THE ELASTIC PROPERTIES OF WOOD
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THE ELASTIC PROPERTIES OF WOOD[1]

Young's Moduli and Poisson's Ratios of Sitka Spruce

And Their Relations to Moisture Content[2]

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Summary

This report presents data obtained at the Forest Products Laboratory on the Young's moduli and Poisson's ratios of Sitka spruce as found from tests in compression at moisture content values of approximately 7, 13, 16, and 22 percent. A summary table is presented showing averages for each of 14 planks and grand averages for the three Young's moduli and their ratios and for the six Poisson's ratios. Graphs are presented to illustrate the effects of moisture content on the elastic constants and the relation of the elastic constants to specific gravity.

Although trends are somewhat obscured by variability among specimens, it appears that Young's moduli show some tendency toward increase with increase in specific gravity, whereas Poisson's ratios show no correlation. The three Young's moduli and their ratios, and the six Poisson's ratios

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[1]This is one of a series of progress reports prepared by the Forest Products Laboratory relating to the use of wood in aircraft. Results here reported are preliminary and may be revised as additional data become available.

[2]This report is the second of a series of reports presenting the elastic properties of wood. The first report was "The Elastic Properties of Wood -- The Young's Moduli, Moduli of Rigidity, and Poisson's Ratios of Balsa and Quipo," Forest Products Laboratory Report No. 1528.

[3]Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

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are variously influenced by moisture. Each of the three Young's moduli increase with a reduction in moisture, but the increase is at a much greater rate for E_R and E_T than for E_L; hence the ratios E_R/E_L and E_T/E_L increase with a decrease in moisture content. The four larger Poisson's ratios tend to decrease with a reduction in moisture, whereas the reverse is true of the two smaller ratios. The tests indicate that the two small Poisson's ratios, μ_{TL} and μ_{RL}, can probably be calculated more accurately from elastic constant relations using measured values of related constants than they can be measured directly by available methods.

Introduction

In the past, the determination of average values for the elastic properties of wood has been given less attention than the establishment of strength values. Tests have been conducted recently at the Forest Products Laboratory to determine the elastic constants of a number of species used in aircraft and to show their correlation, if any, with density and moisture content of the wood.

This report, which presents data on the elastic properties of Sitka spruce, is the second of a series on "Elastic Properties of Wood." A previous report[2] has been published for balsa and quipo. All symbols and terminology used in the present report conform to the definitions and nomenclature presented in the previous report.

Description of Material

Type of Specimens

Standard 2- by 2- by 8-inch compression prisms were used for all tests included in this study. The anisotropic character of wood requires for the determination of the three Young's moduli and the six Poisson's ratios the use of three types of compression prisms differing in the way in which they are oriented with respect to the grain and the growth rings of the tree. Figure 1 shows the orientation of the three types in relation to the tree. The longitudinal (L)-type is the standard compression-parallel-to-grain specimen. Particular care was taken to aline the annual rings parallel to the long axis of the L-specimens. The radial (R)- and tangential (T)-types were cut so that their long axes would be as nearly as possibly perpendicular and tangential respectively to the growth rings. Figure 1 in Report[2] No. 1528 shows the five types of specimens used in these tests.

Source and Selection of Material

Material for these tests was obtained from 14 planks selected from Sitka spruce on hand at the Laboratory. Details about the logs from which the planks were cut are given in table 1.

The logs were cut at the Laboratory into 3-inch planks of various widths. Most of the planks were flat-sawn, but about 24 planks from logs Nos. 24 and 28 were quarter-sawn. The planks were kiln-dried to about 13 percent moisture content and subsequently stored in an open shed.

The material for test purposes was selected to include a variety of growth conditions and densities so that the elastic constants might be expected to represent the range of material ordinarily found in Sitka spruce. Several planks of low density and wide annual rings were taken from near the pith. Others were taken from the outer portion of the log, typical of close-grained, slow-growth wood, and the remainder from intermediate positions representing average growth conditions.

In addition to covering a range of density and growth conditions, it was necessary to provide for radial and tangential specimens by selection of suitable planks. Three quarter-sawn pieces were taken so that 8-inch solid radial compression specimens might be prepared. Some of the flat-sawn planks were selected for minimum curvature of the rings to provide material for 8-inch tangential specimens. Straightness of grain and freedom from defects were factors which governed the selection of the material throughout. Table 1 shows the source and characteristics of the pieces. Two flat-sawed planks provided a total of 12 solid tangential specimens, and three quarter-sawed planks provided a total of 18 solid radial specimens. In addition, 45 radial and 46 tangential specimens representing material from each of the 14 planks were built up by gluing together 4 ring-matched 2-inch cubes. A total of 182 specimens were included in this study.

Preparation of Planks and Test Pieces

The selected planks were surfaced on both faces to reveal the characteristics of grain. A section about 6 feet long, with a minimum of knots and other defects and with straight grain, was selected from each plank for compression specimens. The material when selected had no serious checks or shrinkage defects in the portions used for specimens.

In nine of the planks, namely, those flat-sawn pieces which had comparatively sharp ring curvature, the 2- by 2- by 8-inch compression specimens parallel to the grain (L) were end-matched. For this purpose a stick about 2-1/2 inches square in cross section, with its faces parallel and perpendicular to the annual rings, was cut parallel to the grain from the 6-foot test section (upper diagram, fig. 2). The individual specimens were taken in succession along the stick, thus placing them end-to-end in the same band of annual rings. Minor changes in direction were made in the final cutting so that alinement of the faces parallel to grain and tangential to the rings would be most favorable.

The remaining five planks, namely, those for solid radial specimens (series 30, 40, and 110), and for tangential specimens with flat rings (series 60 and 90), were dressed to approximately 10-inch width and cut to produce 6 transverse and 18 longitudinal pieces as shown in the lower diagram of figure 2. The individual pieces were reduced to final size, surfaced to true parallel and perpendicular faces, and stored in a 75° F., 65 percent relative humidity room for conditioning. Equilibrium moisture content of approximately 13 percent was attained prior to test.

Marking of Specimens

The specimens from each plank (table 1) are referred to as a series within which the individual pieces were matched so that direct comparisons could be made. Each specimen carried the series designation by means of the first digit or the first two digits of its number, and a final digit which showed its location in the plank. The digit following the decimal point in some of the specimen numbers differentiated between the three specimens cut from the same longitudinal section of a plank (fig. 2).

In series 10 and similar series having no solid radial or tangential specimens, the arrangement for matching and marking was as shown in the upper diagram of figure 2, and in table 2.

In series 30 and similar series in which solid radial or tangential specimens could be obtained, the specimens were arranged as shown in the lower part of figure 2. Each plank thus provided one group of six solid radial or tangential specimens (depending on the grain of the plank) in the transverse direction, together with six sets of three specimens each in the longitudinal direction. From each longitudinal set one specimen was tested in compression parallel to the grain (making a group of six longitudinal specimens from each plank), and the other two pieces were cut into 2-inch cubes for radial and tangential glued specimens. Positions of the longitudinal pieces were alternated to provide the best matching, according to the schedules in tables 3 and 4.

Matching of Specimens

The available material did not provide stock which would meet the requirements for ideal matching of specimens. In order to obtain longitudinal, radial, and tangential compression specimens of 8-inch length with the best matching it would be necessary to have a block about 9 inches in its minimum dimension, and in which the growth rings have but little curvature.

Since the planks available for these tests were not over 3-1/2 inches thick, any one plank could provide only the longitudinal specimens and matched specimens in one of the two remaining directions. In the third direction, that of the plank thickness, it was necessary to resort to gluing.

A reasonable approach to the ideal matching was made in series 110 and 120, in which planks 28-34 and 28-36 (table 1) were radial and tangential pieces adjacent to each other and at the same average distance from the pith. Otherwise, the material available did not permit direct matching, and comparisons between series were necessarily based upon density values.

Testing Procedure

Instruments and their arrangement, methods of computation, and general testing procedure were as described in Forest Products Laboratory Report[2] No. 1528.

Longitudinal specimens were loaded to approximately 1,250 pounds per square inch; radial and tangential specimens to about 125 pounds per square inch.

Three to five independent sets of values (each from two or more runs at each instrument setting) were made at the initial moisture content of about 13 percent. Specimens were then conditioned successively at 80° F., 30 percent relative humidity (approximately 7 percent moisture content), 80° F., 90 percent relative humidity (approximately 16 percent moisture content), and 80° F., 97 percent relative humidity (approximately 22 percent moisture content), and two or three independent sets of values were obtained with each instrument arrangement at each moisture content. All specimens were finally reconditioned to approximately 13 percent moisture content (80° F., 65 percent relative humidity) and then tested to failure. In these final tests measurements for Young's modulus were made on one pair of faces, and one Poisson's ratio was obtained.

Explanation of Tables and Figures

Tables 1, 2, 3, and 4 present data on the cutting, matching, and marking of specimens as referred to previously.

Table 5 presents a summary of the average Young's moduli and Poisson's ratios for each of the 14 planks at each of the 4 moisture content conditions, and, in addition, average values for all individual specimens of each type. In forming the averages for the individual specimens, values from individual specimens were given equal weight. The averages at approximately 13 percent moisture do not include the values obtained in the final runs when specimens were reconditioned and tested until they failed.

Table 6 compares the average Young's moduli and Poisson's ratio values for solid radial and tangential specimens with those for glued specimens.

Table 7 shows ratios of the various elastic constants calculated from the averages listed in table 5.

Table 8 shows a comparison of average measured values for the two small Poisson's ratios, μ_{RL} and μ_{TL}, with values calculated from the averages for related constants as shown in table 5, and with values calculated from computed constants determined by means of best-fit curves (figs. 14 and 15).

In figures 3, 4, and 5 the values of the three Young's moduli at approximately 13 percent moisture content are plotted against specific gravity. The points shown, for individual specimens, represent average values for modulus of elasticity (E_L, E_T, or E_R) from measurements on the two sets of faces at the initial moisture condition of about 13 percent.

Figures 6 through 11 show the values of Poisson's ratio for individual specimens at the initial moisture content of about 13 percent, plotted against the corresponding specific gravity.

Figures 12 and 13 are graphs showing the average ratios E_R/E_L and E_T/E_L for each of the 14 planks used in this study at approximately 13 percent moisture content, plotted against the average specific gravity of the plank. Calculation of ratios for individual specimens was not feasible because of a lack of one-to-one matching. All planks included at least 2 specimens of each type.

Figure 14 shows the variation of the 3 Young's moduli with moisture content. The individual points represent average values from approximately 60 specimens of each type tested at each of the 4 values of moisture content (table 5). The values for the Young's moduli are plotted on a logarithmic scale as ordinates, and the moisture content on a uniform scale as abscissas. The curves shown are the best-fit linear relationships calculated by the method of least squares(regression of log E on moisture content). The figures in parentheses show the percentage increase for a 1 percent decrease in moisture content.

Figure 15 shows the variation of the Poisson's ratios with moisture content. The individual points represent average values from approximately 60 specimens of each type tested at 4 moisture content values. The Poisson's ratio values are plotted to a logarithmic scale as ordinates and the moisture content to a uniform scale as abscissas. The curves shown are the best-fit linear relationships for each series of points determined by the method of least squares (regression of log μ on moisture content). The figures in parentheses represent the percentage increase (positive values) or decrease (negative values) for 1 percent decrease in moisture content. The dashed lines represent values of μ_{RL} and μ_{TL} computed from the elastic constant relationships using values of the other 4 Poisson's ratios and of Young's moduli as read from the straight lines shown in figures 14 and 15.

Figure 16 shows the effect of moisture on the ratios E_R/E_L, E_T/E_L, E_T/E_R, μ_{RL}/μ_{LR}, μ_{TL}/μ_{LT}, and μ_{TR}/μ_{RT}. Individual points on each curve represent the average ratios for all specimens included in the study (table 5). The ratios are plotted to a logarithmic scale as ordinates and the moisture content to a uniform scale as abscissas. The curves shown are the best-fit linear relationships determined by the method of least squares (regression of log R on moisture content). The figures in parentheses show the percentage increase (positive values) or decrease (negative values) in the ratios for each 1 percent decrease in moisture content.

Figure 17 shows the stress at proportional limit and maximum crushing strength for each of the 61 longitudinal specimens plotted against specific gravity.

Discussion of Results

Variability of Young's Moduli and Poisson's Ratios

The values for the elastic constants in table 5 represent average values for the planks and for Sitka spruce as a species, but all elastic constants were variable for a particular moisture content and specific gravity. For example, at about 13 percent moisture content and a specific gravity of 0.375, the measured values for Young's moduli ranged as follows: E_L from 1,100,000 to 2,100,000 pounds per square inch (fig. 3), E_R from 110,000 to 180,000 pounds per square inch (fig. 4), and E_T from 60,000 to 90,000 pounds per square inch (fig. 5).

It is apparent from figures 3, 4, and 5 that the values of Young's modulus as found in these tests are not closely correlated with specific gravity. For specimens of a given species, E_L is expected to vary approximately as the 5/4 power of specific gravity, and a curve of that power for Sitka spruce is shown for comparison with the plotted points (fig. 3). Figure 4 indicates practically no relationship of E_R to specific gravity, while figure 5 suggests a tendency of E_T to increase as specific gravity increases. Consistent with this is the indication from figure 12 of no relation between the ratio E_R/E_L and specific gravity and but a slight suggestion from figure 13 of an increase in the ratio E_T/E_L with increase in specific gravity.

Figures 6 to 11 fail to disclose any relationship between the several Poisson's ratios and specific gravity.

