SURVEY OF STRENGTH AND RELATED PROPERTIES OF YELLOW-POPLAR

Revised June 1953

This Report is One of a Series Issued in Cooperation with the AIR FORCE-NAVY-CIVIL SUBCOMMITTEE on AIRCRAFT DESIGN CRITERIA Under the Supervision of the AIRCRAFT COMMITTEE of the MUNITIONS BOARD

(Report)

No. 1516

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison 5, Wisconsin
In Cooperation with the University of Wisconsin

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SURVEY OF STRENGTH AND RELATED PROPERTIES OF YELLOW-POPLAR[1]

By

R. F. LUXFORD, Engineer
and
L. W. WOOD, Engineer

Forest Products Laboratory,[2] Forest Service
U. S. Department of Agriculture

Summary

A review of the strength and related properties of yellow-poplar, particularly as affected by color and stain, was made at the Forest Products Laboratory in 1944. Tests were made on specimens from 96 boards obtained from 7 mills in the southern Appalachian district and representing the range of stain and coloration found in stock at those mills. Eleven stain and color groups of sapwood and heartwood were recognized. The tests included were static bending, toughness, compression parallel to grain, compression perpendicular to grain, hardness, shear parallel to grain, cleavage, and tension perpendicular to grain.

Differences in strength among the various color groups were closely related to differences in specific gravity. Averages for sapwood and for sound heartwood were the same in weight, and exhibited small differences in strength that may not be significant.

The more important strength values correlated closely with specific gravity, but much less so with rate of growth. Specific gravity decreased with slower rate of growth.

There is some relationship between modulus of rupture and toughness of yellow-poplar, but it is not so definite as that between modulus of rupture and specific gravity. Analysis of the data on toughness indicated that 55 inch-pounds per specimen (5/8 by 5/8 by 10 inches, 8-inch span, center loading) is a suitable acceptance value for yellow-poplar airplane lumber, to eliminate brash material and that containing decay and pre-existing compression failures.

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[1]The Division of Forest Pathology, Bureau of Plant Industry, Soils, and Agricultural Engineering, assisted in the selection of test material and in the identification and classification of stains and discoloration. The following mills furnished lumber for tests: Saluda River Lumber Co., Cleveland, S. C.; J. M. English & Sons, Kyle, N. C.; Conasauga River Lumber Co., Conasauga, Tenn.; Mt. Fork Lumber Co., Bluefield, W. Va.; Mower Lumber Co., Omar, W. Va.; Birch Valley Lumber Co., Tioga, W. Va., Damascus Lumber Co., Damascus, Va.

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

Introduction

Yellow-poplar (Liriodendron tulipifera), a member of the magnolia family and known also as tuliptree, is an important species of the southern Appalachian hardwood forest. This wood is permitted as a substitute for spruce in the same sizes for airplane construction, and requirements for this and other exacting uses have made heavy demands on the available supply of high-grade material.

The heartwood of yellow-poplar is extremely variable in normal coloration, and stain is of common occurrence in sapwood. Decay and other abnormalities are also sources of discoloration. The variations in color have been the cause for rejection of considerable yellow-poplar of otherwise high grade. There has been much discussion of the relationship between coloration and strength, and some information[3] has been published on the relationship of toughness to color of yellow-poplar veneer.

To check further the desirability of the use of yellow-poplar in aircraft construction, a review of the strength and related properties of yellow-poplar, with particular attention to the effect of coloration, was made at the Forest Products Laboratory in 1944.

More specifically the objectives were:

(1) To establish more conclusively the relation of various colorations, including sap stain, to strength properties, and to determine whether yellow-poplar that is colored or sap-stained but without visual evidence of decay is deficient in strength properties.

(2) To study the accuracy of rings per inch and specific gravity as criteria of strength.

(3) To explore the correlation between the strength properties important in airplane parts, particularly those used in design, and toughness test values.

(4) To establish values of toughness appropriate to the use of the toughness test as an acceptance or inspection method for airplane lumber and parts.

Material Used

Through the cooperation of the Appalachian Forest and Range Experiment Station, 187 boards were obtained from 7 mills[1] in the southern Appalachian district. Figure 1 shows the locations of these mills with respect to the

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[3] Hepting, G. H., Roth, E. R., and Luxford, R. F., "The Significance of the Discolorations in Aircraft Veneers: Yellow-poplar;" Forest Products Laboratory Rept. No. 1375, 1952 (Revised).

known botanical range of yellow-poplar and also with respect to the more restricted area of optimum development.[4] Within that area, recent production has been heaviest in the southern Appalachian district.

Boards about 3 feet long, 3 to 12 inches wide, and 1 to 1-1/2 inches thick were selected at the mills by representatives of the Appalachian Forest and Range Experiment Station. Preference was given to edge-grained pieces, covering the range of rate of growth and of color, without regard to specific gravity. As soon as received at the Forest Products Laboratory, the boards were kiln-dried to about 12 percent moisture content in accordance with schedule No. 4 of Army-Navy Specification AN-W-2a.

