard to which to adjust values resulting from tests of seasoned wood. Also if M_p for the particular species is not known from mechanical tests and no shrinkage or other data from which to estimate M_p are available, the best estimate is probably the average of known values, which is about 24 per cent. In Figure 38 are plotted values of the quantity A of equation (13) for $M_q = 24$, $M_2 = 12$, $M_1 = 2$ to 18 per cent, and $M_p = 20$ to 28 per cent. This graph simplifies estimates of the limits of accuracy when M_q is taken as 24 per cent in making adjustments to 12 per cent moisture.

In considering Figure 38 it must be remembered that the error is measured, not by A alone, but by the product of A and log $\frac{S_1}{S_p}$. Hence, although A increases numerically as M_1 increases above 12 per cent, $\frac{S_1}{S_p}$ at the same time decreases. On the other hand, as M_1 decreases below 12 per cent, both A and $\frac{S_1}{S_p}$ increase.

EXAMPLES OF THE EFFECT OF ERRORS IN ESTIMATED VALUES OF M_p AND K ON THE ACCURACY OF ADJUSTED VALUES

EFFECT OF ERROR IN M_p

United States Department of Agriculture Bulletin 556 (7) gives the maximum crushing strength of balsam fir as 2,400 and 6,640 pounds per square inch in the green condition and at 4.8 per cent moisture, respectively. If the strength is adjusted to 12 per cent moisture, using M_q, the assumed or estimated value of M_p as 24 per cent, and the true value of M_p is between 20 per cent and 28 per cent, what are the limits of error in the adjusted value?

$$S_1 = 6{,}640,\ S_p = 2{,}400 \text{ and } \log \frac{S_1}{S_p} = \log \frac{6{,}640}{2{,}400} = 0.442$$

From Figure 38,

$$\text{for } M_1 = 4.8$$
$$A = 0.098 \text{ if } M_p = 20$$
$$A = -0.067 \text{ if } M_p = 28$$

Then

$$0.098 \times 0.442 = 0.0433 = \log 1.10$$
$$-0.067 \times 0.442 = \bar{1}.9704 = \log 0.93$$

and the estimate is that S_2, the value of maximum crushing strength adjusted to 12 per cent moisture with 24 per cent as the assumed value of the moisture content at the intersection point will be between 93 and 110 per cent of the true value if the true intersection point moisture content is not less than 20 nor greater than 28 per cent.

As another example, United States Department of Agriculture Bulletin 556 (7) gives 2,060 and 3,400 pounds as the maximum crushing

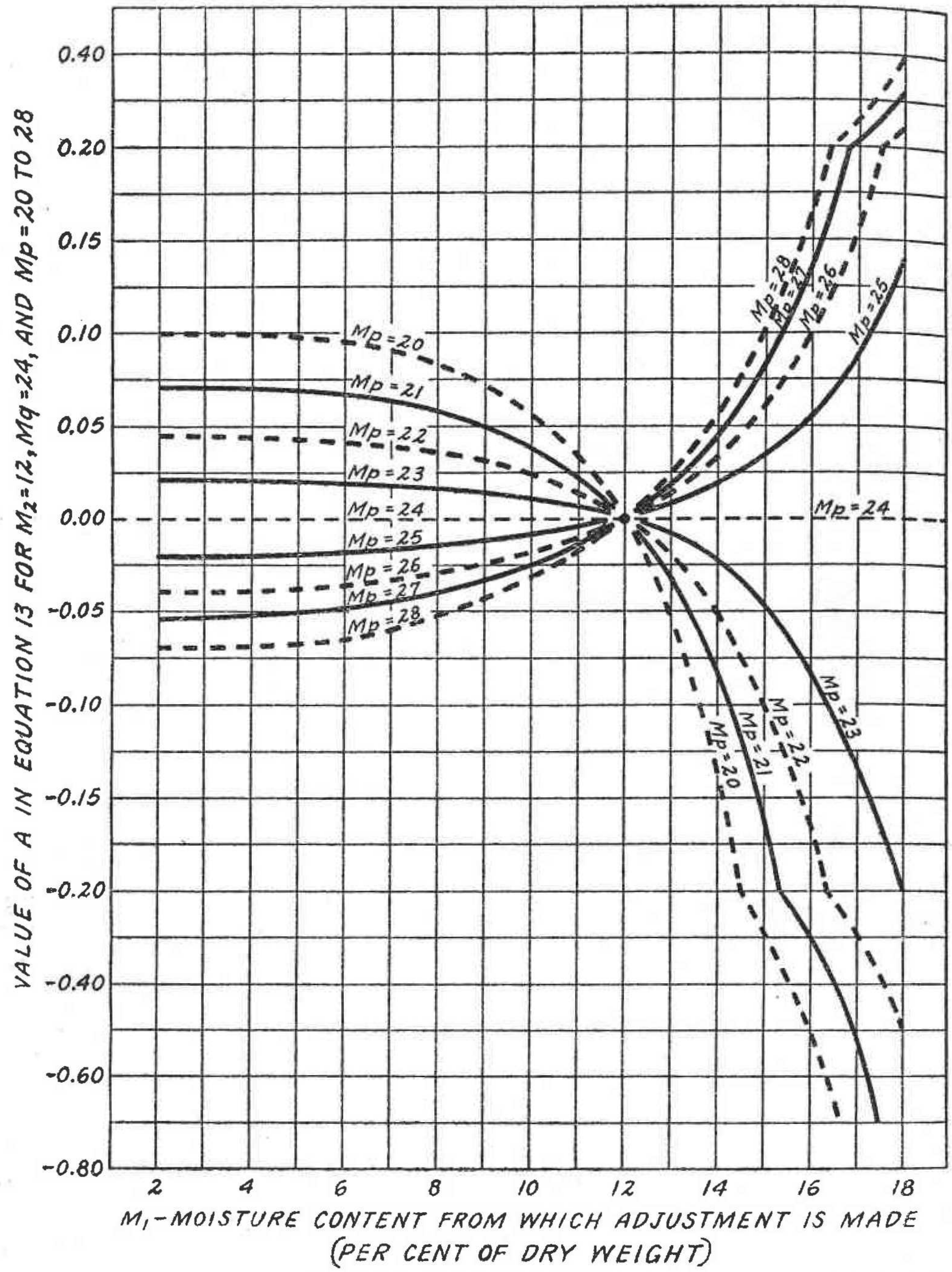

FIGURE 38.—Chart for estimating effect on adjusted strength value resulting from error in estimating the intersection-point moisture content (M_p)

strength of alpine fir green and at 15.9 per cent. Here $S_1=3{,}400$; $S_p=2{,}060$.

$$\text{Log}\,\frac{S_1}{S_p}=\frac{3{,}400}{2{,}060}=0.217$$

From Figure 38 for $M_1 = 15.9$

$$A = 0.49 \text{ if } M_p = 20$$
$$A = 0.16 \text{ if } M_p = 28$$
$$-0.49 \times 0.217 = -0.106 = \log 0.78$$
$$0.16 \times 0.217 = 0.035 = \log 1.08$$

and S_2, the value of maximum crushing strength adjusted to 12 per cent moisture, is estimated as being between 78 and 108 per cent of the true value if the true intersection point is not less than 20 nor greater than 28 per cent moisture. In other words, under this condition -22 per cent and $+8$ per cent are the limits of error in S_2.