Individual values of the Poisson's ratios ranged as follows: μ_{LR} from 0.225 to 0.475; μ_{LT} from 0.275 to 0.690; μ_{RT} from 0.295 to 0.655; μ_{RL} from 0.017 to 0.070; μ_{TR} from 0.145 to 0.335; μ_{TL} from 0.011 to 0.055. As with the averages shown in table 5, comparisons from the same specimens or from closely matched specimens show μ_{LT} consistently greater than μ_{LR} and μ_{RT} greater than μ_{TR}.

Effect of Location of Axial Compressometer

In the process of obtaining the two Poisson's ratios associated with any one specimen, two independent determinations were made of the Young's modulus, each with the vertical compressometer attached to a different pair of faces. Generally these two determinations gave different values for Young's modulus, although theoretically the same property was measured each time. The differences between the two values of Young's modulus were variable in magnitude and direction and are not considered to be significant. On the average (at all moisture contents), E_L was 0.7 percent higher as found from measurements on the LR face; E_R was 4.3 percent higher on the LR face; and E_T was 1.5 percent higher on the LT face. Individual specimens, however, showed differences between the two determinations that ranged from 0 to 15 percent in magnitude, and approximately 40 percent of them showed differences in the direction opposite to the average trend. Specimens that showed large differences in the two values of the elastic modulus were rerun in an attempt to reduce the discrepancy and to determine the correct value, but no amount of checking changed the results appreciably. Since no precedence could be given to either value, both were given equal weight in forming the averages entered in columns 6, 9, and 12 of table 5.

Effect of Glue

To avoid a wide range of growth conditions represented by the numerous growth rings in solid radial specimens, and to provide better matching to longitudinal and tangential specimens, some of the radial prisms were constructed by gluing together ring-matched 2-inch cubes, thereby reducing from 8 to 2 inches, the distance over which growth variation could exist. A comparison of group averages at all moisture content values (table 6) shows that, in general, the glued specimens had a Young's modulus (E_R) about 6 percent higher than the solid specimens. The Poisson's ratio (μ_{RL}) was about 12 percent higher for the glued specimens, but due to uncertainties in its measurement this difference is not considered significant. The Poisson's ratio (μ_{RT}) varied slightly and inconsistently, tending to be about 4 percent smaller for the glued specimens. Considering the variation among specimens of each type, these percentage differences seem insignificant. It is believed that the advantages gained by gluing ring-matched cubes for radial specimens offset any errors introduced by the presence of glue lines.

In order to avoid excessive curvature of the growth rings in the tangential specimens, some of the prisms were fabricated by gluing together four 2-inch cubes stacked in the T direction. A comparison of group averages at all moisture content values (table 6) shows that, in general, the glued specimens had a Young's modulus (E_T) about 9 percent higher than the solid specimens. The Poisson's ratios (μ_{TL} and μ_{TR}) of the glued specimens were, on the average, 2 percent higher than those for the solid specimens. By comparison with the variation of results for individual specimens of either type, this percentage difference seems relatively unimportant. It is probable that the unequal stress distribution due to excessive ring curvature that would develop in a solid tangential specimen bending as a column under load, would give rise to errors more serious than those introduced by the presence of glued joints.

Relations Between Elastic Constants

Frequently the ratios E_R/E_L and E_T/E_L are used to estimate vlues for the Young's moduli perpendicular to grain from measured values of E_L.

Table 5 and figures 12 and 13 show that these ratios vary greatly for the 14 planks included in the study. For example, at about 13 percent moisture content the ratio E_R/E_L ranges from 58 to 136 percent of the average for all specimens and E_T/E_L from 84 to 158 percent. No correlation between these ratios and specific gravity is apparent from figures 12 and 13.

With wood considered as an orthotropic material, the following relations among the elastic constants should exist:

$$\frac{\mu_{LR}}{E_L} = \frac{\mu_{RL}}{E_R};\ \frac{\mu_{LT}}{E_L} = \frac{\mu_{TL}}{E_T};\ \text{and}\ \frac{\mu_{RT}}{E_R} = \frac{\mu_{TR}}{E_T} \qquad (1)\ (2)\ (3)$$

A consideration of table 7 shows that these relations do not hold for the first two equations, except for the 7.1 moisture content. For the third equation they do, however, agree reasonably well at all moisture contents. It may be noted that the first two equations involve the two smallest Poisson's ratios, μ_{RL} and μ_{TL}, which have a magnitude on the order of 0.02 to 0.04. The third relation, which checks reasonably well, involves neither. Considering the difficulties encountered in measuring the extremely small lateral strains (approximately 0.00005 inch) involved in determining μ_{RL} and μ_{TL} over a 2-inch gage length, it seems probable that these ratios are in error and that the first two relationships would check if more accurate measurements could have been made. Further discussion of this point will be found under "Effect of Moisture." It would seem that Jenkin[4] was justified in measuring only the four larger ratios together with the Young's moduli and computing the two smaller ratios from the first two elastic constant relationships.

Effect of Moisture

Studies at the Laboratory regarding the effect of moisture on strength properties of wood have led to the derivation of a general formula for strength adjustment which has been demonstrated to represent adequately the strength-moisture relations for numerous properties. This formula, known as the exponential formula[5], is based on the fact that for any one species and strength property, moisture-content values within certain limits and the logarithms of corresponding strength values have been found to conform closely to a straight-line relationship.

Reports of previous investigations[6] have included some information on the variation of E_L with moisture, but no comparable data regarding other elastic properties. Results from this study show that when the average

[4] Jenkin, C. F., "Report on Materials of Construction Used in Aircraft and Aircraft Engines," Aeronautical Research Committee (British), 1920, p. 104.

[5] $S = S_o \times 10^{-KM}$ 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.

[6] U. S. Dept. Agr. Tech. Bull. No. 282; U. S. Dept. Agr. Tech. Bull. No. 479; U. S. Dept. Agr. "Wood Handbook"; Forest Products Laboratory Reports 1306, 1313, and 1519.

values of Young's moduli for all specimens (table 5) are plotted to a logarithmic scale as ordinates and the corresponding moistures to a uniform scale as abscissas, (fig. 14), the data for E_L conform closely to a straight-line relationship, and those for E_R and E_T show reasonable conformity. Inasmuch as the values at the several moisture content levels were obtained on the same specimens rather than on matched materials, the agreement to a straight-line relationship serves as further substantiation of the general formula.

It is evident that if the Young's moduli are influenced by moisture, to maintain equality in the elastic constant relations shown in equations (1) to (3), the Poisson's ratios must likewise be affected. Average values for Poisson's ratios (table 5) at the four moistures, when plotted as previously indicated (fig. 15), conform reasonably well to a straight-line relationship (solid lines) except for μ_{RL} and μ_{TL}, the two ratios that are small and difficult to measure accurately. The dashed lines marked "computed" for these two ratios are discussed later in the report.

The elastic constant relations previously given (formulas (1), (2), (3)) may be rearranged as follows:

$$\frac{E_R}{E_L} = \frac{\mu_{RL}}{\mu_{LR}}; \quad \frac{E_T}{E_L} = \frac{\mu_{TL}}{\mu_{LT}}; \quad \frac{E_T}{E_R} = \frac{\mu_{TR}}{\mu_{RT}} \qquad (4)\ (5)\ (6)$$

It is apparent that the ratios of the Young's moduli and the Poisson's ratios in equations (4) and (5) will be considerably influenced by moisture because of the difference in effect on the values comprising the numerator and denominator, whereas in equation (6) they will be little affected.

These relationships are shown graphically in figure 16 where average ratios for all specimens of a type at the 4 moistures are plotted on semilog paper, together with average lines representing the relationship. For perfect conformity to equations (4), (5), and (6) the lines representing ratios of E and of μ should coincide. This condition is nearly satisfied in the case of μ_{TR}/μ_{RT} and E_T/E_R (equation 6). For the other 2 cases it may be noted that the slope of lines representing Poisson's ratio and Young's moduli is nearly the same, but the ratios involving μ are somewhat greater in magnitude than those involving E. In these cases, μ_{RL} and μ_{TL}, which are probably in error, are involved. If it is assumed that the moisture relations involving E_R, E_T, μ_{LR}, and μ_{LT} are essentially correct (which would appear reasonable from an examination of the moisture relations for these factors in figs. 14 and 15) it follows that μ_{RL} and μ_{TL} must, on the average, be reduced in order to have the corresponding Poisson's ratio and Young's moduli lines coincide in figure 16.

It should be noted further that the points representing μ_{RL}/μ_{LR} and μ_{TL}/μ_{LT} esentially coincide with those for E_R/E_L and E_T/E_L at the lowest moisture content value (7.1 percent). The dashed lines shown in figure 15 for μ_{RL} and μ_{TL} represent the relationship of these Poisson's ratio values to moisture content which would yield a ratio with μ_{LR} and μ_{LT} such that the lines representing the ratios of μ in figure 16 would coincide with those for E_R/E_L and E_T/E_L. This is equivalent to calculating μ_{RL} and μ_{TL} from elastic constant relations in which values for the related constants are computed from values read from the solid curves shown in figures 14 and 15.

As previously pointed out, the values for μ_{RL} and μ_{TL} are frequently calculated by use of the elastic constant relations. Thus

$$\mu_{RL} = \frac{E_R}{E_L}\mu_{LR} \text{ and } \mu_{TL} = \frac{E_T}{E_L}\mu_{LT} \quad (7)\ (8)$$

It is interesting to note that values calculated by this method agree closely with those obtained from computations based on the dashed lines in figure 15. A comparison of the average measured values with values computed by the 2 methods described is shown in table 8.

It must be recognized that the effect of moisture may, to a large extent, be obscured by the great variability existing in measured values of the elastic constants and their ratios.

Ultimate Strength

Figure 17 shows that for mazimum crushing strength in compression parallel to grain, the correlation with specific gravity is somewhat better than for the elastic moduli (figs. 3, 4, and 5). In the present tests, with an average moisture content of 13 percent and specific gravity of 0.378, the average maximum crushing strength was 5,190 pounds per square inch. In tests reported in U. S. Department of Agriculture Technical Bulletin No. 479, the maximum crushing strength was 5,610 pounds per square inch when moisture content was 12 percent and specific gravity was 0.40. The difference in maximum crushing strength for the material used in these tests and the species' average reported in Bulletin 479 would appear to be due to the differences in specific gravity and moisture content.

No definite maximum load could be determined in compression perpendicular to grain. The average stress at proportional limit for radial specimens was 230 pounds per square inch and for tangential specimens 190 pounds per square inch.

Conclusions

The conclusions from this study, based upon compression tests of solid and glued Sitka spruce specimens, are as follows:

1. The average maximum crushing strength of the material used in this series of tests appears to agree closely with the species' average for Sitka spruce.

2. Both Young's modulus and Poisson's ratio values are quite variable. The averages shown in table 5 are probably fairly representative of the species, but it must be recognized that values for individual specimens may differ considerably from the average values.

3. The values for Young's moduli show some tendency to increase with an increase in specific gravity, but those for Poisson's ratios exhibit no correlation with specific gravity.

4. The three Young's moduli are affected by moisture, but to a different degree. The moduli in the directions perpendicular to grain (E_R and E_T) change with moisture at about five times the rate for the modulus parallel to grain (E_L).

5. The six Poisson's ratios are likewise affected by moisture, each to a different degree. The four larger ratios (μ_{LT}, μ_{RT}, μ_{LR}, and μ_{TR}) tend to decrease with a decrease in moisture, while the two smaller ratios (μ_{RL} and μ_{TL}) increase with a decrease in moisture.

6. Use of average ratios for E_R/E_L and E_T/E_L to calculate Young's moduli perpendicular to grain is not recommended if direct measurements can be made, both because such ratios are extremely variable and because they are considerably influenced by moisture.

7. More accurate values for the two small Poisson's ratios, μ_{TL} and μ_{RL}, can probably be calculated from the elastic relationships utilizing measured values for E_L, E_T, E_R, μ_{LT} and μ_{LR} than can be obtained by direct measurement under available procedures.

Table 1.--Source and characteristics of specimens for determination of elastic constants of Sitka spruce

Series number	Log number[1]	Log diameter	Plank number	Type of plank	Distance from center[2]	Average rings per inch
		Inches			Inches	Number
10	23	46	23-10	Flat-sawed	8	13
20	23	46	23-12	.....do......	14	23
30	24	71	24-31	Quarter-sawed	25	14
40	24	71	24-44	.....do......	27	15
50	24	71	24-77	Diagonal	6	4
60	24	71	24-79	Flat-sawed	31	19
70	25	53	25-3	.....do......	16	39
80	25	53	25-14	.....do......	23	34
90	26	52	26-31	.....do......	20	25
100	27	56	27-11	.....do......	12	32
110	28	58	28-34	Quarter-sawed	23	17
120	28	58	28-36	Flat-sawed	23	20
130	29	42	29-26	.....do......	18	6
140	29	42	29-35	.....do......	15	8

[1]Log Nos. 23 to 27, inclusive, were received at the Laboratory September 20, 1940 from Tillamook, Oregon; log Nos. 28 and 29 were received May 5, 1941, from Clatsop County, Oregon.

[2]Distance measured from the pith center of the log to the mid-point of the plank.