The kiln-dried rough boards were surfaced and examined for defects. The examination consisted largely of an appraisal of cross grain, though other imperfections were also considered. The appraisal for cross grain was made by drawing a swiveled scribe (fig. 2) along the full length of each board. Maximum permissible slope of grain in test specimens was fixed at 1 in 20.

The appraisal of cross grain resulted in the complete rejection of 36 of the boards and in the rejection of some portions of a considerable additional number. Since spiral grain commonly has greater slope in the outer parts of the tree, the rejected material included a disproportionate amount of sapwood. Some boards showed large variations of grain direction within short distances, and it was necessary to cull additional specimens because of cross grain that was not detected until after test.

Color Groupings

Eleven color groups were recognized in the yellow-poplar for test as follows:

Sapwood

Unstained.--A light shade of tan, varying through cream and ivory to almost white.

Sap stain: light gray[5].--Infrequent light-grayish areas irregularly distributed in otherwise normal wood.

Sap stain: medium gray[5].--Similar to light gray sap stain but with darker or more frequent color areas.

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[4]The areas as shown in figure 1 are as defined in "Yellow-poplar, Characteristics, Growth and Management," E. F. McCarthy, U. S. Dept. Agr. Tech. Bull. No. 356, 1933.

[5]The stain described in these color groups is also known as "bluestain."

Sap stain: heavy gray[5].--Abundant streaks or areas of gray or pinkish-gray, occasionally with a tinge of tan or brown; this degree of staining, although the heaviest found in the test boards, is not particularly severe in comparison with that frequently observed in unprotected or carelessly handled lumber.

Discoloration: tan.--Irregularly distributed zones of tan to light-brown color, probably unrelated to fungus infection.

Discoloration: tan, streaked.--Streaks of tan to light-brown color, mostly following the boundaries between growth rings, and apparently unrelated to fungus infection.

Heartwood

Normal.--Pale buff or yellowish to greenish, grading in the wider boards to deeper buff or light brown near the pith edge.

Normal: streaked.--The normal hues are varied by buff to dark brown, narrow, longitudinal streaks, some of which follow the boundaries between growth rings.

Bluebutt: red, purple, gray.--A wide variety of dark hues, commonly in narrow or wide longitudinal bands; the majority of colors have a component of red, which may appear as reddish brown, lavender, or purple; reddish brown may vary to tan or to darker brown and thus merge with other color groups; lavender or purple may become almost blue, or in darker shades vary to iron gray, or almost black.

Bluebutt: brown.--A variation of the foregoing to a deeper tan or to light or dark brown, similar to the color indicative of decay, although no positive evidence of decay found.

Decay.--A deep brown color, not necessarily dark, accompanied by positive evidence of the presence of decay fungus; since the boards were selected at the lumber mill, it is probable that the most severely decayed lumber had previously been culled, so that this group can be considered as only moderately infected.

In addition to the colors described in these groups, some of the boards showed insect or mineral streaks, usually of very dark color. These streaks were of limited lateral extent, and were not included in the evaluation of strength properties.

Preparation of Specimens

Limitations in the amount of available material, particularly of sapwood, made it impossible to run a complete series of strength tests on matched specimens from each of the color groups. Static bending, toughness, and compression parallel to grain were therefore designated as the more

important tests and given preference in the layout of specimens. Hardness, shear, compression perpendicular to grain, tension perpendicular to grain, and cleavage were designated as less important tests and were run only insofar as available material permitted, with preference for hardness and shear tests.

This principle for the selection of specimens was developed into three general layout plans (figs. 3, 4, and 5): One for all sapwood, one for discolored heartwood, and one for normal heartwood. A random distribution of the specimens of normal heartwood was obtained by reversing the layout between the odd-numbered and the even-numbered boards (fig. 5). These general plans show one series or cycle of test specimens; the cycle was repeated as many times as width of board permitted.

Figure 6 gives a typical board layout and illustrates the numbering of specimens, showing also an enlarged sketch of the reference strip that was kept to indicate the position of specimens as finally cut out.

Comparison of figures 3, 5, and 6 reveals some deviation in actual layout of specimens from the general plan, particularly in the order from left to right. Variations of this kind were made to fit the characteristics of individual boards, and also to avoid local imperfections, such as knots, or insect or mineral streaks.

Tests for the determination of specific gravity based on volume when oven-dry, toughness, and compression parallel to grain, were made on the uninjured end portions of specimens broken in the static bending test. These broken specimens were marked in accordance with the general plans of figures 3, 4, and 5. The toughness specimens were 5/8 by 5/8 inch in cross section, and were so cut out as to obtain radial and tangential surfaces.

Normal heartwood was present in most of the boards containing sapwood and in some of the boards containing discolored heartwood; specimens of normal heartwood were obtained from these boards. Boards that contained only normal heartwood were not used. A total of 96 boards was used; the corresponding total number of specimens was 1,560, distributed as shown in table 1.

Limitation in the amount of available material precluded matching of individual specimens, but numbers of specimens in the various color groups were large enough to give a rough match on a group basis. Table 1 shows the irregular distribution of specimens by mills. Within and between individual color groups, this distribution by mills was even more irregular; so that the matching of groups by mills fell considerably short of perfection.