EFFECT OF ERROR IN K

It is interesting to compare the estimates of error of solution of these two examples with errors that might result if an estimated or assumed value of K rather than of M_p were used. The best estimate of a value of K for such use is the grand average of the values given in Table 24 for maximum crushing strength or about 0.025 and from a consideration of the range of average values in Table 24, it is estimated that the true value of K for an individual species might differ from this grand average by as much as ± 0.009. For such an error in K, Figure 37 indicates errors in the adjusted values of about $+16$ or -14 per cent for the first example and $+8$ or $-7\frac{1}{2}$ per cent for the second. Ordinarily, the error in the estimated value of K probably would not exceed ± 0.007, and the error of adjusted value would be correspondingly less. Also since K is smaller for most other properties the error in applying a general average value of K to some particular species will be less for other properties than for maximum crushing strength.

The errors in the illustrations given in this and the preceding section are about as large as are likely to occur, and in most instances it will be possible to estimate the value of K or M_p with such accuracy that error in the adjusted value of a strength property will be much less.

LIMITATIONS OF ADJUSTMENT METHODS

The preceding discussion of the errors that may occur in making moisture-strength adjustments has been presented to enable those making such adjustments to estimate what errors may be incurred and thereby to appraise the accuracy of an adjusted value. It is to be remembered that the adjustment methods are applicable only to results on specimens in which the moisture is very nearly uniformly distributed. Such distribution does not ordinarily obtain in pieces whose average moisture content is near the intersection-point value, and the adjustment of test results obtained at moisture-content values between about 15 or 16 per cent and the intersection-point values is subject to errors of considerable magnitude.

The adjustment methods have been derived from wood in which no abnormal amounts of resin or other infiltrated substances were present, and caution needs to be exercised in applying them to wood containing exceptional amounts of such substances. The effect of moisture on the strength properties of wood that contains abnormal amounts of resin has not been thoroughly investigated. Such tests as have been made on material of this character indicate that strength-moisture relations are erratic. This may be due to inaccuracies in moisture determinations in such instances. If the amount of moisture held in the wood substance could be determined accurately such material might display as definite strength-moisture relations as wood without resin or with only normal amounts of resin. It has been found that in some species that contain large amounts of other infiltrated substances, these substances have the effect of raising the strength of green wood without exerting a corresponding effect on dry material. Consequently, such wood is increased in strength by drying less than is wood that does not contain such substances.

Although the methods of adjustment outlined are believed to be the best that is now possible to devise, they should be used with care and judgment and with a full realization of the possibility of error. It is evident that in all cases the risk of error is least when the difference between the moisture-content values from and to which adjustment is made is small. Necessity for adjustments for any but comparatively small differences in moisture content can ordinarily be avoided by care in conditioning specimens for test. Usually seasoning to a moisture content not far from 12 per cent can be readily accomplished either by natural (air) or artificial (kiln or conditioning chamber) drying, and 12 per cent is suggested as a standard moisture content at which to test seasoned specimens.

In tests, such as may be made for the determination of the effect of a preservative, fireproofing, or other treatment, it is advisable to season both control and treated specimens to equilibrium under atmospheric conditions simulating those that will obtain in service. In this way the need, in analyzing results to determine the effect of the treatment, for adjustments, other than for small differences in moisture content, will be avoided. Furthermore, the treatment may so modify the hygroscopicity of the wood that control and treated specimens will not come to equilibrium at the same moisture content, and in such instances it may be proper to compare the test results directly without adjustment for the moisture difference.

OTHER PHASES OF STRENGTH-MOISTURE RELATIONS

The preceding discussion has been concerned with the relation between moisture content and strength properties in pieces of wood that are free from defects and in which the moisture is practically uniformly distributed. The methods of adjustment developed are applicable to such pieces only and not to pieces containing defects or to pieces in which the moisture is nonuniformly distributed, that is, pieces in which a moisture gradient of considerable magnitude exists. Two important phases of strength-moisture relations in wood remain for consideration. These are the instances when (1) the moisture content is nonuniformly distributed and considerable moisture gradient exists between the interior and exterior parts of the cross section, and (2) when the piece contains such defects as knots, cross grain, shakes, or checks.

THE EFFECT OF NONUNIFORMLY DISTRIBUTED MOISTURE ON THE STRENGTH OF WOODEN MEMBERS

When a piece of wood is held for a long period under nearly constant conditions of atmospheric temperature and humidity, all parts of it reach approximate equilibrium, and only small variations in moisture content between parts obtain. Normally, however, wood is not held under constant conditions, and usually drying is carried out in such a manner as to produce moisture gradients of considerable magnitude during the time the piece is approaching equilibrium. The results of tests on chestnut specimens with moisture nonuniformly distributed are illustrated in Figure 5. In this instance, the effect of the greater dryness of the outer parts of the specimens resulted in a strength-moisture curve well above that for specimens with moisture uniformly distributed. As may be seen from Figure 5, the strength of specimens with a nonuniformly distributed moisture content of 42 per cent was as great as that of specimens with a uniformly distributed moisture content of 18 per cent, and for specimens with nonuniform moisture content averaging about 25 per cent the strength was as great as for those having a uniformly distributed moisture content of 14 per cent. That wood tested in a partially seasoned condition and displaying large moisture gradients does not always yield results similar to these is demonstrated by a recent investigation.

The specific object of this investigation was to obtain information applicable to values from tests of partially and nonuniformly seasoned wood. Such information would prove valuable since preservative and other treatments of timber frequently dry the surface to a low moisture content and leave the moisture content progressively higher toward the center of the piece. Conclusions concerning the effect of such treatments on strength properties of wood could be reached very quickly if specimens could be tested soon after treatment and the results so adjusted as to be comparable to those from control specimens. Again, telephone poles of different species and different groups of poles of the same species have been tested at various stages of seasoning. The data from these tests would be of much greater utility if they could be adjusted to a strictly comparable basis.