Table 2.--Matching plan for specimens used in determining the elastic constants of Sitka spruce (Series 10, 20, 50, 70, 80, 100, 120, 130, and 140)

Specimen number[1]	Type of specimen	Values measured
11	Longitudinal - solid	E_L, μ_{LR}, μ_{LT}
13	Radial - glued	E_R, μ_{RL}, μ_{RT}
14	Tangential - glued	E_T, μ_{TL}, μ_{TR}
15	Radial - glued	E_R, μ_{RL}, μ_{RT}
17	Tangential - glued	E_T, μ_{TL}, μ_{TR}
18	Longitudinal - solid	E_L, μ_{LR}, μ_{LT}
[2]19	Longitudinal - solid	E_L, μ_{LR}, μ_{LT}
11-b	Longitudinal - solid	E_L, μ_{LR}, μ_{LT}

[1]Numbers shown are for series 10. In the other series the last digit was kept the same for comparable specimens and the first digit was replaced by another digit or two digits to indicate the series (plank) number. Final dimensions of specimens were 2 by 2 by 8 inches. Specimens were taken in numerical order along stick. (See fig. 2, upper diagram.)

[2]This specimen was also tested for proportional limit and ultimate compression strength on the initial tests at approximately 13 percent moisture.

Table 3.--Matching plan for specimens used in determining the elastic constants of Sitka spruce (Series 30, 40, and 110)

Group	Specimen number[1]	Direction	Solid or glued	Values measured
1	31.1, 33.3, 34.2 35.1, 37.3, 38.2	Longitudinal	Solid	E_L, μ_{LR}, μ_{LT}
2	32.1, 32.2, 32.3 36.1, 36.2, 36.3	Radial	Solid	E_R, μ_{RL}, μ_{RT}
3	31.2, 33.1, 34.3 35.2, 37.1, 38.3	Radial	Glued	E_R, μ_{RL}, μ_{RT}
4	31.3, 33.2, 34.1 35.3, 37.2, 38.1	Tangential	Glued	E_T, μ_{TL}, μ_{TR}

[1]Numbers shown are for series 30. In the other series the last digit and decimal were kept the same for comparable specimens, and the first digit was replaced by another digit or two digits to indicate the series number. Final dimensions of specimens were 2 by 2 by 8 inches. Specimens were taken as shown in figure 2, lower diagram.

Table 4.--Matching plan for specimens used in determining the elastic constants of Sitka spruce (Series 60 and 90)

Group	Specimen number[1]	Direction	Solid or glued	Values measured
1	61.1, 63.3, 64.2 65.1, 67.3, 68.2	Longitudinal	Solid	E_L, μ_{LR}, μ_{LT}
2	62.1, 62.2, 62.3 66.1, 66.2, 66.3	Tangential	Solid	E_T, μ_{TL}, μ_{TR}
3	61.2, 63.1, 64.3 65.2, 67.1, 68.3	Tangential	Glued	E_T, μ_{TL}, μ_{TR}
4	61.3, 63.2, 64.1 65.3, 67.2, 68.1	Radial	Glued	E_R, μ_{RL}, μ_{RT}

[1]Numbers shown are for series 60. In series 90 the last digit and decimal were kept the same for comparable specimens, and the first digit was replaced by 9 to indicate the series number. Final dimensions of specimens were 2 by 2 by 8 inches. Specimens were taken as shown in figure 2, lower diagram.

Table 5.--Summary of Young's moduli and Poisson's ratios for Sitka spruce

Series No.	Average moisture content[1]	Average specific gravity[1,2]	Average Young's moduli[1]: Compression L (E_L): Compressometer on LR faces	Compression L (E_L): Compressometer on LT faces	Compression L (E_L): Average	Compression R (E_R): Compressometer on LR faces	Compression R (E_R): Compressometer on RT faces	Compression R (E_R): Average	Compression T (E_T): Compressometer on LT faces	Compression T (E_T): Compressometer on RT faces	Compression T (E_T): Average	Ratios of Young's moduli: $\frac{E_R}{E_L}$[4]	Ratios of Young's moduli: $\frac{E_T}{E_L}$[5]	Average Poisson's ratios[3]: Compression L: μ_{LR}	Compression L: μ_{LT}	Compression R: μ_{RL}	Compression R: μ_{RT}	Compression T: μ_{TL}	Compression T: μ_{TR}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)
	Percent		1000 psi	1000 psi	1000 psi	1000 psi	1000 psi	1000 psi	1000 psi	1000 psi	1000 psi								
10	6.8	....	1,362	1,363	1,362	123	172	148	98	98	98	0.109	0.072	0.434	0.602	0.033	0.530	0.039	0.271
	13.4	0.382	1,239	1,233	1,236	130	126	128	90	77	84	.104	.068	.436	.619	.046	.472	.040	.286
	16.4	....	1,180	1,218	1,199	112	94	103	78	69	74	.086	.062	.442	.630	.046	.516	.037	.342
	19.7	....	1,216	1,252	1,234	90	76	83	56	82	69	.067	.056	.468	.685	.034	.478	.029	.348
20	7.1	....	1,499	1,475	1,487	168	172	170	....	....	....	.114	....	.425	.537	.047	.374	....	....
	13.5	.437	1,438	1,420	1,429	154	128	141	....	....	....	.099	....	.408	.580	.047	.430	....	....
	16.5	....	1,388	1,336	1,362	116	110	113	....	....	....	.083	....	.427	.591	.041	.464	....	....
	20.6	....	1,339	1,332	1,336	94	88	91	....	....	....	.068	....	.389	.640	.026	.460	....	....
30	6.9	....	1,781	1,788	1,784	161	169	165	87	80	84	.092	.047	.398	.428	.035	.479	.024	.238
	13.2	.368	1,778	1,763	1,770	143	127	135	78	63	70	.076	.040	.403	.494	.041	.435	.027	.248
	16.6	....	1,703	1,682	1,692	115	107	111	56	50	53	.066	.031	.409	.524	.029	.529	.017	.276
	21.0	....	1,632	1,607	1,620	93	87	90	39	36	38	.056	.023	.394	.533	.025	.517	.015	.261
40	7.3	....	1,423	1,446	1,434	142	148	145	80	80	80	.101	.056	.420	.503	.037	.498	.025	.273
	12.3	.351	1,416	1,425	1,420	143	121	132	71	64	68	.093	.048	.430	.552	.046	.443	.031	.267
	16.1	....	1,341	1,324	1,332	106	104	105	58	55	56	.079	.042	.429	.571	.031	.572	.025	.285
	21.4	....	1,232	1,297	1,264	88	84	86	46	42	44	.068	.035	.452	.616	.024	.560	.024	.292
50	7.3	....	1,340	1,246	1,293	106	118	112	50	48	49	.087	.038	.449	.418	.040	.764	.020	.244
	11.8	.304	1,184	1,148	1,166	101	94	98	43	40	42	.084	.036	.464	.497	.045	.593	.024	.241
	16.9	....	1,226	1,191	1,208	74	78	76	36	35	36	.063	.030	.481	.512	.032	.752	.017	.302
	22.3	....	1,164	1,145	1,154	50	48	49	24	21	22	.042	.019	.512	.490	.042	.566	.015	.178
60	7.2	....	1,439	1,410	1,424	173	184	178	87	89	88	.125	.062	.371	.465	.043	.421	.027	.232
	12.3	.355	1,433	1,392	1,412	149	150	150	75	72	74	.106	.052	.390	.535	.044	.365	.030	.226
	16.7	....	1,361	1,306	1,334	128	109	118	58	59	58	.088	.043	.362	.548	.042	.462	.027	.267
	20.9	....	1,359	1,291	1,325	110	103	106	49	49	49	.080	.037	.376	.592	.023	.501	.022	.270
70	6.6	....	2,094	1,978	2,036	166	146	156	104	104	104	.077	.051	.290	.290	.027	.300	.022	.194
	12.6	.386	2,012	1,989	2,000	173	113	143	96	80	88	.072	.044	.273	.354	.040	.296	.023	.190
	15.3	....	1,944	1,912	1,928	105	99	102	76	63	70	.053	.036	.266	.377	.021	.336	.020	.194
	21.1	....	1,755	1,797	1,776	80	78	79	54	48	51	.044	.029	.198	.358	.018	.309	.017	.210
80	7.2	....	1,473	1,443	1,458	159	165	162	98	89	94	.111	.064	.333	.381	.034	.434	.029	.203
	11.9	.347	1,442	1,428	1,435	159	144	152	90	78	84	.106	.058	.318	.398	.053	.390	.036	.178
	16.1	....	1,360	1,350	1,355	120	110	115	64	60	62	.085	.046	.322	.459	.036	.481	.025	.234
	21.8	....	1,329	1,322	1,326	98	86	92	46	48	47	.069	.035	.278	.477	.028	.466	.020	.240
90	7.0	....	1,936	1,901	1,918	144	140	142	74	79	76	.074	.040	.322	.364	.025	.414	.014	.237
	12.8	.371	1,922	1,902	1,912	131	117	124	66	69	68	.065	.036	.276	.382	.026	.380	.018	.247
	15.9	....	1,812	1,814	1,813	89	96	92	52	54	53	.051	.029	.312	.433	.016	.467	.012	.260
	21.5	....	1,781	1,816	1,798	78	76	77	40	41	40	.043	.022	.323	.476	.010	.467	.009	.255
100	6.8	....	2,316	2,473	2,394	125	130	128	97	118	108	.053	.045	.300	.327	.016	.319	.013	.231
	11.6	.421	2,352	2,359	2,356	101	112	106	76	91	84	.045	.036	.309	.359	.020	.303	.012	.222
	15.7	....	2,180	2,356	2,268	76	78	77	64	68	66	.034	.029	.286	.364	.014	.332	.012	.239
	20.4	....	2,321	2,391	2,356	52	56	54	45	48	46	.023	.020	.318	.345	.012	.326	.014	.244
110	7.3	....	1,825	1,828	1,826	152	145	148	89	88	88	.081	.048	.411	.456	.035	.478	.019	.263
	13.6	.411	1,793	1,818	1,806	132	119	126	76	68	72	.070	.040	.415	.499	.040	.493	.024	.262
	17.1	....	1,694	1,725	1,710	99	95	97	60	56	58	.057	.034	.407	.525	.032	.566	.022	.336
	22.7	....	1,633	1,672	1,652	78	76	77	44	42	43	.047	.026	.395	.514	.025	.554	.018	.342
120	7.3	....	2,003	1,979	1,991	160	160	160	98	101	100	.080	.050	.389	.438	.033	.428	.022	.288
	13.1	.427	1,966	1,964	1,965	158	128	143	74	72	73	.073	.037	.377	.420	.044	.452	.028	.276
	15.9	....	1,925	1,869	1,897	110	118	114	63	66	64	.060	.034	.396	.487	.032	.549	.022	.310
	21.4	....	1,788	1,790	1,789	90	90	90	52	54	53	.050	.030	.391	.560	.018	.518	.016	.328
130	7.1	....	1,801	1,797	1,799	166	164	165	102	115	108	.092	.061	.379	.421	.032	.475	.016	.310
	13.8	.420	1,765	1,598	1,682	146	131	138	88	92	90	.082	.054	.384	.410	.038	.438	.019	.319
	16.3	....	1,684	1,642	1,661	116	108	112	75	74	74	.067	.045	.374	.462	.027	.502	.019	.312
	21.9	....	1,582	1,506	1,544	77	76	76	54	56	55	.049	.036	.373	.497	.017	.474	.014	.328
140	7.3	....	2,032	1,979	2,006	132	132	132	80	86	83	.066	.041	.297	.402	.024	.503	.014	.300
	12.6	.373	1,938	1,986	1,962	118	110	114	74	72	73	.058	.037	.292	.371	.025	.422	.018	.284
	15.9	....	1,926	1,901	1,914	92	94	93	56	54	55	.049	.029	.296	.447	.016	.570	.011	.298
	22.4	....	1,689	1,570	1,630	70	72	71	40	38	39	.044	.024	.285	.423	.010	.538	.010	.284
Averages[6]	7.1	....	1,726	1,712	1,719	151	155	153	85	87	86	.089	.050	.375	.436	.034	.468	.022	.248
	12.8	.378	1,696	1,679	1,688	138	124	131	74	70	72	.078	.043	.372	.467	.040	.435	.025	.245
	16.3	....	1,618	1,607	1,612	105	101	103	59	57	58	.064	.036	.374	.504	.030	.527	.020	.278
	21.6	....	1,561	1,552	1,556	85	81	83	45	45	45	.053	.029	.371	.539	.022	.512	.017	.278

[1] Values recorded for each series are the averages of from 8 to 24 specimens of all types.

[2] Specific gravity based on weight when oven-dry and volume at approximately 13 percent moisture content.

[3] Values recorded for each series are the averages of from 2 to 12 specimens of each type.

[4] Column (9) divided by column (6).

[5] Column (12) divided by column (6).

[6] Values shown are averages for individual specimens (61 longitudinal, 63 radial, and 58 tangential.)

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Table 6.--Effect of glue lines on the elastic constants of radial and tangential specimens of Sitka spruce built up from 2-inch cubes as compared to solid prisms[1]

Moisture content	Type of specimen	E_R	E_T	μ_{RL}	μ_{RT}	μ_{TL}	μ_{TR}
Percent		1,000 lb. per sq. in.	1,000 lb. per sq. in.				
7.0	Solid	144	78	0.031	0.466	0.022	0.248
12.8		122	67	.035	.449	.025	.245
16.2		100	54	.029	.542	.020	.278
21.8		82	44	.021	.548	.017	.278
7.2	Glued	156	88	.035	.469	.022	.254
12.9		134	74	.043	.429	.026	.248
16.6		104	59	.030	.521	.021	.284
22.1		84	45	.023	.498	.017	.284
7.1	Ratio: $\frac{\text{Glued}}{\text{Solid}}$	1.08	1.13	1.13	1.01	1.00	1.02
12.8		1.10	1.10	1.23	.96	1.04	1.01
16.3		1.04	1.09	1.04	.96	1.05	1.02
21.6		1.02	1.02	1.10	.91	1.00	1.02
	Average ratio	1.06	1.09	1.12	.96	1.02	1.02

[1]The number of specimens of each type was as follows: 18 solid radial, 45 glued radial, 12 solid tangential, and 46 glued tangential.