All specimens were conditioned before test at a temperature of 70° F. and 64 percent relative humidity until moisture equilibrium and constant weight were reached.

Methods of Test

The methods of testing the specimens were, in general, those adopted as standard by the Forest Products Laboratory and described in Technical Bulletin No. 479 of the U. S. Department of Agriculture. Some modifications, necessitated by limitations in the available material, were as follows:

The 1- by 1-inch static bending specimens were tested by center loading on a 14-inch span. Load was applied to a tangential face, or the face nearest to tangential and nearest to the pith. The loading block was curved to a radius of 1-1/2 inches, and movement of the loading head was at the rate of 0.046 inch per minute. Load-deflection readings were taken until the load, after reaching maximum, had decreased to 100 pounds. Work done on the specimen up to this point is herein termed "total work."

The 5/8- by 5/8- by 10-inch toughness specimens were loaded on the tangential face nearest the pith and at the center of an 8-inch span.

Compression-parallel-to-grain tests were made on 1- by 1-inch specimens 4 inches long. Loading was continued to failure, which was usually complete at the maximum load. Brooming was prevented by a brief drying of the ends in an oven where the sides were protected to prevent loss of moisture. Load was applied at a rate of strain of 0.003 inch per inch per minute.

Specimens for compression perpendicular to grain were tested with the 1-inch dimension vertical. Since this height was one-half of the standard, the rate of loading was likewise one-half of the standard. Test was continued to 0.1-inch depth of compression.

Hardness specimens were also 1 inch thick, and some were not full 6 inches in length. Two impressions were made in each of two mutually perpendicular sides, (not necessarily radial and tangential surfaces) and two in the ends.

Tests for shear, cleavage, and tension perpendicular to grain were made by standard methods, except that the width of specimen was 1 inch instead of 2 inches.

All tests, except toughness, were performed in the atmosphere in which the specimens had been conditioned.

To avoid the necessity of making counts of growth rings on individual specimens, these counts were made on the reference strips (fig. 6) cut from each of the boards. One count was made for each static bending specimen, and that count was used for all other specimens in the same zone of growth. Additional counts were made for specimens in zones of growth that included no static bending specimen. The number of counts in each board varied from 2 to 10, while the number of specimens per board ranged as high as 44. Counting was done for the most part under a hand lens, with visibility aided by cutting a smooth cross section and wetting with water.

The orientation of annual growth rings with respect to the direction of force is significant for some strength properties of coniferous species, but is of less importance in the hardwoods. In the present investigation, the majority of boards were not truly edge grained, though they were nearer to that than to flat grained. Specimens for test thus represented a fairly wide range in direction of growth rings. This direction was recorded for specimens tested in static bending, compression perpendicular to grain, shear, cleavage, and tension perpendicular to grain. Since preliminary analysis of data from these tests indicated no significant effect upon these strength properties, no further study of direction of rings was made. By cutting toughness specimens in such a way as to obtain radial and tangential surfaces, the effect of variations of the placement of rings on toughness values was avoided.

Explanation of Tables and Charts

The results of the tests performed in this survey are summarized by color groups in table 2. This table is in two parts: The first relates to static bending, toughness, and compression parallel to grain; the second, to compression perpendicular to grain, hardness, shear parallel to grain, cleavage, and tension perpendicular to grain. Averages of all sapwood and of all sound heartwood are given, the latter excluding the group of decayed heartwood specimens.

The averages shown in table 2 bring out the differences between the various color groups, but fail to show the variation of individuals within the groups. The extent of such variations is indicated in table 3. This tabulation of modulus of rupture illustrates how the range of individual values within groups compares with the differences between groups. Even in the weakest groups there are individual specimens that are stronger than some of the individual specimens in the strongest groups, and the range of individual specimens within groups is, for the most part, greater than the range between the highest and lowest group averages.

Specific gravity and strength values for the various color groups of table 2 are shown graphically in figures 7 to 14, inclusive, each of which relates to one strength property. Insofar as possible, similar designations for plotted points and similar scales are used in these eight figures. For ease in comparing the positions of the plotted points, parabolic curves of the form $y = ax^b$ were fitted to them (excepting "decay") by means of the following method: Suitable powers for specific gravity were first computed by the method of least squares.[6] Previous

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[6] Formulas for computation are $b = \frac{\sum \log x \sum \log y - N \sum (\log x \log y)}{(\sum \log x)^2 - N \sum (\log x)^2}$ and $\log a = \frac{\sum \log y - b \sum \log x}{N}$, where x and y are variables and a and b are constants, in the type equation $y = ax^b$. In all cases, except toughness, the values of x and y used were color group averages, rather than those from individual specimens.

work[7] has determined corresponding powers for the specific gravity-strength relationship between species and has indicated that the power of the relationship within any species is about 0.25 greater than that between species. The powers computed in this study were approximately 0.25 above those from the previous work between species, and were therefore rounded off to the higher values. With the powers of specific gravity in the parabolic relationship thus chosen, the appropriate coefficients were determined by the method of least squares.[6] These powers and coefficients are shown for each strength property in figures 7 to 14.