The tests of the effect of partial seasoning were made on pole and rectangular (2 by 4 inches in cross section) specimens. The species of wood were chestnut, Douglas fir, loblolly pine, shortleaf pine, and tamarack.

Static-bending and compression-parallel-to-grain tests were made on partially dry and on matched green control specimens. The 2 by 4 inch specimens for test in the partially seasoned condition were prepared in 3 by 4 inch size, and the wide faces were coated with a preparation to retard drying so that the principal drying would take place from the narrow faces. When the specimens had been dried for the requisite period of time one-half inch was removed from each of their wide faces and the tests made. This resulted in test specimens 2 by 4 inches in cross section whose moisture content was nearly uniform across the width or narrow dimension but varied from a comparatively low value at each narrow face to a higher value at the middle. The pole specimens for test in the partially seasoned condition were dried in such a way as to produce a comparatively low moisture content at the surface, increasing to a higher value at the center.

The more important of the data on 2 by 4 inch specimens of chestnut and loblolly pine are presented in Figures 39 to 43, inclusive.

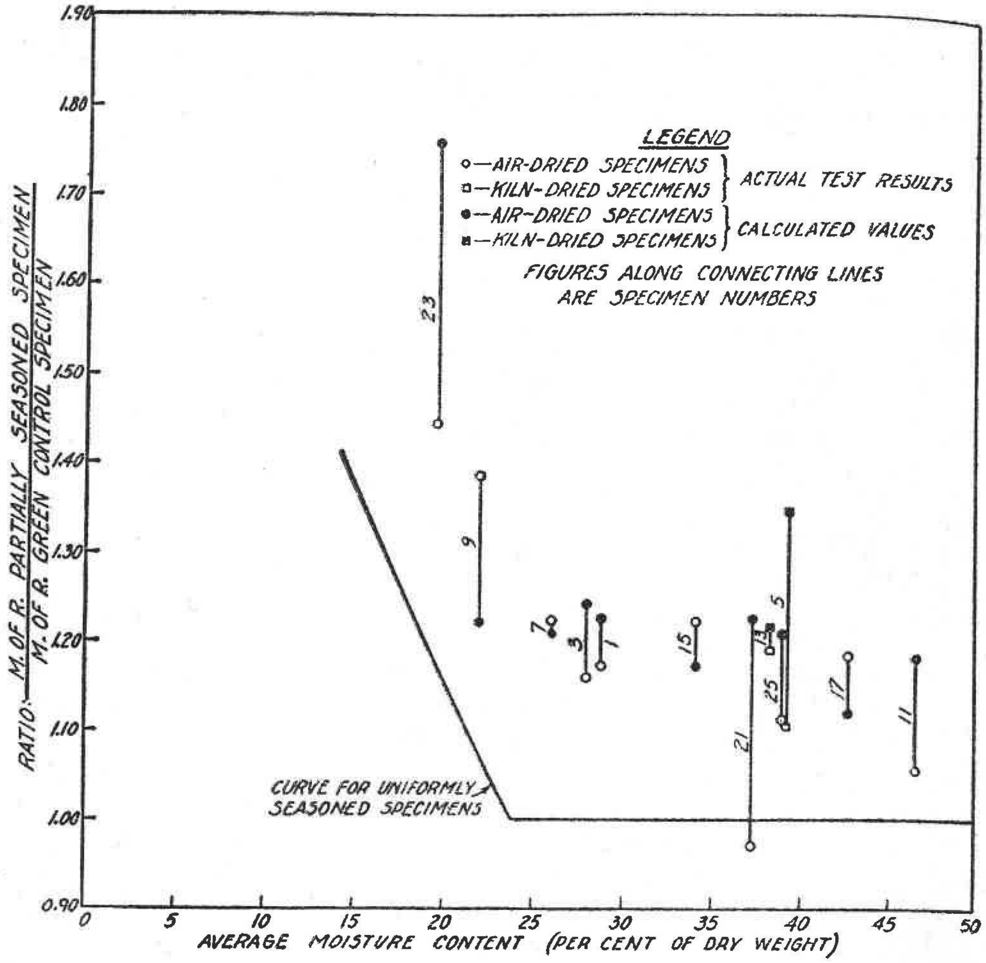

FIGURE 39.—Results of the determination of the modulus of rupture of nonuniformly seasoned 2 by 4 inch specimens of chestnut. For data on moisture distribution, see Table 25

TABLE 25.—*Moisture distribution data for nonuniformly seasoned 2 by 4 inch specimens of chestnut plotted in Figures 39, 40, and 41*

Specimen	Moisture content of successive slices from compression face of static bending specimen				
	First ⅛ inch	Second ⅛ inch	Second ¼ inch	Third ¼ inch	Fourth ¼ inch[1]
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
No. 1	12.7	15.8	18.3	22.3	26.2
No. 3	12.6	16.0	18.1	20.4	25.0
No. 5	8.4	12.5	14.9	19.3	27.1
No. 7	13.1	15.8	18.3	21.1	24.7
No. 9	13.7	16.2	18.0	19.7	21.7
No. 11	11.5	15.3	21.4	39.8	102.4
No. 13	9.7	12.2	15.1	22.2	33.7
No. 15	13.8	16.5	19.0	23.0	29.0
No. 17	13.8	16.0	19.8	25.5	33.6
No. 19	11.1	13.3	19.5	30.0	50.5
No. 21	11.4	14.8	17.8	22.2	29.2
No. 23	9.6	11.6	13.8	16.0	18.1
No. 25	12.4	15.4	18.1	23.6	31.6

[1] The average moisture content in the second inch of all specimens was above the intersection-point value except that in the second inch of specimen No. 23, which was 20.5 per cent.

In each of these diagrams, the ratios of the strength of a partially seasoned specimen to the strength of its own green control specimen are plotted over the average moisture content of the partially seasoned specimen. There is also shown for comparison a moisture-strength curve for uniformly seasoned pieces. Where suitable data on specimens from the same logs as the partially seasoned specimens were available, they were used in establishing the moisture-strength curve for uniformly seasoned specimens.