Table 7.--Relations between the elastic constants of Sitka spruce[1]

Moisture content	$\frac{\mu_{LR}}{E_L}$	$\frac{\mu_{RL}}{E_R}$	$\frac{\mu_{LT}}{E_L}$	$\frac{\mu_{TL}}{E_T}$	$\frac{\mu_{RT}}{E_R}$	$\frac{\mu_{TR}}{E_T}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Percent	Sq.in.per lb. $X10^{-6}$	Sq.in.per lb. $X10^{-6}$	Sq.in.per lb. $X10^{-6}$	Sq.in.per lb. $X10^{-6}$	Sq.in.per lb. $X10^{-6}$	Sq.in.per lb. $X10^{-6}$
7.1	0.218	0.222	0.254	0.256	3.06	2.88
12.8	.220	.305	.277	.347	3.32	3.40
16.3	.232	.291	.313	.345	5.12	4.79
21.6	.238	.265	.346	.378	6.17	6.18

[1]From theoretical relations among the constants, the values in column (2) should equal those in column (3); similarly, column (4) should equal (5), and column (6) equal (7).

Table 8.--Comparison of the average measured values for μ_{RL} and μ_{TL} for Sitka spruce specimens with those calculated from average values of related elastic constants and from best-fit curves

Average moisture content	Average values from table 5		Values computed from elastic constant relations[1]		Values computed from moisture relations[2]	
	μ_{TL}	μ_{RL}	μ_{TL}	μ_{RL}	μ_{TL}	μ_{RL}
7.1	0.022	0.034	0.022	0.033	0.022	0.034
12.8	.025	.040	.020	.029	.019	.028
16.3	.020	.030	.018	.024	.018	.024
21.6	.017	.022	.016	.020	.016	.020

[1] $\mu_{TL} = \frac{E_T}{E_L}\mu_{LT}$ and $\mu_{RL} = \frac{E_R}{E_L}\mu_{LR}$. Values for E_L, E_T, E_R, μ_{LT} and μ_{LR} were obtained from averages shown in table 5.

[2] Values for E_L, E_T, E_R, μ_{LT} and μ_{LR} were read from the best-fit lines shown in figures 14 and 15 and used in the equations shown in footnote 1, above.

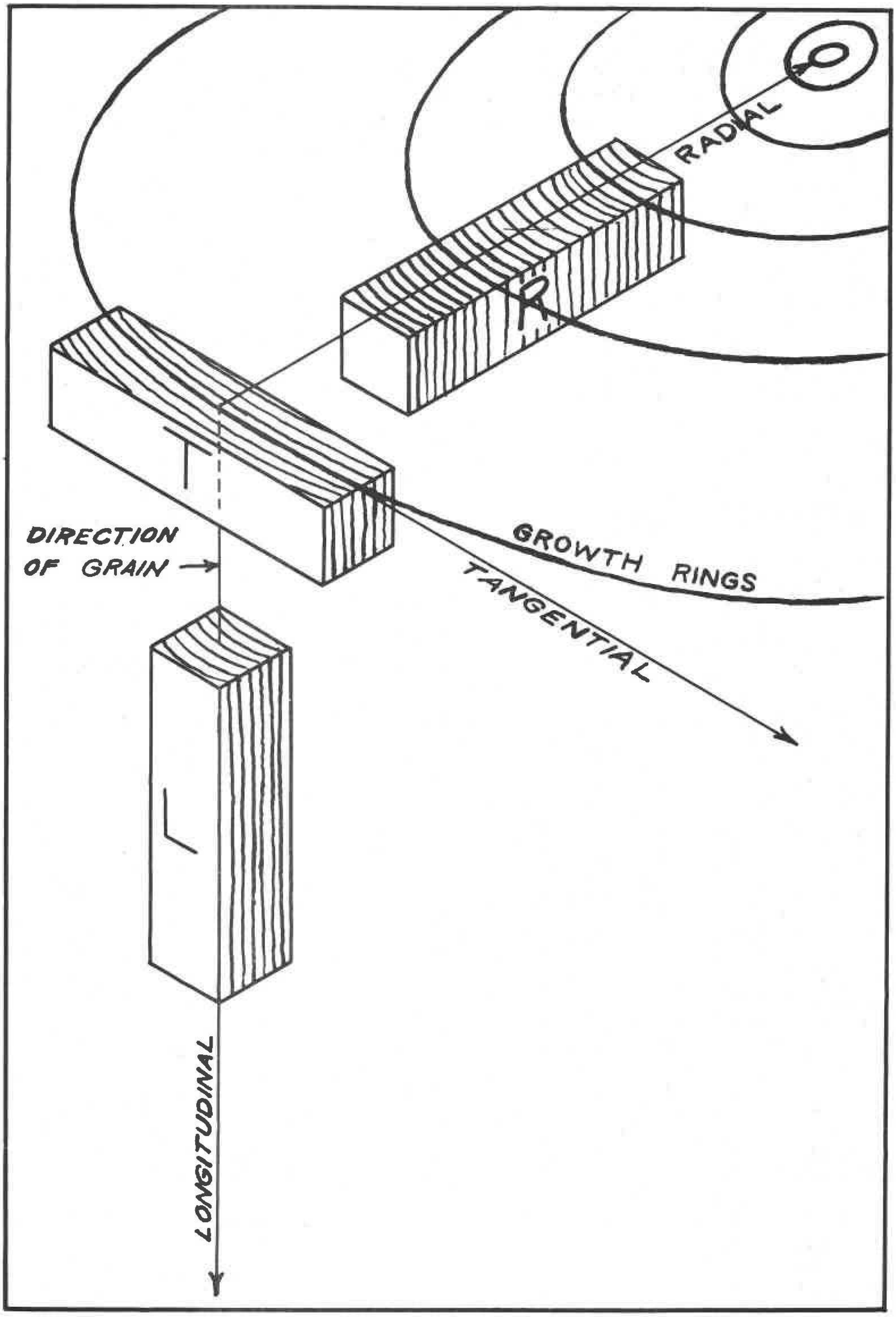

Figure 1.--Orientation of specimens with the grain and growth rings of a tree for tests to determine the elastic constants of Sitka spruce. Load was applied in the direction of the long axis of each test specimen.

Z M 68857 F

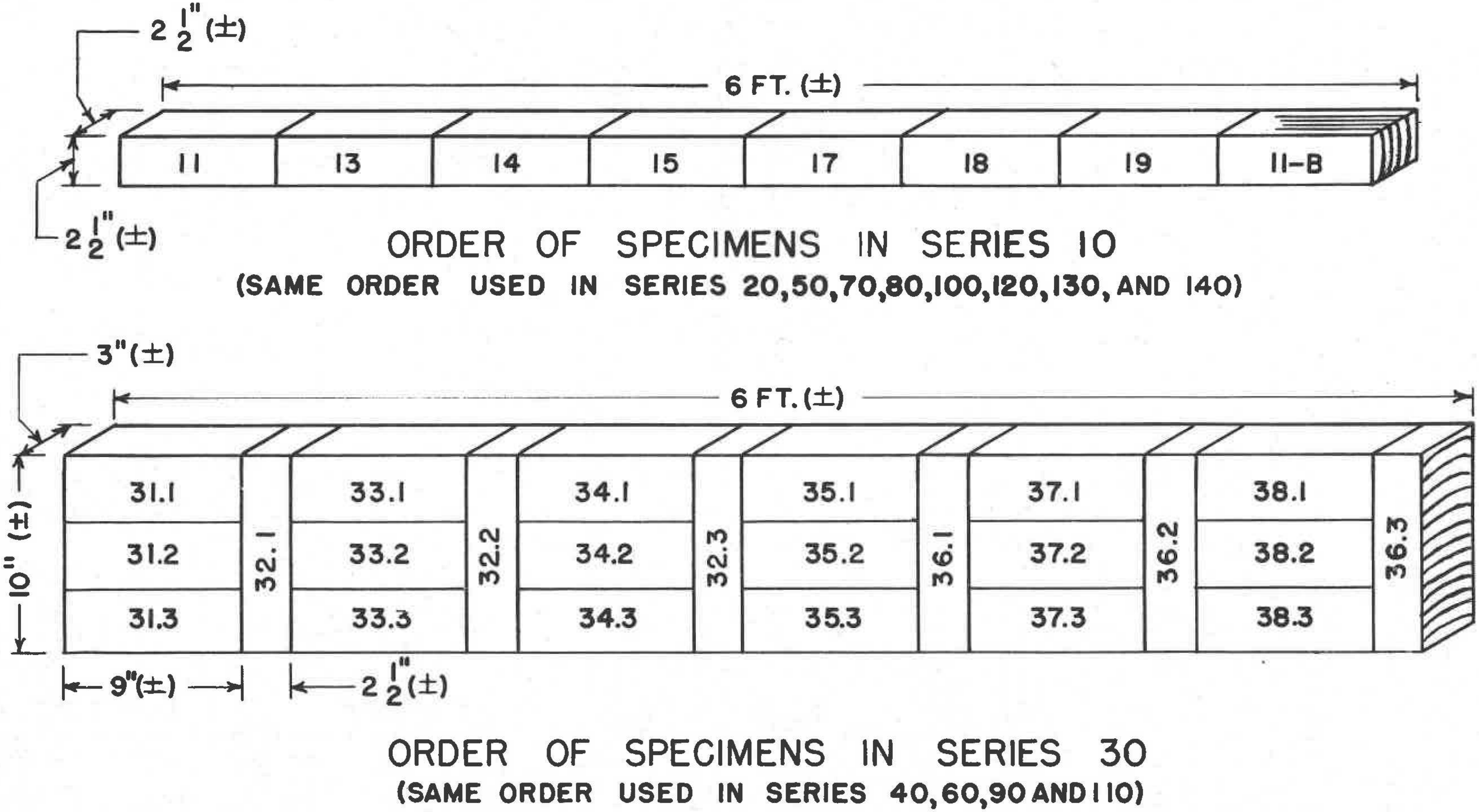

Figure 2.--Method of cutting and numbering specimens for tests of elastic constants of Sitka spruce.

2 M 68858 F

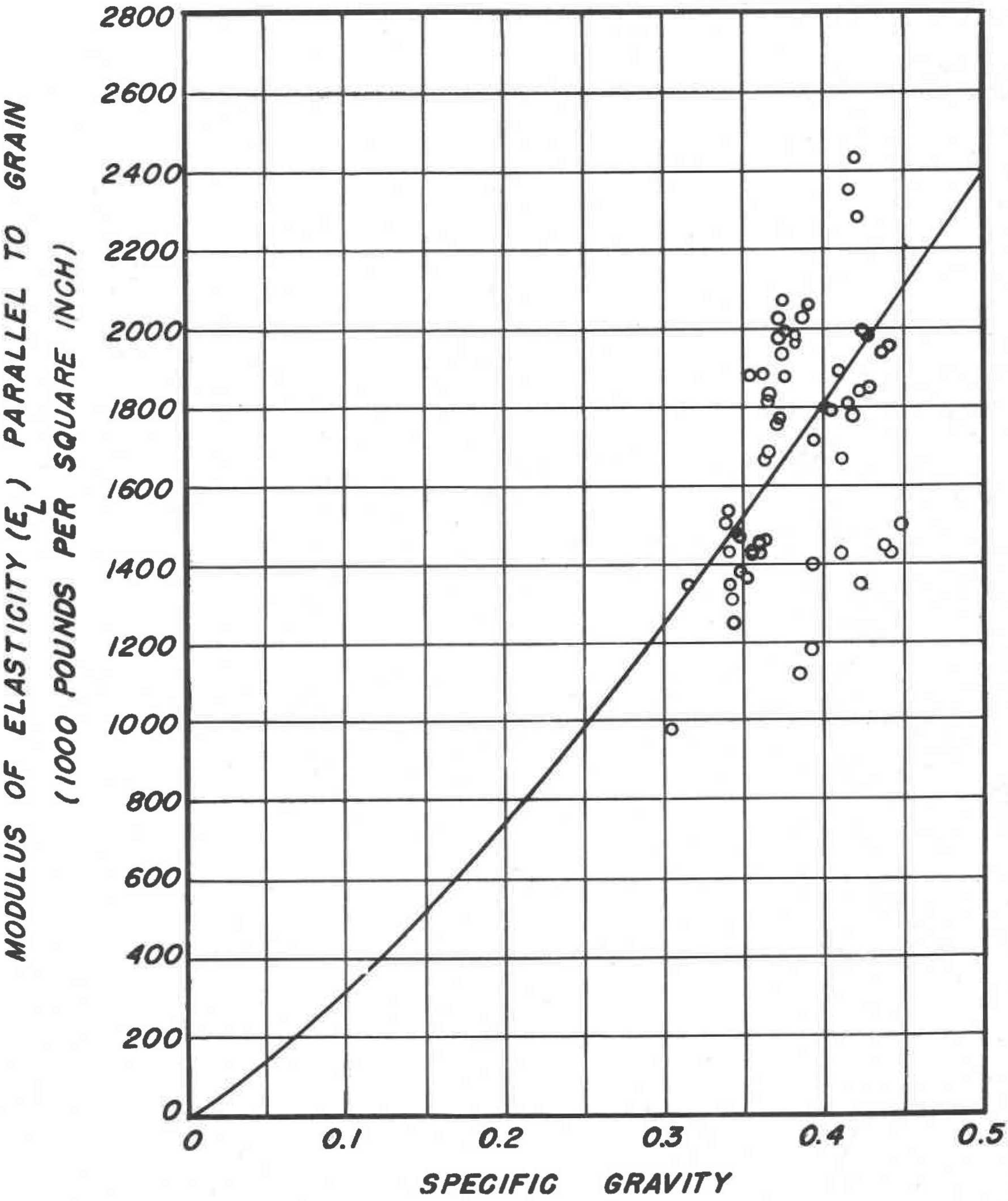

Figure 3.--Values of Young's modulus parallel to the grain (E_L), plotted against specific gravity, for Sitka spruce at approximately 13 percent moisture content. Specific gravity based on weight when oven-dry and volume at test. The curve shown is based on the 5/4 power of specific gravity, but is not intended to represent the best-fit relationship for regression of E on specific gravity.