For toughness (fig. 10) there is no previous work from which a suitable power of specific gravity may be chosen. The equation for the curve was therefore computed on the basis of the individual values shown on figure 16 rather than on the basis of the color groups.

Figures 15 and 17 show graphically the relationship for individual specimens, with the exception of those of the "decay" group, between specific gravity and two important strength properties, modulus of rupture and maximum crushing strength. Figure 16 shows a similar relationship for toughness, but differs from figures 15 and 17 in that specific gravity is based on the volume when oven-dry, the same basis as that of data obtained from other sources (p. 10). Figures 18, 19, and 20 show the relationship between rate of growth and modulus of rupture, toughness, and maximum crushing strength, respectively. These two groups of figures have similar scales and similar designations for the plotted points, and afford a comparison between specific gravity and rate of growth as a means of estimating strength or shock resistance.

Figures 15 and 17 show vertical lines drawn through a specific gravity of 0.36. In this study, comparisons were made between specific gravities on the basis of weight when oven-dry and volume when kiln-dried (volume at test), and weight when oven-dry and volume when oven-dry, on a considerable number of closely matched specimens. These comparisons indicated the specific gravity on the basis of volume when kiln-dried to be 95 percent of that on the volume when oven-dry, a ratio almost identical with that computed from moisture content values of these specimens and volumetric shrinkage characteristics of the species. Army-Navy specifications require a minimum specific gravity of 0.38 on the basis of weight and volume when oven-dry, and that figure times 0.95 equals 0.36, a minimum specific

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[7] "The Relation of the Shrinkage and Strength Properties of Wood to its Specific Gravity," U. S. Dept. Agr. Bull. No. 676, table 1 and figures 1 to 4, and "Strength and Related Properties of Woods Grown in the United States," U. S. Dept. Agr. Tech. Bull. No. 479, p. 36-39.

gravity directly applicable to the plotted data. The same ratio was used to convert the observed values of specific gravity of toughness specimens to the basis of volume when oven-dry for plotting in figure 16. Since this specific gravity basis is the same as in the Army-Navy specifications, the vertical line on figure 16 representing a minimum of 0.38 is plotted directly.

Figure 16 also shows a horizontal line representing a possible minimum toughness of 55 inch-pounds.

The curves plotted in figures 15 and 17 are the same as in figures 7 and 11. The curve plotted in figure 10 is similar to that in figure 16 but differs slightly because of the different basis for computing specific gravity.[8] Since the curves of figures 15 and 17 were computed from color group averages, they do not fit perfectly the distribution of points representing individual specimens. They are satisfactory, however, to facilitate comparison of the positions of the plotted points.

A plot of the relationship between rate of growth and specific gravity for individual specimens shows a wide dispersion of points, similar to that in figures 18, 19, and 20. Since any trend in the relationship of these two properties is largely obscured by this dispersion, the values are plotted by rate of growth groups and corresponding specific gravity averages in figure 21. The trend of these averages is also compared with that observed in other studies of yellow-poplar at the Forest Products Laboratory. Table 4 gives further details of the grouping of values into the averages used in figure 21.

The relationship between toughness and modulus of rupture for individual end-matched specimens is shown in figure 22. The curve plotted in this figure represents an equation obtained by combining[9] the previously developed

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[8] Since the ratio of specific gravity values on the bases of volume when oven-dry and volume at test is 0.95, the ratio of corresponding toughness values is $(0.95)^3$ or 0.86. The coefficient of x in the equation of the curve in figure 10 (1,020) times 0.86 equals the coefficient in the equation of the curve in figure 16 (870).

[9] The method of combining these two equations is as follows:

Specific gravity-toughness equation (fig. 10) $T = 1020\ G^3$

Specific gravity-modulus of rupture equation (fig. 7) $R = 37000\ G^{1.5}$

Solving these equations for G gives

$$G = \sqrt[3]{\frac{T}{1020}}$$

and

$$G = \sqrt[1.5]{\frac{R}{37000}}$$

Equating to eliminate G $\quad \sqrt[3]{\frac{T}{1020}} = \sqrt[1.5]{\frac{R}{37000}}$

Cubing both sides of the equation $\quad \frac{T}{1020} = \left(\frac{R}{37000}\right)^2$

Whence $R = 1160\ T^{0.5}$

gravity-toughness and specific gravity-modulus of rupture equations. It shows the relationship of the computed equation to the experimental data.

Toughness data obtained in the present study are confirmed by comparison with values obtained from other sources. The Boeing Airplane Company[10], in connection with research and inspection operations, has made determinations of toughness and corresponding specific gravity on four groups, comprising in all 946 yellow-poplar specimens. A distribution of the toughness values obtained by them is shown in figure 23, where it may be compared with a corresponding distribution of values from the present study. Comparison is aided by the close agreement in averages of specific gravity, 0.438 for the Boeing data and 0.434 for the present study. Toughness of the Boeing specimens was determined at an average moisture content of 7.8 percent, but is adjusted to the basis of 10.4 percent moisture by means of a toughness-moisture relationship determined at the Forest Products Laboratory[11] for this species. Figure 23 also shows toughness averages corresponding to the distribution curves. The four groups of Boeing data exhibit considerable differences in toughness, the group averages ranging from 63 to 105.