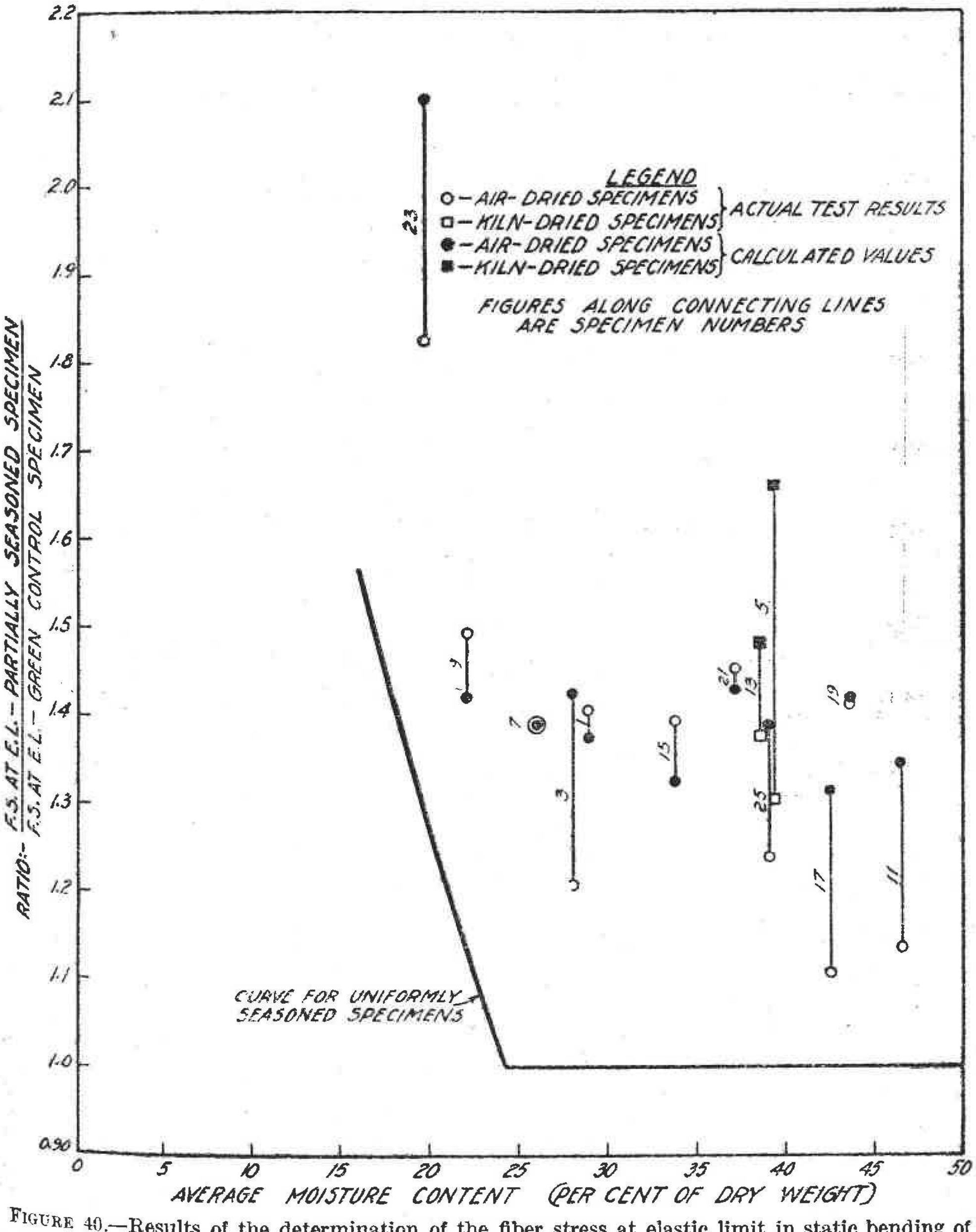

FIGURE 40.—Results of the determination of the fiber stress at elastic limit in static bending of nonuniformly seasoned 2 by 4 inch specimens of chestnut. For data on moisture distribution, see Table 25

The data demonstrate that the strengths of different species are differently affected by partial seasoning, as may be seen from a comparison between chestnut and loblolly pine. Figures 39, 40, and 41 show the results of tests on chestnut. The fact that in these diagrams the points are consistently well above the moisture-strength curve for uniformly seasoned specimens demonstrates that the specimens with moisture nonuniformly distributed were much higher in strength than they would have been had the moisture content averaged the same but been uniformly distributed in the cross section, and confirm with respect to chestnut the results shown in Figure 5.

Figures 42 and 43 present similar data for loblolly pine and show that specimens with an average moisture content above the fiber-saturation point have, on an average, received no increase in strength