Z M 68859 F

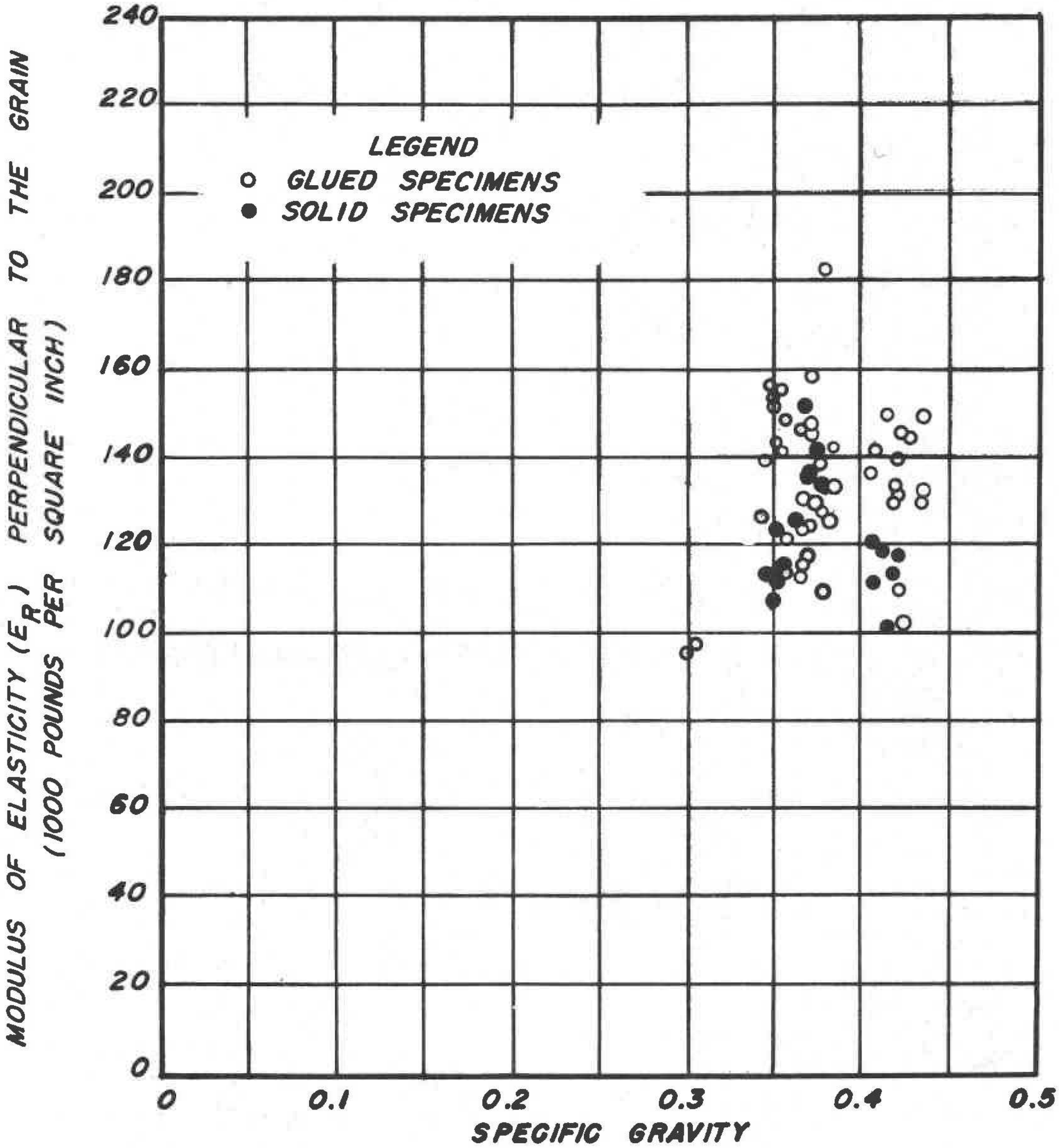

Figure 4.--Values of Young's modulus across the grain, perpendicular to the annual rings (E_R), plotted against specific gravity, for Sitka spruce at approximately 13 percent moisture content. Specific gravity based on weight when oven-dry and volume at test.

Z M 68860 F

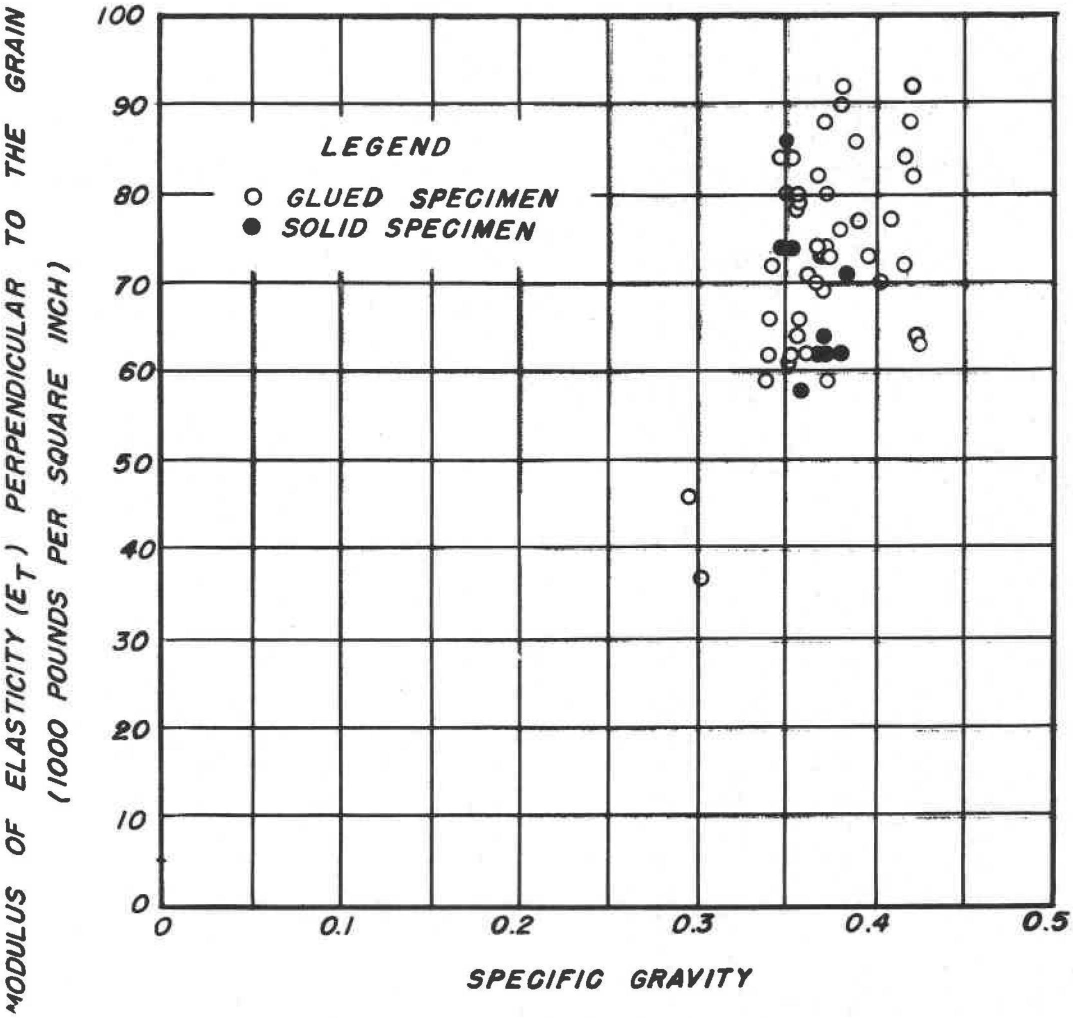

Figure 5.--Values of Young's modulus across the grain, parallel to the annual rings (E_T), plotted against specific gravity, for Sitka spruce at approximately 13 percent moisture content. Specific gravity based on weight when oven-dry and volume at test.

Z M 68861 F

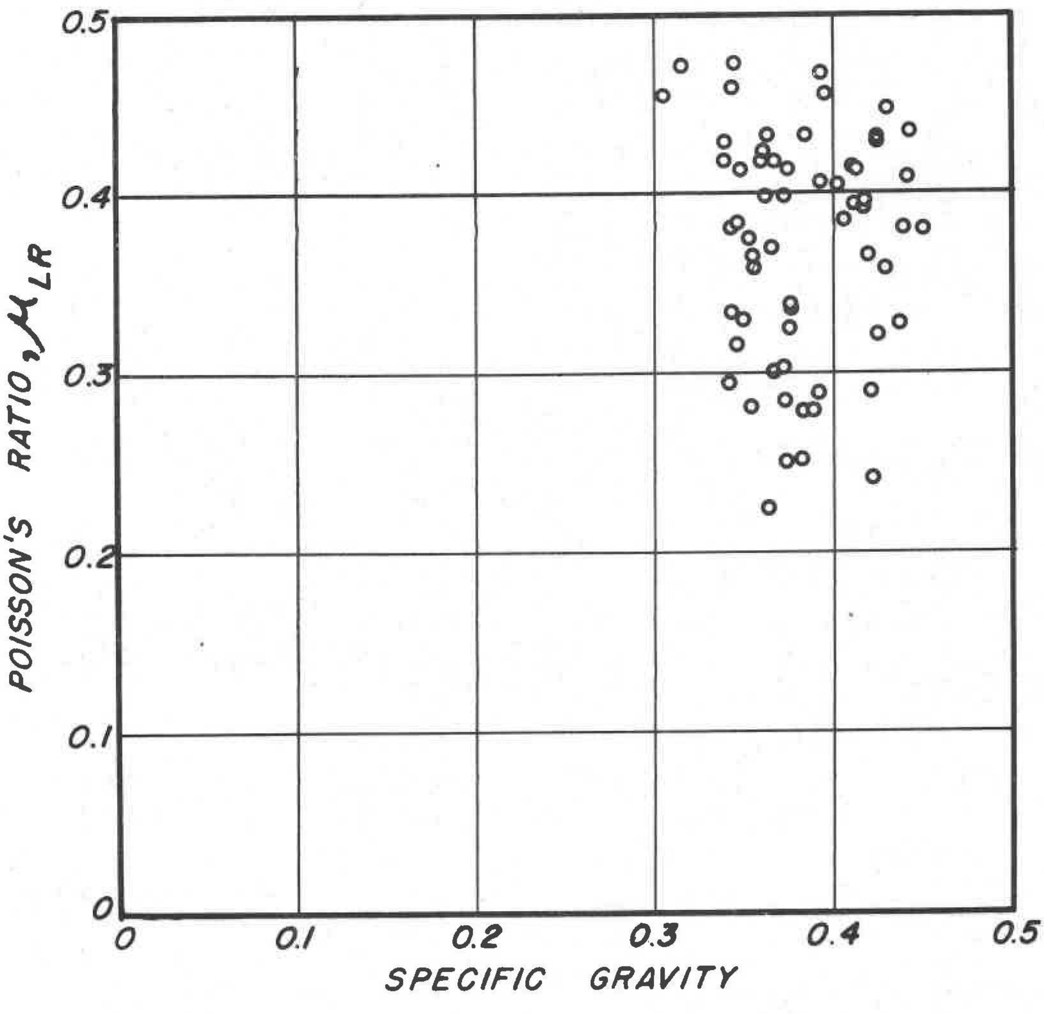

Figure 6.--Values of Poisson's ratio, μ_{LR}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