A relationship between specific gravity and toughness was computed for the Boeing data by the method of least squares, and is shown as the graph of an equation in figure 24. Here also the toughness value is adjusted to the basis of 10.4 percent moisture content by modifying the coefficient of $\underline{G}$ in the computed equation by the ratio obtained from the toughness-moisture study. Figure 24 shows also the specific gravity-toughness curve of figures 10 and 16, here in the form $T = 870\ G^3$, as in figure 16. Average values of specific gravity and toughness are plotted.[12]

Universal Moulded Products Corporation[13] has made specific gravity and toughness determinations on a large number of samples of yellow-poplar. Corresponding individual values of specific gravity and toughness are not available, but the average specific gravity (0.46) and average toughness (89.8 inch-pounds) are plotted as a single point on figure 24. Moisture contents of these specimens are reported to range from 8 to 12 percent, and no adjustment to the common basis of 10.4 percent is made. Individual toughness values from this source range from 14 to 225.

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[10] Boeing Airplane Company, Wichita Division, "Yellow-poplar Strength Tests," Rept. No. 6358, 1943, and "Yield and Strength Data for Yellow-poplar Spars," Rept. No. WD-11150, Parts I and II and Appendix, 1943.

[11] Previous tests showed an average toughness of 115.8 at 7.8 percent moisture content, and 107.6 at 10.4 percent moisture. Toughness obtained at the one moisture content was adjusted to the basis of the other by multiplying by the ratio of these two toughness values.

[12] By construction, the plotted curves pass through the geometric means of the individual values. These geometric means are slightly different from the arithmetic means or averages.

[13] Universal Moulded Products Corporation, Bristol Aircraft Division, "A Statistical Analysis of the Toughness Data on Yellow-poplar," Engineering Research Rept. No. 23, 1943.

Discussion of Test Results

The discussion of the test results is divided into several parts, corresponding to the specific objectives stated at the beginning of this report.

Relation of Weight and Strength to Color

Table 2 shows the differences in average strength values among the 11 color groups into which the test specimens were divided. Although moisture differences between groups are small, specific gravity differences are large enough to be significant; the relationships between the more important strength properties and specific gravity are therefore shown in figures 7 to 14, inclusive. Comparison of the positions of the group average points with the fitted curves in these eight figures shows that the differences in strength are closely related to differences in specific gravity. In some of the properties, such as modulus of rupture, the relationship is very close.

The group of heartwood specimens containing decay is consistently lower in weight than other groups. It is also below the weight-strength curves for work to maximum load and toughness, both measures of shock resistance, which property is affected first and to the greatest degree by decay. The other properties, such as modulus of rupture and maximum crushing strength in compression parallel to grain, are at or near the average curve, which indicates that while decay possibly affected shock resistance, it was not sufficiently advanced to affect other properties. Since most strength properties would be greatly lowered if the weight was appreciably affected, the relatively low weight of the decay group is not believed to be caused by decay.

Many lumbermen recognize two fairly distinct types of yellow-poplar. According to their division, the "white" poplar is heavier and harder to work and has a conspicuous dark line at the end of each annual growth ring; while "yellow" poplar has more yellow in the normal heartwood, is easier to work, and lacks the distinct line at the end of the annual growth ring. In the present study the "tan-streaked, discolored" group of sapwood specimens has the appearance and physical properties ascribed to "white poplar." Examination of this group and of the boards from which it was cut shows also a rapid rate of growth and generally wide sapwood, characteristics commonly associated with young trees growing under favorable environment. Although in most properties the group falls below the strength value to be expected from its weight, it has more than average strength. Heartwood of similar characteristics may have been present in this material, but it was not recognized in sufficient amount to be placed in a separate group.

Comparison of Sapwood and Heartwood

Sapwood and heartwood, excluding decayed material, may be compared by means of the averages given in table 2. This comparison shows a rather small difference in specific gravity (column 2 of table 2), a difference that disappears entirely when the "tan-streaked, discolored" group of sapwood is excluded. The average modulus of rupture for sapwood is about 97 percent of that for heartwood, even though heartwood is lower in specific gravity. Sapwood is lower in modulus of elasticity in the same ratio. In work to maximum load, the sapwood average is 15 percent above that for heartwood, while in toughness, sapwood appears to be superior by about 7 percent. In compression parallel to grain, the ratio of average sapwood to average heartwood is 93 percent for maximum crushing strength and 95 percent for modulus of elasticity. Sapwood appears to have a slight advantage in compression perpendicular to grain, hardness, and shear parallel to grain.

Specific Gravity and Rate of Growth as Criteria of Strength

The specific gravity-strength graphs, figures 7 to 14, inclusive, indicate rather close relationships between specific gravity and the more important strength properties. The accuracy of specific gravity as a criterion of strength is also seen in the graphs of individual specimens, figures 15, 16, and 17. These charts show a close correlation of modulus of rupture and maximum crushing strength with specific gravity, and a less perfect though still definite relation for toughness.