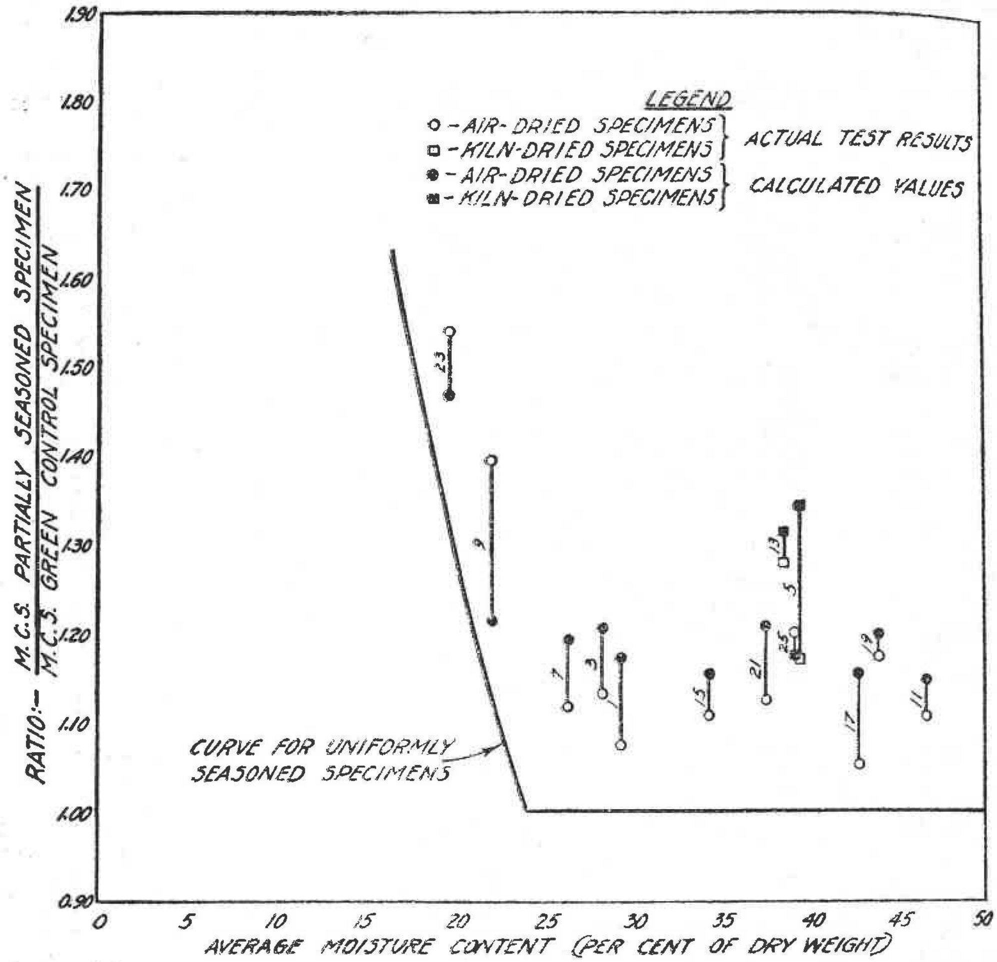

FIGURE 41.—Results of the determination of the maximum crushing strength of nonuniformly seasoned 2 by 4 inch specimens of chestnut. Figures along connecting lines are specimen numbers. For data on moisture distribution, see Table 25

from partial drying, some specimens having been strengthened and others weakened.

The results demonstrate a contrast between chestnut and loblolly pine with respect to the effect of partial seasoning. The other species tested are intermediate. This difference with respect to the effect of partial seasoning is due to variations in the way adjacent layers differing in moisture content act together when strained in compression. The cooperation of these layers depends on their stress-strain relations.

Two types of behavior of wood under compressive stress and strain, either in pure compression or in bending, are as follows:

TYPE A.—Maximum stress is reached at comparatively small deformation, and the stress decreases rapidly with small additional deformation; the strain, or deformation, soon becoming localized at a single point or in a small region. When local failure has once occurred, not enough stress can be sustained to cause the formation of other failures. This type of behavior is more common in dry wood than in green and more common in coniferous species than in hardwoods. Its extreme is exemplified by very dry wood, in which maximum stress is reached at a small deformation and sudden and complete failure occurs immediately.

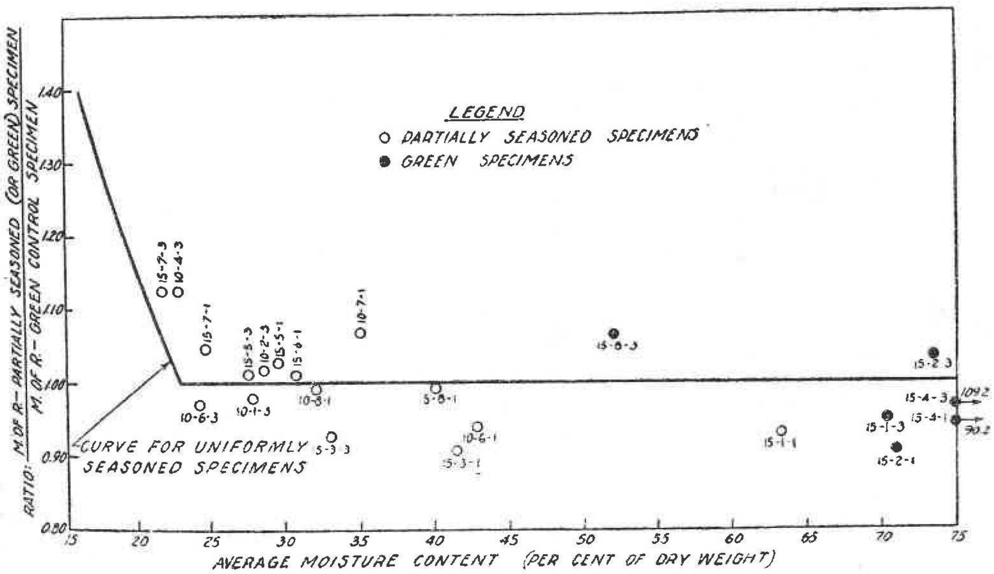

FIGURE 42.—Results of the determination of modulus of rupture of nonuniformly seasoned 2 by 4 inch specimens of loblolly pine. The solid circles represent specimens that were intended to be partially seasoned with comparatively low moisture content at the surface but were found to have moisture content values above the intersection point value throughout. See Table 26 for data on moisture distribution

TABLE 26.—*Moisture distribution data for nonuniformly seasoned 2 by 4 inch specimens of loblolly pine plotted in Figures 42 and 43*

Specimen	Moisture content of successive slices from compression face of static bending specimen				
	First ⅛ inch	Second ⅛ inch	Second ¼ inch	Third ¼ inch	Fourth ¼ inch [1]
	Per cent	*Per cent*	*Per cent*	*Per cent*	*Per cent*
No. 10-1-3	12.7	16.8	22.9	25.7	27.9
No. 10-2-3	14.1	18.1	23.3	25.6	27.1
No. 10-4-3	12.0	17.8	22.6	25.2	------
No. 10-6-1	17.2	45.6	43.4	59.4	55.8
No. 10-6-3	14.1	16.0	20.6	24.1	26.0
No. 10-7-1	14.7	17.7	23.0	36.7	56.8
No. 10-8-1	13.1	16.9	20.7	24.6	28.9
No. 15-1-1	17.4	21.7	26.9	25.3	36.6
No. 15-3-1	12.6	17.0	20.6	26.9	33.6
No. 15-3-3	20.0	30.8	44.0	57.2	50.6
No. 15-5-1	15.4	19.1	21.5	23.2	24.5
No. 15-5-3	17.9	28.6	31.7	35.6	29.0
No. 15-6-1	22.4	26.2	29.0	29.8	31.2
No. 15-7-1	12.9	15.9	21.6	27.5	34.3
No. 15-7-3	14.2	16.0	18.3	21.6	24.0
No. 15-8-1	20.8	28.4	29.4	46.0	43.6

[1] The moisture content in the second inch of all specimens was above the intersection-point value.

TYPE B.—Maximum stress does not occur until a comparatively large deformation has taken place, stress decreases but slowly with further increase in deformation, deformation continues to be well distributed longitudinally for a time but finally becomes localized at a number of points, and numerous failures appear simultaneously or in close succession before there is an appreciable decrease in stress. This type of behavior is more common in green wood than in dry and more common in hardwoods than in conifers. It is exhibited by both green and air-dry wood of such species as hickory and reaches its extreme in hickory that has been obtained from near the base of some trees. Distributed rather than localized failure is characteristic of material in which the stress is maintained very nearly at its maximum value through a considerable range of strain or deformation.