2 M 68862 F

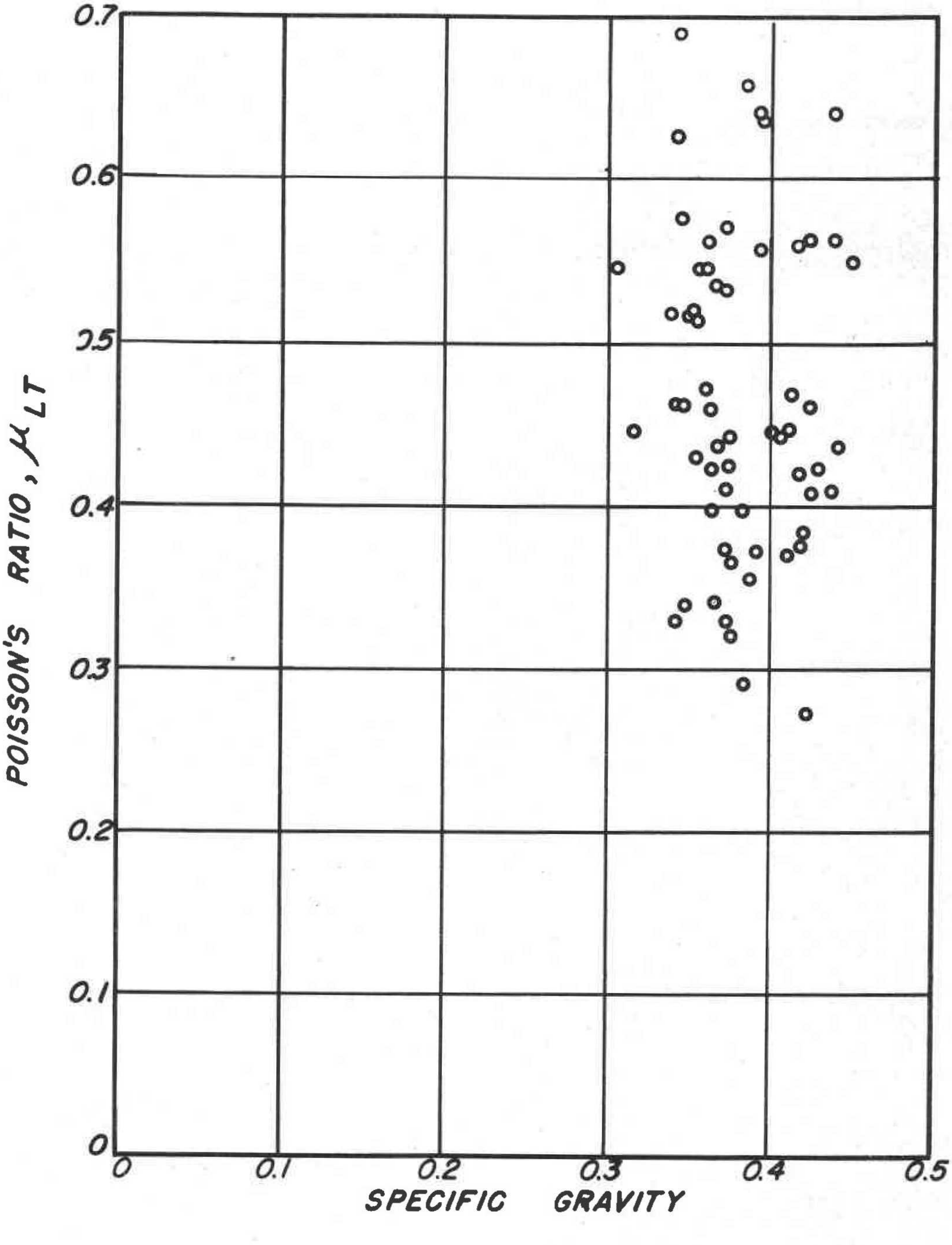

Figure 7.--Values of Poisson's ratio, μ_{LT}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

Z M 68863 F

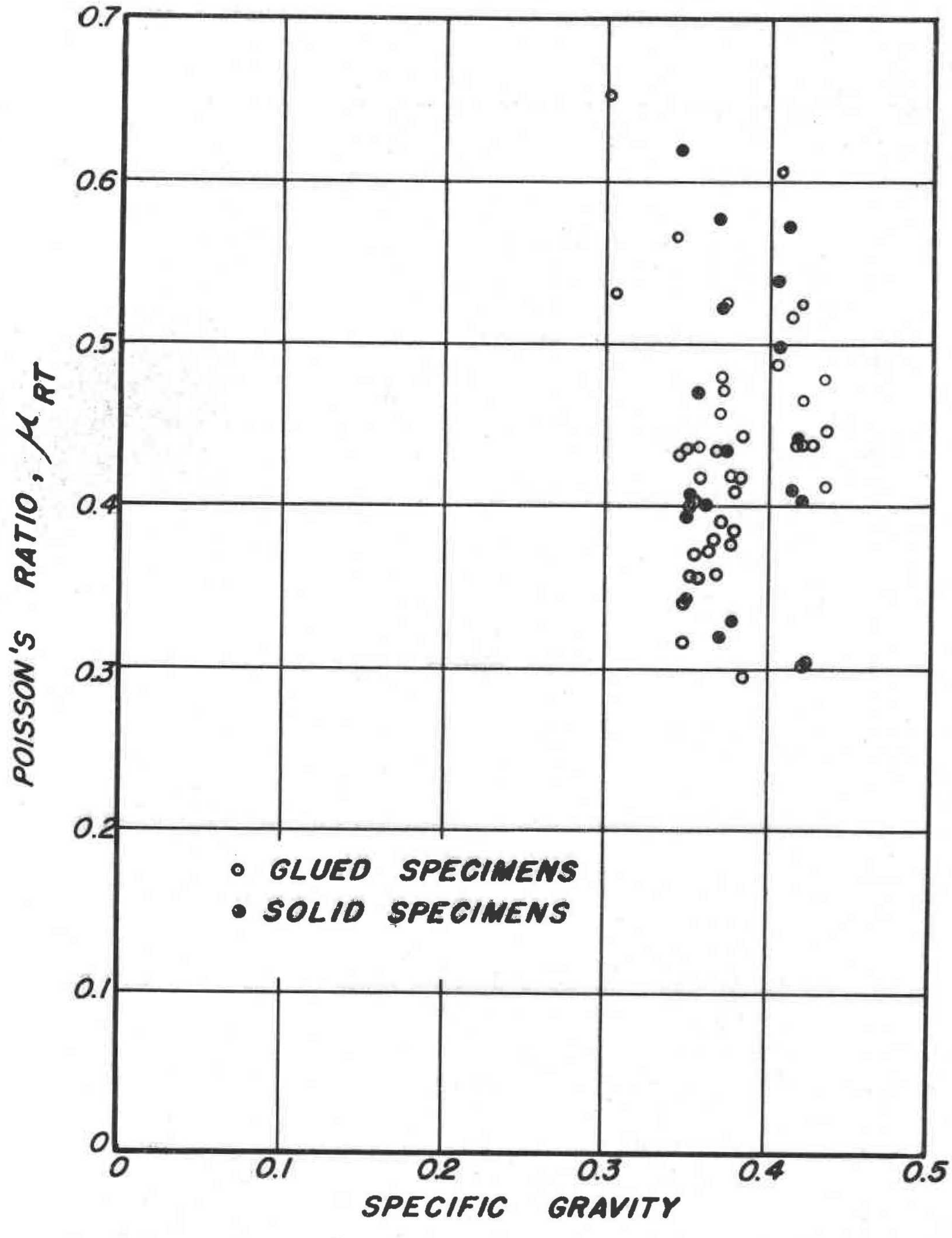

Figure 8.--Values of Poisson's ratio, μ_{RT}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

Z M 68864 F

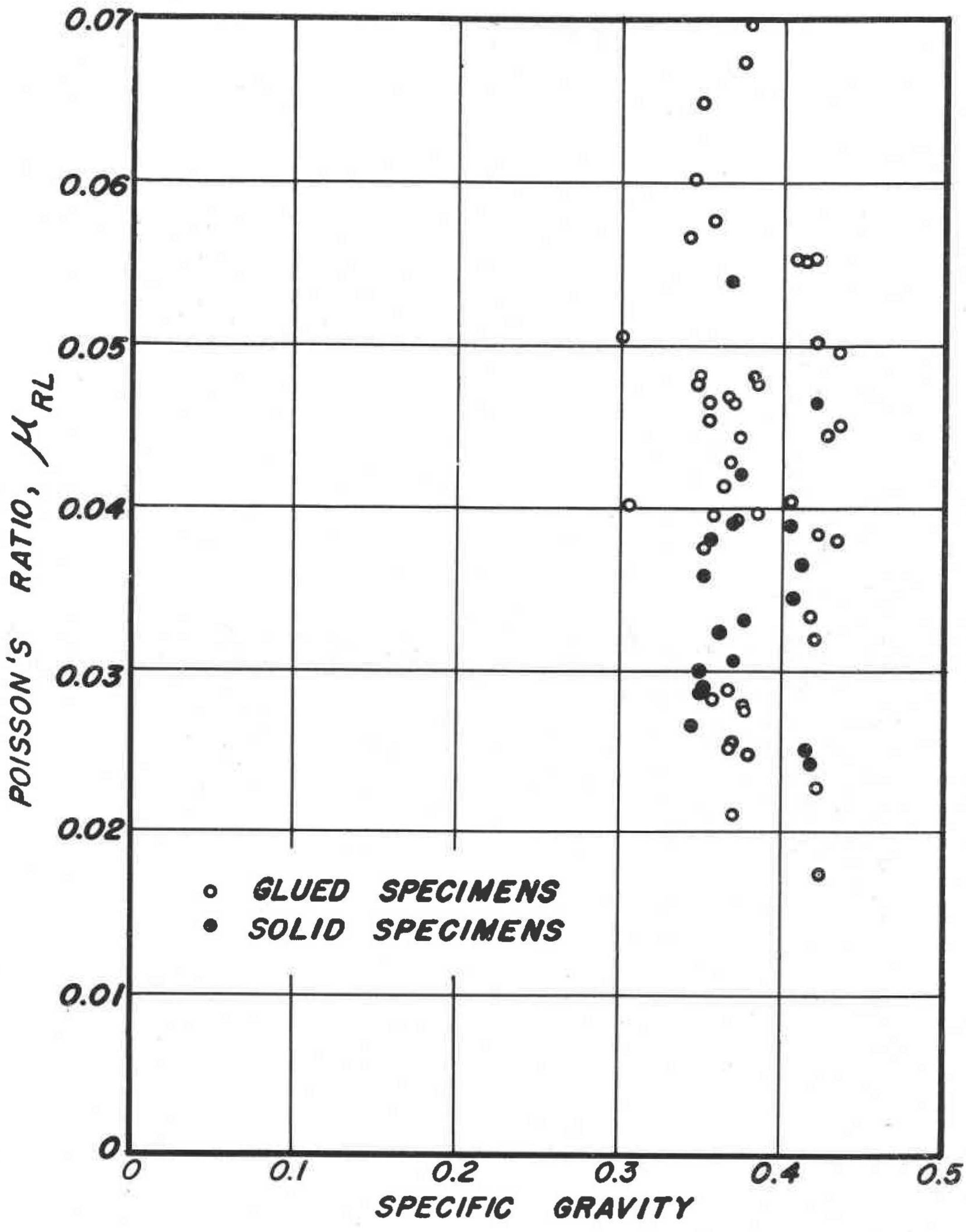

Figure 9.--Values of Poisson's ratio, μ_{RL}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

Z M 68865 F

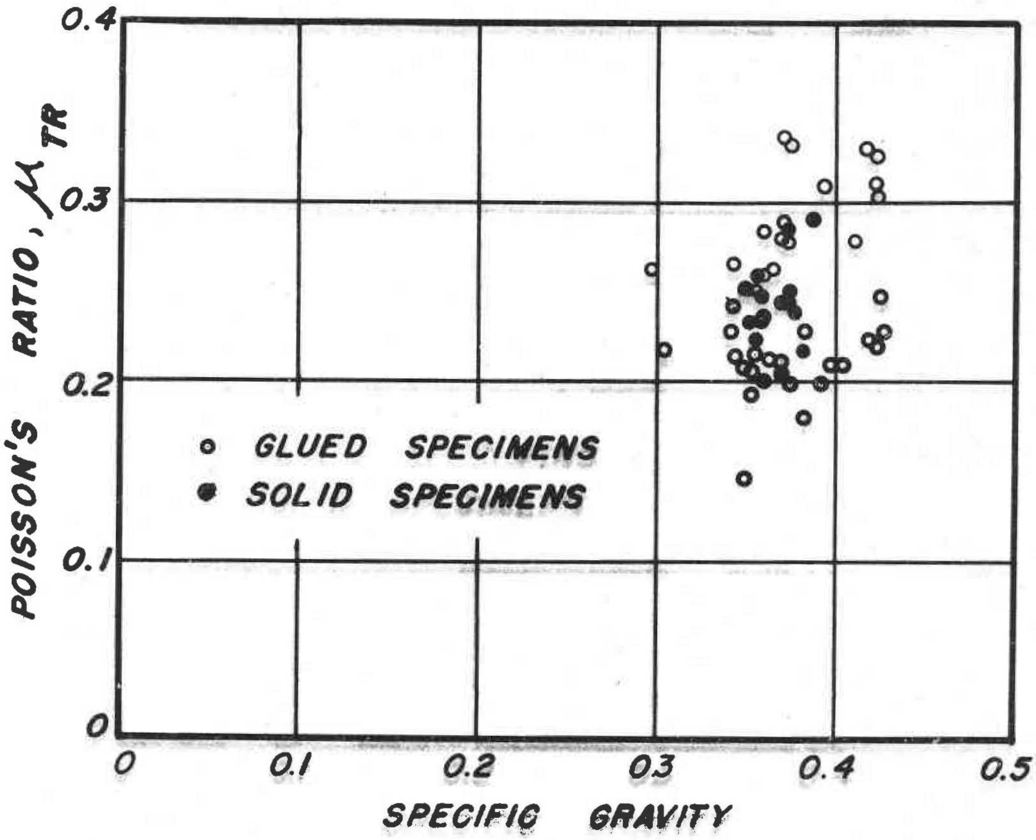

Figure 10.--Values of Poisson's ratio, μ_{TR}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