Figures 18, 19, and 20 show modulus of rupture, toughness, and maximum crushing strength plotted against rate of growth. A comparison of these charts with figures 15, 16, and 17, reveals much more scattering of the points for rate of growth. There is a trend in the direction of lower modulus of rupture and lower toughness with slower growth, but little or no trend for maximum crushing strength. Hence, it is clear that these three properties are related more closely to specific gravity than to rate of growth.

The specific gravity-rate of growth relationship for yellow-poplar of the present and previous studies is shown in figure 21 and table 4. In general, the highest specific gravity appears to be associated with a rate of growth between 10 and 12 rings per inch. All curves show a decrease in specific gravity for slower rates of growth, and all but two show a decrease for rates more rapid than 10 rings per inch.

The present study is represented in figure 21 by separate curves for heartwood and for sapwood. The investigations previously made were mostly on heartwood and thus are more nearly comparable to the heartwood curve for the present study, which shows a decrease in specific gravity for very rapid rate of growth. The present sapwood group has high specific gravity values for the most rapid rate of growth. It has been observed

by Paul[14] and others that high specific gravity is associated with rapid growth in a favorable environment, except that wide rings near the center of the trunk may be of a specific gravity below the average. That observation is confirmed in the present study: Although the distance of these specimens from the centers of the parent trees is not known, it is obvious that rapidly grown heartwood may be from the inner portion of the trunk, while sapwood from any tree of merchantable size is necessarily at some distance from the center.

Correlation between Toughness and Strength

Figure 22 illustrates how a computed relationship of toughness to modulus of rupture[9] is verified by actual test results on matched specimens. The vertical dispersion of points, as compared with figure 15, indicates that modulus of rupture may be estimated more reliably from specific gravity. A similar study of toughness and maximum crushing strength in compression parallel to grain also showed that specific gravity is better than toughness as a criterion of crushing strength.

Toughness Values for Inspection Use

In the determination of a toughness acceptance requirement for yellow-poplar, consideration is given primarily to the group of specimens included in the present study. Comparisons with the larger group of data obtained by the Boeing Airplane Company (toughness distribution in figure 23 and specific gravity-toughness relationship in figure 24) show a close similarity. Data from Universal Moulded Products Corporation are less complete, but the average plotted on figure 24 indicates the similarity of that group. Since the data from these three sources are so nearly comparable, it is possible to conclude that the group in the present study is representative of the species and that a suitable toughness requirement can be determined largely from this group alone.

This study includes 227 toughness specimens of sapwood and sound heartwood. Of this number, 25 percent have a toughness value of 56.4 or less; the remainder, above that figure. In the Boeing data, 25 percent of the specimens have toughness (adjusted to 10.4 percent moisture content) of 54.0 or less.

On figures 16, 19, and 22, certain toughness specimens are designated as brash. This designation refers to a brash-appearing break, independent of the toughness value. These brash specimens are low in toughness and are associated with low specific gravity and a rate of growth significantly slower than average. As may be seen in figure 16, a minimum toughness requirement of 55 would eliminate 26 of the 27 brash specimens.

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[14] Paul, B. H., and Norton, N. A., "Variations in the Wood of Yellow-poplar from the Southern Appalachian Region," J. Forestry, Vol. 34, No. 10, pp. 936-942 (1936).

Figure 16 indicates a fairly consistent relationship between toughness and specific gravity. The present Army-Navy minimum specific gravity requirement on yellow-poplar is 0.38 on the basis of weight and volume when oven-dry. A minimum toughness value corresponding to this minimum specific gravity may be estimated from the average of individual toughness values at or near that minimum specific gravity. In this study, 22 specimens having specific gravity of 0.37 to 0.39, inclusive, were found to have an average toughness value of 52.3

A toughness acceptance requirement of 55 inch-pounds per specimen would reject 51 of the 227 specimens tested. Of these 51 specimens, 33 have less than the required specific gravity, and 18 have more (fig. 16). Of the 18 specimens of satisfactory specific gravity, 9 showed a brash break, indicating possible preexisting compression failures or other undesirable characteristics. Of the 176 specimens admitted under this acceptance requirement, 8 would be excluded by the specific gravity limitation.

Conclusions

Sapwood stain in the yellow-poplar studied was moderate, and this material showed normal weight-strength relations. The various discolorations of heartwood were also normal in their weight-strength relationships. Certain brown colorations of sound heartwood, however, were almost indistinguishable from the brown of decay, and pieces with such colorations should be excluded, or admitted only with extreme caution. A variety of the species known to the trade as "white" poplar was characterized by greater weight and somewhat higher strength.

There was no significant difference in specific gravity between sapwood and sound heartwood. Test averages indicated some superiority of sound heartwood over sapwood of the same weight in bending strength and stiffness, and a superiority of sapwood in shock resistance, but the differences were not large, and may not be significant.