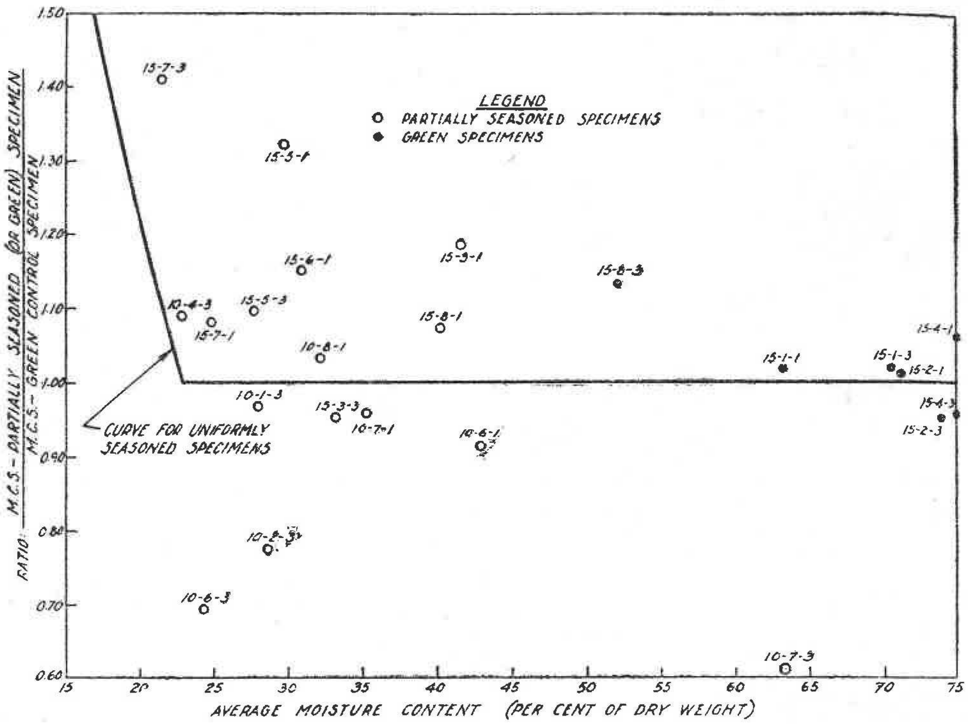

FIGURE 43.—Results of the determination of maximum crushing strength of nonuniformly seasoned 2 by 4 inch specimens of loblolly pine. The solid circles represent specimens that were intended to be partially seasoned with comparatively low moisture content at the surface but were found to have moisture-content values above the intersection-point value throughout. See Table 26 for data on moisture distribution

The stress-strain relation corresponding to type A behavior is illustrated by the diagram for air-dry loblolly pine as shown in Figure 44, while that for type B is illustrated by the diagrams for green loblolly pine and for green and air-dry chestnut. The diagrams in this figure were taken from actual tests and are typical with respect to the shape of the stress-strain curves but not with respect to the relative amounts of deformation at maximum stress.

If the stress-strain relations are of type B both for green and for air-dry material, as illustrated for chestnut in Figure 44, all or several of the successive layers of a nonuniformly seasoned piece may develop their maximum or nearly their maximum stress at the same deflection. This is obviously true for pieces loaded in compression parallel to grain. How it may also be true of beams can be seen from the fact that when tension failure occurs in a beam the neutral plane has moved downward and the deformation not only at the upper surface but for a considerable distance below it comes into the range within which the stress is maintained at very nearly its maximum. Such a nonuniformly seasoned piece would carry a larger load either in compression or in bending than if it were thoroughly green.

If type A stress-strain relations obtain at all degrees of dryness, the parts of a nonuniformly seasoned piece loaded in compression parallel to grain may not develop their maximum stress at the same deflection with the result that the maximum load for the piece is less than the sum of the maximum loads for its parts and may actually be less than if the piece were thoroughly green.

If the stress-strain relations change from type B for green or wet wood toward type A with decrease in moisture content, the stress in the drier top layer of a partially seasoned beam may in test pass its maximum and decrease greatly before the layers below it attain a high stress. The result is that the layers of different degrees of dryness successively reach their maximum stress and fail, and the beam may be no stronger or may be actually weaker than if it were thoroughly green.

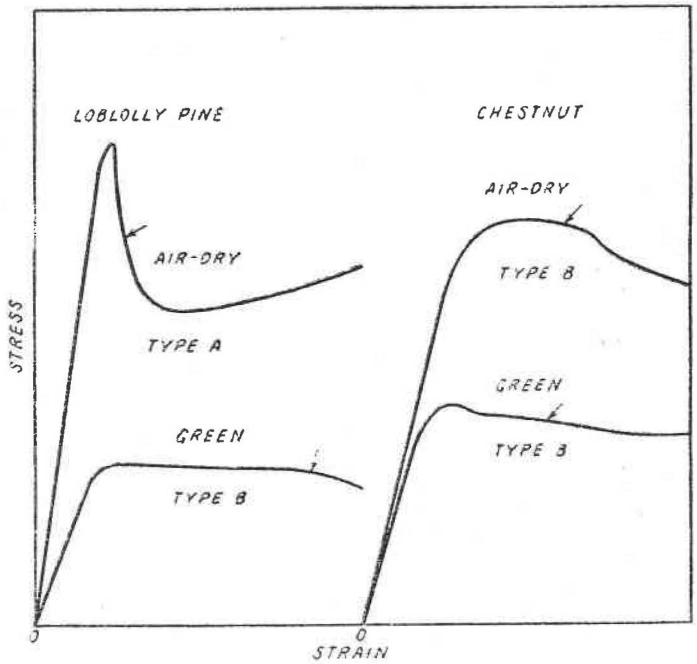

FIGURE 44.—Shape of stress-strain diagrams for green and air-dry loblolly pine and chestnut under compressive stress. Arrows indicate first visible failure

Different types of behavior of nonuniformly seasoned pieces in compression parallel to grain are illustrated by loblolly pine (fig. 43) and chestnut (fig. 41), respectively. Figure 43 indicates that, on an average, loblolly pine was not increased in strength by partial seasoning. Figure 41 shows, on the contrary, that chestnut was increased in strength although in only 3 cases out of 13 was the actual strength value as high as it would have been had each part carried the load (calculated value) corresponding to its moisture content.