Z M 68866 F

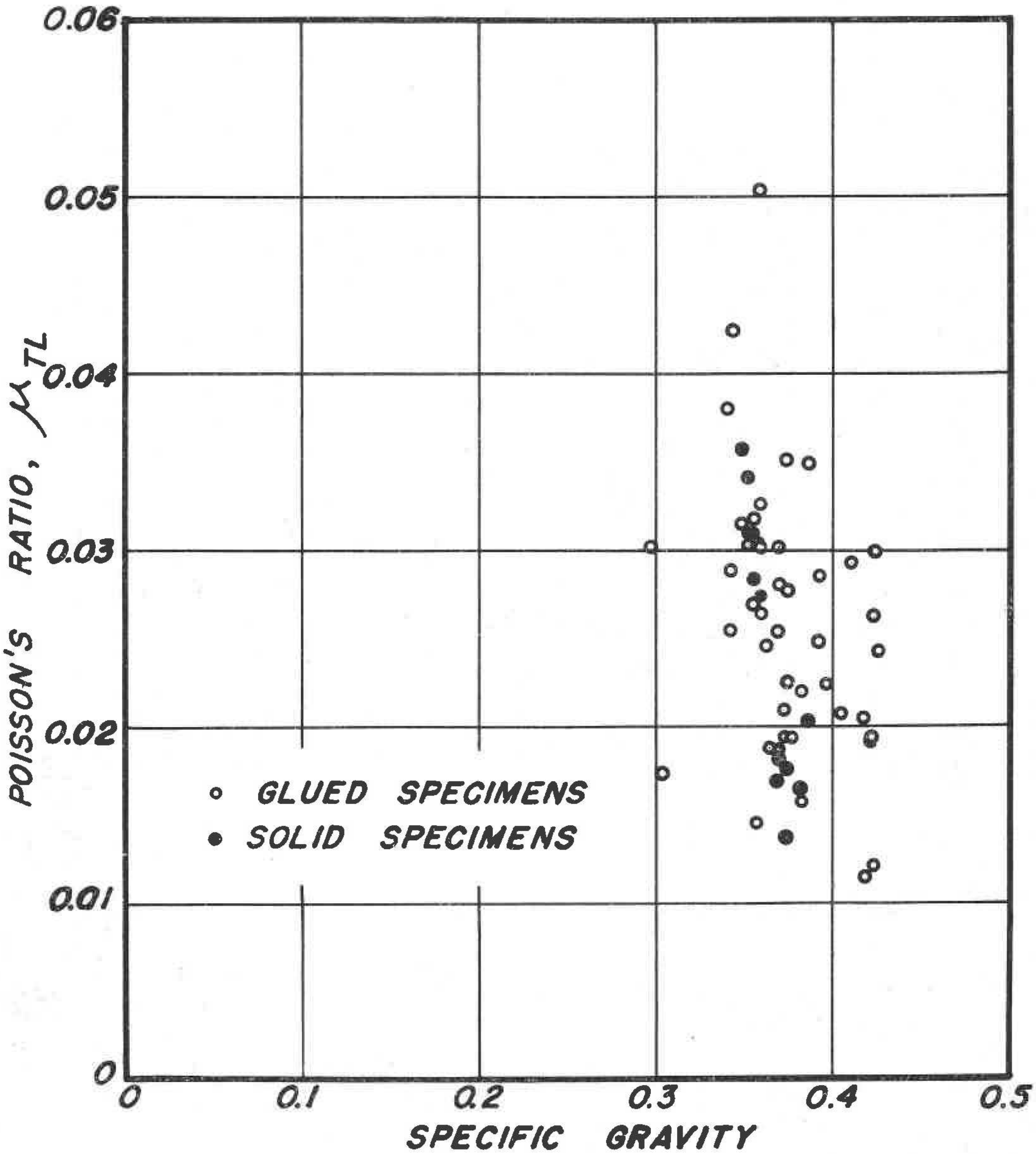

Figure 11.--Values of Poisson's ratio, μ_{TL}, for Sitka spruce at approximately 13 percent moisture content, plotted against specific gravity.

Z M 68867 F

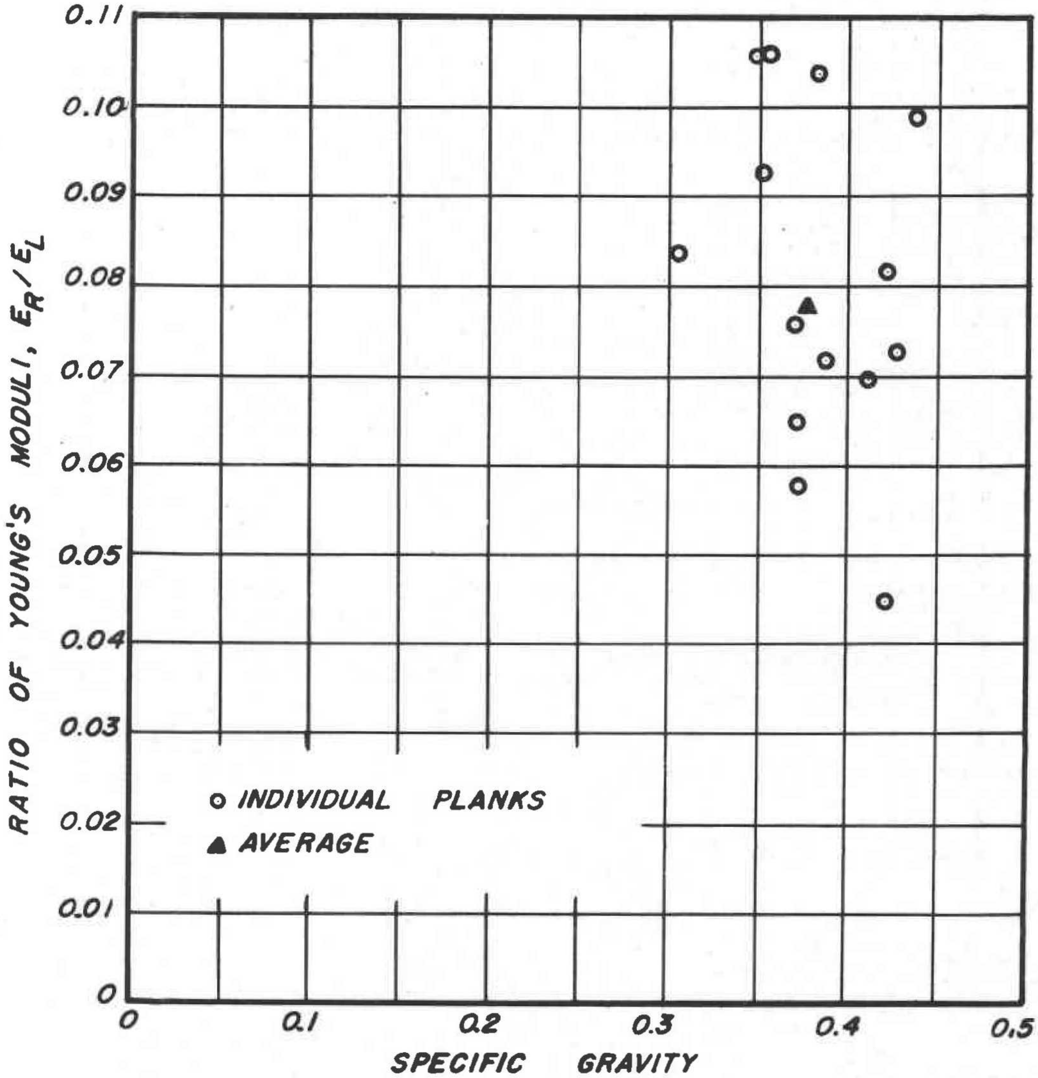

Figure 12.--The average ratio, E_R/E_L, for Sitka spruce planks at approximately 13 percent moisture content, plotted against the average specific gravity of the planks.

Z M 68868 F

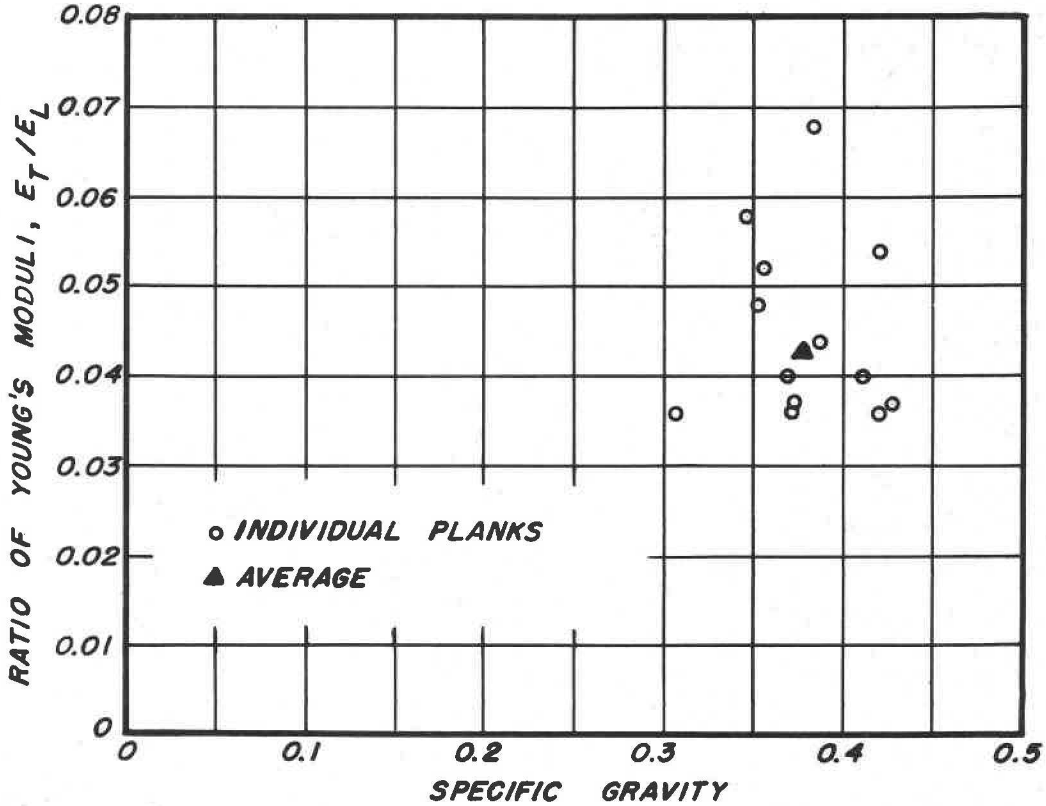

Figure 13.--The average ratio, E_T/E_L, for Sitka spruce planks at approximately 13 percent moisture content, plotted against the average specific gravity of the planks.

Z M 68869 F

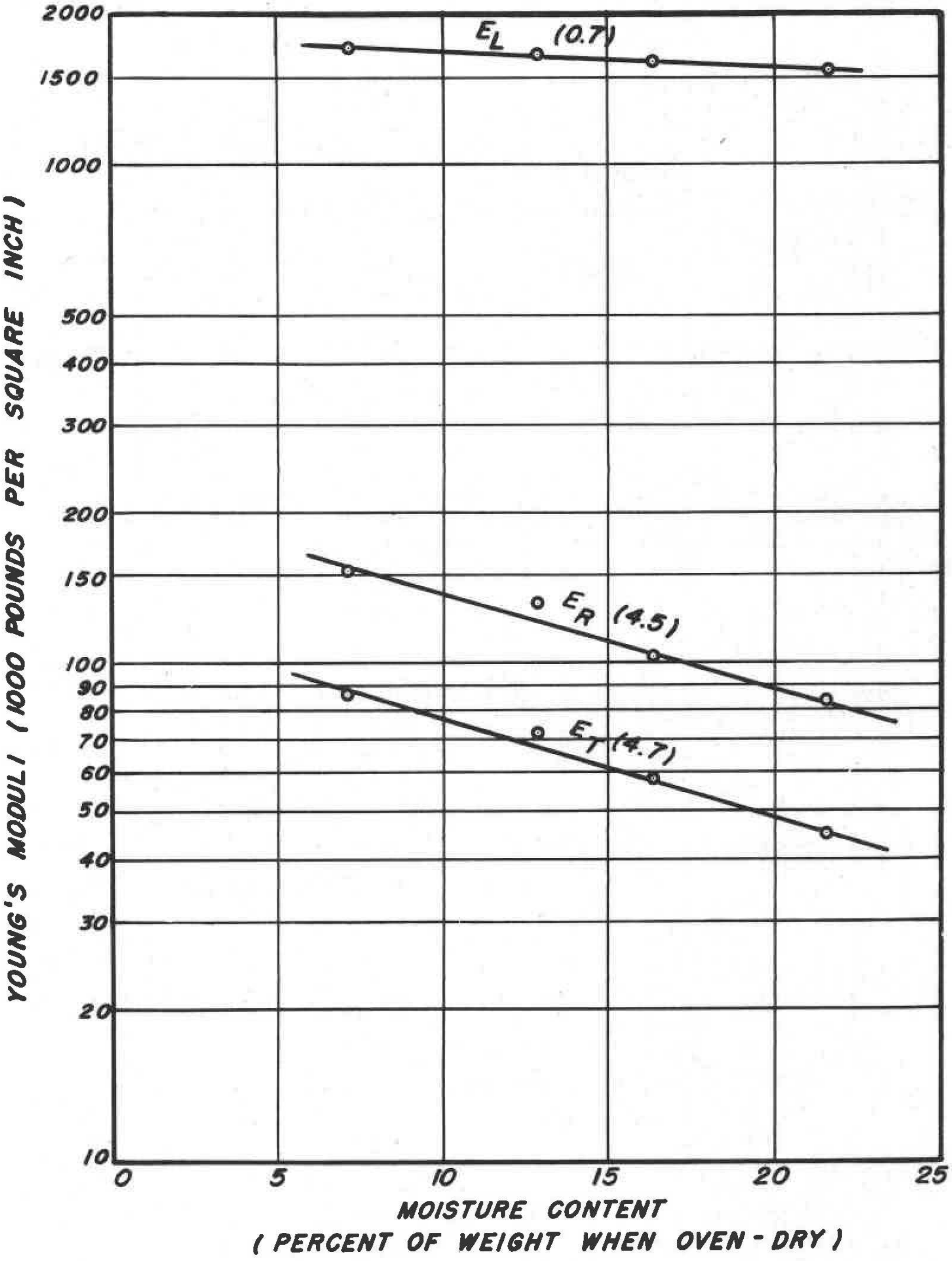

Figure 14.--Relation of average values of Young's moduli to moisture content for Sitka spruce specimens tested in compression. Figures in parentheses are the percentage increase in the moduli for a 1 percent decrease in moisture content.