The more important strength values correlated rather closely with specific gravity, but much less so with rate of growth. There was a trend in the direction of lower specific gravity (and consequently lower strength) with slower rate of growth, although individual exceptions were numerous, and largely obscured the relationship. This trend agreed with that observed in previous studies of the species. Heartwood of rapid growth (less than 10 annual rings per inch) was lower in specific gravity than sapwood of the same rate of growth.

Yellow-poplar in this study showed a more definite relationship between toughness and specific gravity than has been found for some other species. The larger group of data furnished by the Boeing Airplane Company had a similar gravity-toughness relation. There was also a relationship between

toughness and modulus of rupture (and possibly also between toughness and other strength properties), but less perfect than that between specific gravity and modulus of rupture. It is concluded that strength properties of yellow-poplar may be estimated more reliably from specific gravity than from toughness.

A suitable toughness requirement for inspection of yellow-poplar appears to be 55 inch-pounds per specimen. This limit rejects 22 percent of the specimens in the present study and seems to be adequate for the elimination of brash material. Most of the material rejected by a toughness requirement of 55 inch-pounds is deficient in both weight and strength. This toughness requirement should supplement, but not replace, the present specific gravity limitation for yellow-poplar.

Table 1.--Distribution of specimens by mills and by kind of tests

Test	Number of specimens from mill[1]							Total number
	A	B	C	D	E	F	G	
Specific gravity[2]	45	54	8	25	22	39	57	250
Static bending	45	54	8	25	22	39	57	250
Toughness	45	54	8	25	22	39	57	250
Compression parallel to grain	45	54	8	25	22	39	57	250
Compression perpendicular to grain	10	14	12	11	5	6	12	70
Hardness	33	39	13	26	11	23	39	184
Shear parallel to grain	33	41	12	26	14	23	39	188
Cleavage	5	14	11	9	5	5	10	59
Tension perpendicular to grain	5	14	11	9	5	5	10	59
Total number of specimens								1,560

[1] Locations of mills are as follows:
- A - Cleveland, S. C.
- B - Kyle, N. C.
- C - Conasauga, Tenn.
- D - Bluefield, W. Va.
- E - Omar
- F - Tioga, W. Va.
- G - Damascus, Va.

[2] Determinations based on the weight and volume when oven-dry of specimens 2 inches long, taken from static bending tests.

Table 2.--Summary of results of strength tests on yellow-poplar classified by color groups -- Part I[1]

Color group	Specific gravity, weight and volume when oven dry	Rings per inch	Static bending[2]: Specimens	Static bending[2]: Moisture content	Static bending[2]: Specific gravity, weight when oven dry, volume at test	Static bending[2]: Stress at proportional limit	Static bending[2]: Modulus of rupture	Static bending[2]: Modulus of elasticity	Static bending[2]: Work: Proportional limit	Static bending[2]: Work: Maximum load	Static bending[2]: Work: Total[5]	Toughness[3]: Specimens	Toughness[3]: Moisture content	Toughness[3]: Specific gravity, weight when oven dry, volume at test	Toughness[3]: Toughness	Compression parallel to grain[4]: Specimens	Compression parallel to grain[4]: Moisture content	Compression parallel to grain[4]: Specific gravity, weight when oven dry, volume at test	Compression parallel to grain[4]: Stress at proportional limit	Compression parallel to grain[4]: Maximum crushing strength	Compression parallel to grain[4]: Modulus of elasticity
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
		Number	Number	Percent		Lb. per sq. in.	Lb. per sq. in.	1000 lb. per sq. in.	In.-lb. per cu. in.	In.-lb. per cu. in.	In.-lb. per cu. in.	Number	Percent		In.-lb. per specimen	Number	Percent		Lb. per sq. in.	Lb. per sq. in.	1000 lb. per sq. in.
Sapwood																					
Unstained	0.419	21	40	11.3	0.397	4,980	9,070	1,330	1.05	10.11	12.70	39	10.6	0.397	71.2	34	11.1	0.393	3,130	4,770	1,419
Sap stain, light gray	.435	19	22	11.3	.417	5,120	9,800	1,440	1.02	11.04	14.24	22	10.7	.413	75.8	26	11.3	.412	3,410	5,120	1,548
Sap stain, medium gray	.451	18	14	11.3	.426	5,740	10,110	1,551	1.19	11.59	15.18	12	10.4	.429	82.1	13	11.6	.426	3,780	5,570	1,781
Sap stain, heavy gray	.410	22	17	11.0	.387	4,980	8,840	1,336	1.04	8.99	11.08	18	10.3	.392	63.3	18	11.0	.387	3,290	4,880	1,487
Discoloration, tan	.484	14	11	11.1	.451	6,500	10,980	1,588	1.48	11.13	14.20	11	10.3	.451	80.3	13	10.8	.437	3,800	5,740	1,693
Discoloration, tan streaked	.514	12	7	12.2	.486	6,740	11,880	1,630	1.56	14.08	16.26	6	11.2	.504	119.3	8	11.5	.469	3,660	5,850	1,651
Average of sapwood[6]	.437	19	111	11.3	.414	5,370	9,680	1,425	1.13	10.66	13.44	108	10.6	.414	75.6	112	11.2	.411	3,410	5,150	1,550
Sound heartwood																					
Normal	.453	20	40	11.0	.427	6,160	10,710	1,572	1.35	10.55	13.84	39	10.2	.425	76.2	47	10.7	.431	4,130	5,950	1,747
Normal, streaked	.428	18	36	10.8	.405	5,900	9,780	1,482	1.32	8.61	10.70	38	10.4	.406	66.3	38	10.7	.404	3,980	5,470	1,644
Blue-butt, red, purple, gray	.435	12	26	10.7	.416	5,700	10,280	1,449	1.26	9.85	13.55	29	10.1	.417	75.8	25	10.9	.401	3,470	5,250	1,511
Blue-butt, brown	.376	17	15	10.6	.362	4,820	7,860	1,186	1.10	6.83	9.17	13	9.9	.358	54.1	14	10.3	.362	3,100	4,710	1,395
Average of sound heartwood[6]	.431	17	117	10.8	.409	5,810	9,960	1,467	1.29	9.32	12.21	119	10.2	.410	70.5	124	10.7	.409	3,830	5,520	1,628
Decayed heartwood																					
Decay	.363	21	9	10.3	.352	5,090	7,820	1,190	1.23	5.77	6.52	8	9.9	.352	40.4	8	10.5	.341	3,040	4,170	1,169