Figures 39 and 40 show certain calculated values in addition to actual results from bending tests. These values were obtained by multiplying the moment of inertia of each of the parts of the beam whose moisture content was separately determined into the estimated strength value (modulus of rupture or fiber stress at elastic limit) at that moisture content and dividing the sum of these products by the moment of inertia of the entire section. A sample computation is shown in Table 27.

TABLE 27.—*Example of calculated values for modulus of rupture*

[Specimen 2 by 4 inches. Modulus of rupture of green control specimens 5,000 pounds per square inch. Moisture content of successive slices counting from top of the beam are given in column 3. Distribution of moisture assumed to be symmetrical about horizontal center line of section]

Thickness of slice	Moment of inertia of two symmetrically located slices	Moisture content	Modulus of rupture	Moment of inertia times modulus of rupture
		Per cent	*Lbs. per sq. in.*	
⅛ inch	1.878	13.8	7,150	13,430
Do	1.643	16.5	6,500	10,680
¼ inch	2.646	19.0	6,000	15,880
Do	1.896	23.0	5,170	9,800
Do	1.271	29.0	5,000	6,355
1 inch	1.333	39.9	5,000	6,665
	10.667			62,810

62,810÷10.667=5,890=calculated value of modulus of rupture.

As may be observed from Figures 39, 40, and 41, the calculated and actual values for chestnut agree closely in only a few instances. (This was found to be true for other species also.) Furthermore, the calculated value, though in most cases above the actual, is not consistently so, and apparently there is no correlation between the actual and calculated values. Hence, there seems to be little chance that this type of calculation could be made the basis for predicting the strength of a partially seasoned piece or of reducing to some standard moisture condition results of tests on such a piece.

Also the demonstrated fact of the differing effect of partial seasoning on different species indicates that no one type of formula for making such computations would be found applicable to all species and that, consequently, methods of computing the strength of pieces of wood of a species when in a partially seasoned condition can be found, if at all, only after very extended experiments on that species.

CONCLUSIONS FROM THE TESTS OF WOODEN MEMBERS HAVING NONUNIFORMLY DISTRIBUTED MOISTURE

The tests of the strength of specimens with moisture nonuniformly distributed lead to the following conclusions:

A partially seasoned piece of wood whose average moisture content is above the fiber-saturation-point value may or may not be stronger and may conceivably be weaker than the same piece in the green condition. Whether increase in strength occurs as the result of such seasoning depends on the characteristics of the species and on numerous other factors. The available information indicates that the species most likely to be increased in strength are those in which, regardless of the degree of dryness, the stress in compression parallel to grain decreases but slowly as deformation is increased beyond that at which maximum stress occurs. However, the characteristics that determine whether or not wood of a species will be increased by such partial seasoning are not completely known. Consequently, it is not possible to classify species in this respect except from the results of tests. Chestnut specimens were appreciably strengthened by partial seasoning that did not reduce the average moisture content below the fiber-saturation-point value; loblolly pine similarly seasoned was on the average no stronger than when green. Douglas fir rectangular and tamarack pole specimens showed some increase but less than chestnut. Available data are insufficient to indicate the effect of similar seasoning on shortleaf pine.

Timber partially seasoned to an average moisture content below the fiber-saturation-point value may or may not have higher strength than would be expected from the average moisture content. In the tests described, pole specimens of tamarack and chestnut and rectangular specimens of chestnut, shortleaf pine, and Douglas fir were usually higher in strength than would be expected from the average moisture content, whereas the results for pole specimens of shortleaf pine were lower than would be expected. Available data are insufficient to indicate the effect of such seasoning on loblolly pine.

Because of difference in the behavior of different species when partially and nonuniformly seasoned, there is little hope of being able to derive adjustment formulas applicable to results of tests on partially seasoned wood. No attempt should be made to adjust data derived from tests of partially and nonuniformly seasoned timber.

Material for tests intended to afford a comparison between species in the form of such products as poles or between treated and untreated timber should be conditioned to equilibrium under exposure approximately the same as will obtain in service. Adjustment of data for differences in moisture content will then be unnecessary.

MOISTURE AND ITS RELATION TO THE STRENGTH OF WOOD AND TIMBER CONTAINING DEFECTS

It has been emphasized that the tests of Groups 1 and 2 discussed earlier in this bulletin were made on small specimens free from defects and that the changes in strength shown and the methods of moisture-strength adjustment set up apply only to such material. Larger pieces free from defects and structural timbers with the defects commonly found therein differ distinctly from small, clear specimens with respect to strength-moisture relations.

The drying of small, clear specimens produces comparatively large increases in many strength properties because the wood fibers and other small elements of the structure are greatly increased in strength. Although in larger pieces and in pieces with such defects as knots, cross grain, and shakes, similar increase in the strength of the fibers takes place it is not fully effective in increasing the strength of the piece as a whole because drying almost invariably produces checks, particularly in pieces containing the pith of the tree, and also intensifies the effects of previously existing defects. The reason for this is found in the way moisture moves and in the way shrinkage takes place during drying.

With a given change of moisture content below the fiber-saturation point, the shrinkage of a piece of wood or the tendency to shrink differs according to the three principal directions with respect to the structure. The tendency to shrink is greatest in the tangential direction, less radially, and, except in abnormal material, such as compression wood,[15] is negligible longitudinally or along the grain.

[15] Compression wood consists characteristically of annual rings abnormally widened over a part of their circumference. In this widened portion, the summer wood constitutes a large proportion of the width of the ring, but the difference between spring wood and summer wood is less marked than in wood of normal structure. Compression wood occurs only in coniferous species and is formed principally on the lower side of leaning trees and the underside of limbs. In addition to abnormal longitudinal shrinkage, compression wood is characterized by specific gravity above normal and by a deficiency in certain strength properties.

The width of flat-grained or slash-sawn boards is principally tangential to the annual rings, and it is common observation that such boards shrink more in drying and undergo greater changes in width with subsequent fluctuations of moisture content than do edge-grained or quarter-sawn boards, whose width is radial. Owing to this same difference the circumference of a pole or log tends to be decreased by a greater percentage in drying than does the diameter, and stretching or checking is necessary to accommodate the circumference to the diameter. The same is true of sawed timbers that include the pith of the tree. Ordinarily, the wood is incapable of the necessary stretching, and consequently drying is accompanied by checking.

The drying of any piece of wood takes place from the outside, in consequence of which the outer portion acquires a tendency to shrink in advance of the interior. This is the principal cause of checking in pieces that do not contain the pith and enhances the checking of logs, poles, and other products in which the pith is present.