Z M 68870 F

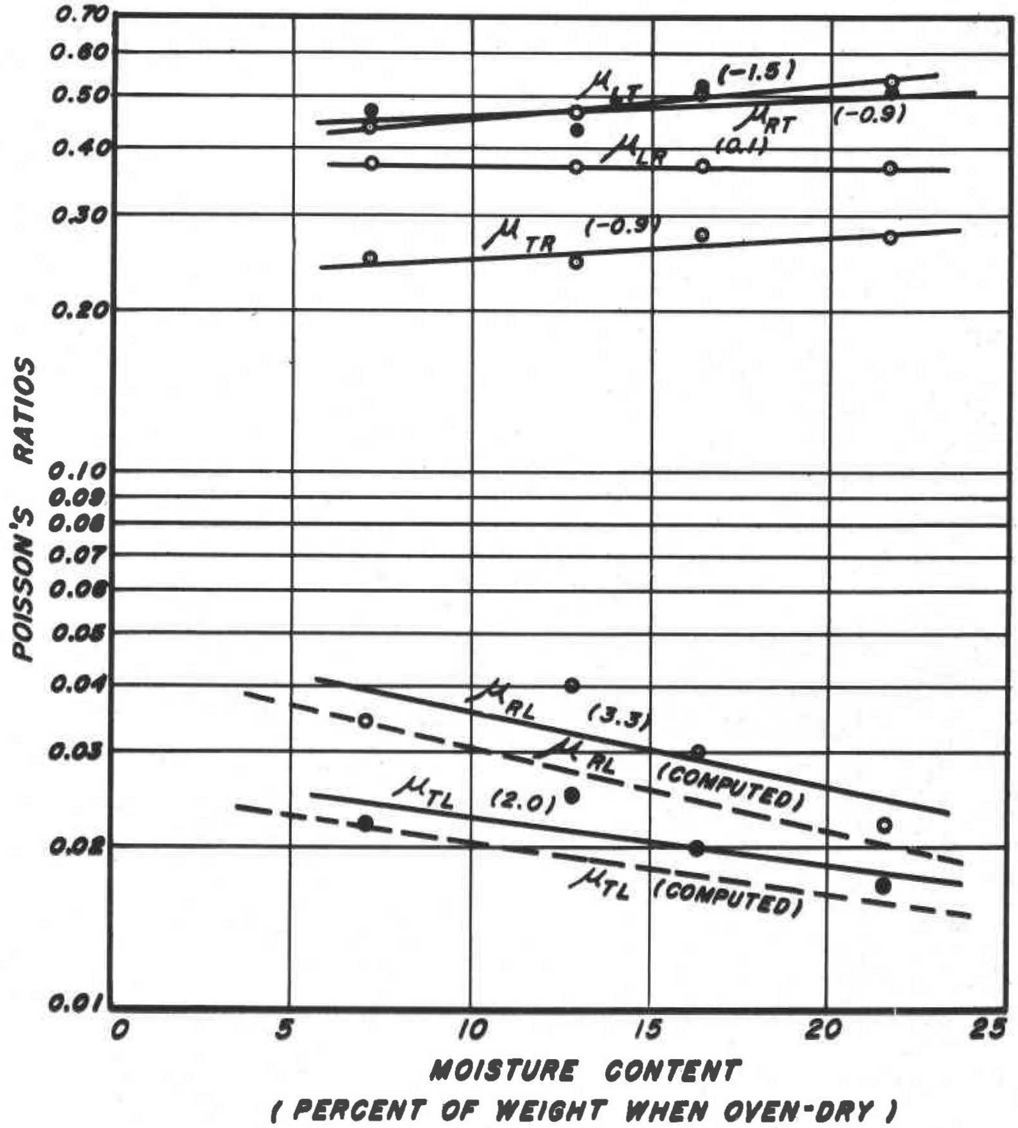

Figure 15.--Relation of average values of Poisson's ratios to moisture content for Sitka spruce specimens tested in compression. Figures in parentheses are the percentage increase (positive values) or decrease (negative values) in the ratios for a 1 percent decrease in moisture content.

Z M 66671 F

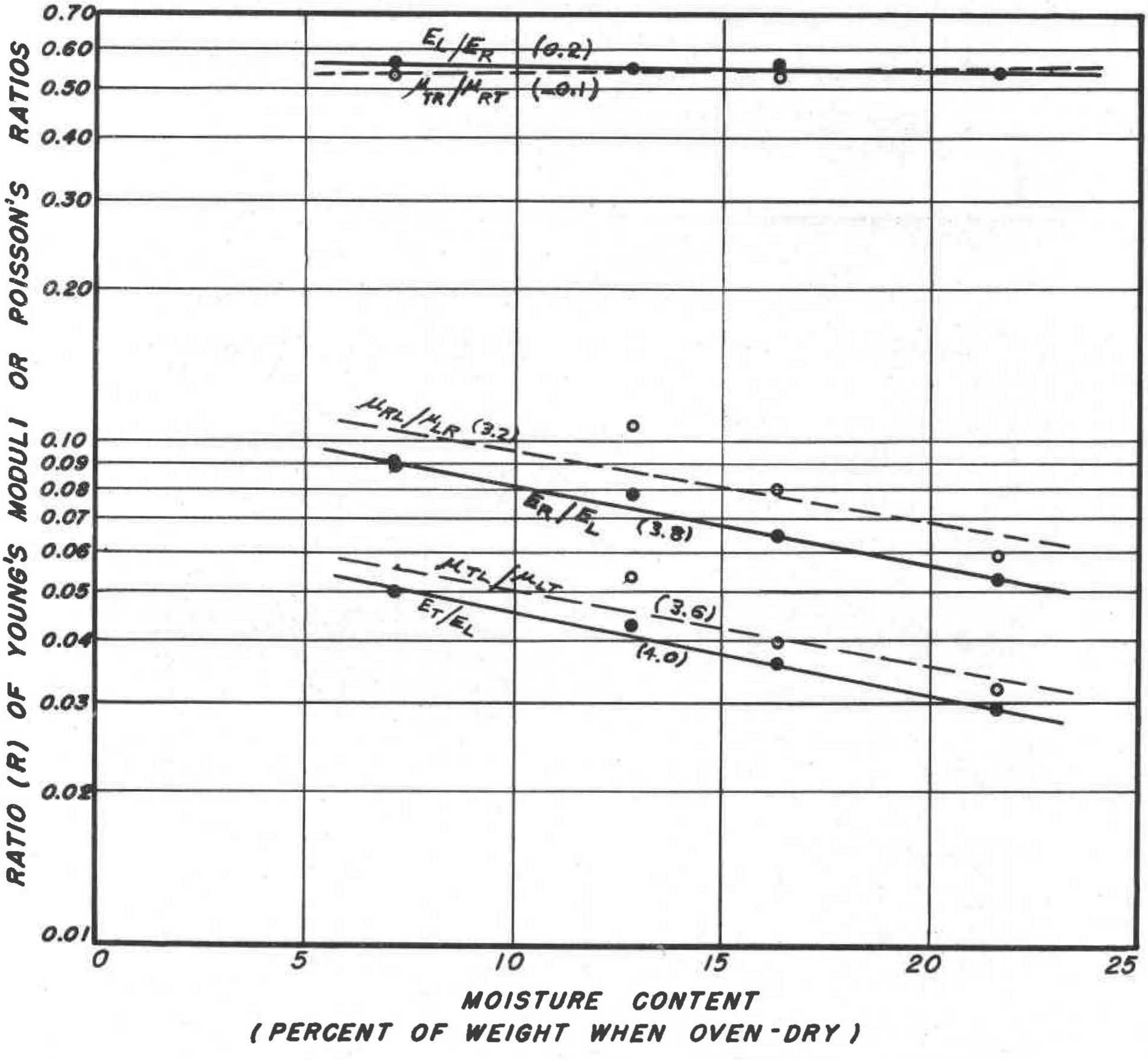

Figure 16.--Average values for ratios of Young's moduli and of Poisson's ratios as related to moisture content for Sitka spruce specimens. Figures in parentheses are the percentage increase (positive values) or decrease (negative values) in the ratios for a 1 percent decrease in moisture content.

Z M 68872 F

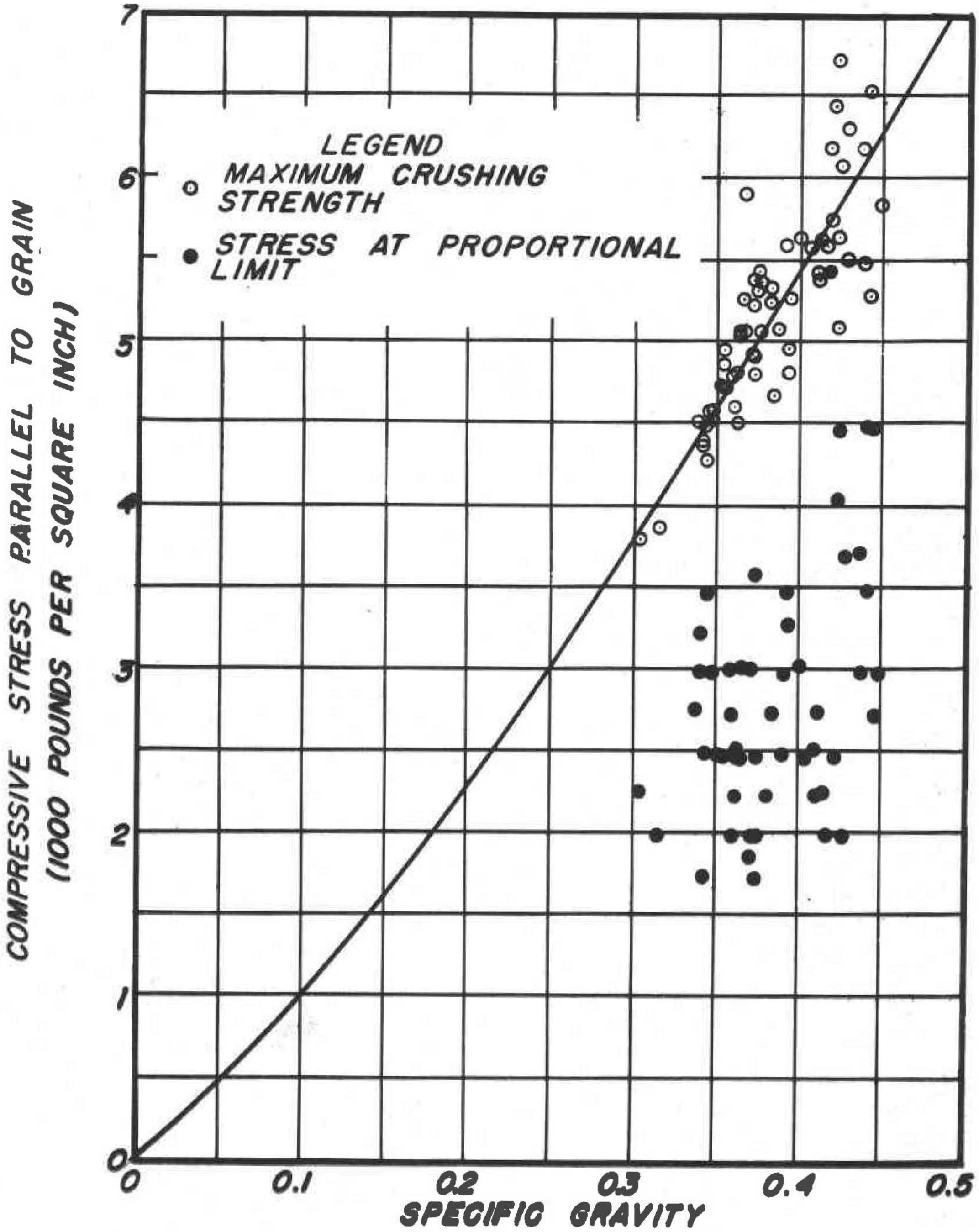

Figure 17.--Values of fiber stress at proportional limit and maximum crushing strength parallel to the grain, plotted against specific gravity, for Sitka spruce at approximately 13 percent moisture content. Specific gravity based on weight when oven-dry and volume at test. The curve shown is based on the 5/4 power of specific gravity, but is not intended to represent the best-fit relationship for regression of strength on specific gravity.

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