Under a given drying condition moisture moves at different rates in the principal structural directions. Movement is most rapid longitudinally and least tangentially, with that in the radial direction intermediate. An illustration of the effect of the more rapid longitudinal movement is afforded by the checks that form at the ends of lumber and timber during drying unless precautions are taken to retard drying from the ends. As a result of the rapid longitudinal movement, the material at and near the ends of the piece soon reaches a moisture content that demands shrinkage, but as shrinkage is resisted by the adjacent portions that have not reached such a moisture condition checking occurs at the ends of the piece.

The combined effect of the differences in moisture movement and shrinkage in the different directions and of the fact that the outer portions of any piece ordinarily reach a moisture content that demands shrinkage in advance of the interior is to stress the wood in compression and tension across the grain. The tension stresses cause checking and increase the extent of any shakes that may be present. Checking and extension of shakes reduce the area available to resist shearing stress parallel to the grain. Checking reduces the strength in longitudinal compression by separating the fibers and thus causes the loss of some of their mutual support against buckling. Decrease in adherence of fibers also lessens the tensile strength.

Shrinkage stresses and the resulting checking are at a minimum in small, clear pieces that are carefully dried. Ordinarily the larger the piece the more severe is the checking that takes place, and, consequently, large pieces, even when free from knots or cross grain so that the checks are parallel to the length, gain less strength in drying than do small specimens. The checks in the pieces having knots [16] and cross or spiral grain extend in directions inclined to the length of the piece. Also shrinkage stresses and checking in such pieces are enhanced by the fact that the movement of moisture to the lateral faces of the piece is in part along the length of the fibers and, consequently, larger differences in moisture content between the surface and the interior occur. Since longitudinal compression and tension stresses have components parallel and at right angles to these

[16] The weakening effect of knots in either green or seasoned timbers is due largely to the fact that the fibers within and surrounding them are not parallel with the length of the piece.

directions, the gain in fiber strength resulting from loss of moisture is further offset in such pieces.

These effects cause any lot of sawed timbers to be more variable in strength when seasoned than when green, and tests of similar groups of green and seasoned timbers have shown that although maximum and average strength values are higher for the seasoned material, minimum values are not appreciably raised by seasoning. A degree of cross grain that has little influence on timbers in the green condition may, because of the formation of checks, greatly affect a seasoned timber.

The statements of the preceding paragraph apply to sawed timbers. Checking and the stresses set up in drying have less effect on the strength of split or of naturally round timbers, such as poles and piling. In such pieces no movement of moisture to the surface along the length of the fibers occurs, and unless the piece is spiral grained, longitudinal stresses do not have components at right angles to the checks. Consequently, round timbers, unless they are spiral grained, are considerably increased in strength by seasoning (*1*) but not so greatly as small, clear specimens.

SUMMARY

This bulletin brings together data resulting from tests of the effect of moisture on the strength properties of wood as made by the Forest Service over a period of 25 years. The data are considered in detail, and from them a type formula to express the relation between uniformly distributed moisture content and various strength properties is derived. The application and limitations of this formula in adjusting test results for differences in moisture content are presented. The effect of partial seasoning on the strength of wood and the pitfalls which attend any attempt to adjust strength values when the moisture is nonuniformly distributed are set forth, as well as the effect of seasoning on the strength of timbers containing defects.

LITERATURE CITED

(1) BETTS, N. DE W.
1914. ROCKY MOUNTAIN MINE TIMBERS. U. S. Dept. Agr. Bul. 77, 34 p., illus.

(2) AMERICAN SOCIETY FOR TESTING MATERIALS.
1927. STANDARD METHODS OF TESTING SMALL CLEAR SPECIMENS OF TIMBER. SERIAL DESIGNATION D143-27. A. S. T. M. Standards. . . . 1927, Pt. II. Nonmetallic Materials, p. 627-663, illus.

(3) DUNLAP, F.
1914. DENSITY OF WOOD SUBSTANCE AND POROSITY OF WOOD. Jour. Agr. Research 2:423-428.

(4) GOSS, O. P. M.
1913. MECHANICAL PROPERTIES OF WESTERN HEMLOCK. U. S. Dept. Agr., Forest Serv. Bul. 115, 45 p., illus.

(5) ———
1913. MECHANICAL PROPERTIES OF WESTERN LARCH. U. S. Dept. Agr., Forest Serv. Bul. 122, 45 p., illus.

(6) MARKWARDT, L. J.
1930. COMPARATIVE STRENGTH PROPERTIES OF WOODS GROWN IN THE UNITED STATES. U. S. Dept. Agr. Tech. Bul. 158, 39 p., illus.

(7) NEWLIN, J. A., and WILSON, T. R. C.
1917. MECHANICAL PROPERTIES OF WOODS GROWN IN THE UNITED STATES. U. S. Dept. Agr. Bul. 556, 47 p., illus.

(8) ——— and WILSON, T. R. C.
1919. THE RELATION OF THE SHRINKAGE AND STRENGTH PROPERTIES OF WOOD TO ITS SPECIFIC GRAVITY. U. S. Dept. Agr. Bul. 676, 35 p., illus.

(9) STAMM, A. J.
1929. DENSITY OF WOOD SUBSTANCES, ADSORPTION BY WOOD, AND PERMEABILITY OF WOOD. Jour. Phys. Chem. 33: 398-414, illus.

(10) ———
1929. FIBER-SATURATION POINT OF WOOD AS OBTAINED FROM ELECTRICAL CONDUCTIVITY MEASUREMENTS. Indus. and Engin. Chem., Analyt. Ed. 1: 94-97, illus.

(11) SUDWORTH, G. B.
1927. CHECK LIST OF THE FOREST TREES OF THE UNITED STATES, THEIR NAMES AND RANGES. U. S. Dept. Agr. Misc. Circ. 92, 295 p.

(12) TIEMANN, H. D.
1906. EFFECT OF MOISTURE UPON THE STRENGTH AND STIFFNESS OF WOOD. U. S. Dept. Agr., Forest Serv. Bul. 70, 144 p., illus.

(13) ———
1907. THE STRENGTH OF WOOD AS INFLUENCED BY MOISTURE. U. S. Dept. Agr., Forest Serv. Circ. 108, 42 p., illus.

(14) TRAYER, G. W., and MARCH, H. W.
1930. THE TORSION OF MEMBERS HAVING SECTIONS COMMON IN AIRCRAFT CONSTRUCTION. Natl. Advisory Com. Aeronaut. Ann. Rpt. (Tech. Rpt. 334) 49: 671-719, illus.

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