[1] Part I includes results from static bending, toughness, and compression parallel to grain. Part II includes results from compression perpendicular to grain, hardness, shear parallel to grain, cleavage, and tension perpendicular to grain.

[2] Specimen 1 by 1 by 24 inches, tested over a 14-inch span, center loading.

[3] Specimen 5/8 by 5/8 by 10 inches, tested over an 8-inch span, center loading.

[4] Specimen 1 by 1 by 4 inches.

[5] Work up to point beyond maximum load where load has decreased to 100 pounds.

[6] Average of color group averages, weighted according to number of specimens in each group. For specific gravity by weight and volume when oven dry, the number of specimens is the same as for the static bending specimens.

Z M 56716 F

Table 2.—Summary of results of strength tests on yellow-poplar classified into color groups -- Part II[1]

Color group	Compression perpendicular to grain[2]					Hardness[3]							Shear parallel to grain[4]				Cleavage[5]				Tension perpendicular to grain[6]			
	Specimens	Rings per inch	Moisture content	Specific gravity, oven dry, when volume at test	Stress at proportional limit	Specimens	Rings per inch	Moisture content	Specific gravity, oven dry, when volume at test	Load required to embed a 0.444-inch ball to half its diameter: End	Load required to embed a 0.444-inch ball to half its diameter: Side[7]	Specimens	Rings per inch	Moisture content	Maximum shearing strength	Specimens	Rings per inch[8]	Moisture content	Load to cause splitting	Specimens	Rings per inch[8]	Moisture content	Maximum tensile strength
1	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	45	46
	Number	Number	Percent		Lb. per sq. in.	Number	Number	Percent		Pounds	Pounds	Number	Number	Percent	Lb. per sq. in.	Number	Number	Percent	Lb. / in. of width	Number	Number	Percent	Lb. per sq. in.
Sapwood																							
Unstained	2	28	10.5	0.382	424	24	22	11.0	0.404	832	549	20	22	11.0	1,227	1	24	11.8	427	1	24	12.1	1,095
Sap stain, light gray	5	15	10.8	.432	597	12	18	11.0	.419	891	584	11	17	11.3	1,293	1	17	11.9	377	1	17	11.9	598
Sap stain, medium gray	—	—	—	—	—	14	19	10.9	.422	872	556	12	17	11.0	1,258	—	—	—	—	—	—	—	—
Sap stain, heavy gray	3	35	10.2	.388	548	13	23	11.2	.395	833	506	15	24	11.1	1,125	2	37	10.8	432	2	37	10.4	906
Discoloration, tan	—	—	—	—	—	8	13	10.6	.436	946	631	7	12	10.7	1,306	—	—	—	—	—	—	—	—
Discoloration, tan, streaked	—	—	—	—	—	4	9	11.6	.490	1,106	846	6	10	11.2	1,438	—	—	—	—	—	—	—	—
Average of sapwood[9]	10	24	10.6	.409	548	75	19	11.0	.416	876	573	71	19	11.1	1,247	4	29	11.3	417	4	29	11.2	876
Sound heartwood																							
Normal	35	19	10.6	.421	544	44	21	10.8	.429	841	591	37	19	10.6	1,183	31	19	11.0	385	32	19	10.7	741
Normal, streaked	23	20	10.5	.400	522	33	19	10.6	.408	772	518	37	19	10.6	1,159	21	20	10.7	387	22	20	10.7	775
Blue-butt, red, purple, gray	1	18	9.6	.400	451	16	11	10.4	.410	844	583	15	12	10.3	1,160	—	—	—	—	—	—	—	—
Blue-butt, brown	1	3	10.4	.354	497	9	16	10.4	.361	650	394	10	13	10.5	1,032	—	—	—	—	—	—	—	—
Average of sound heartwood[9]	60	19	10.5	.411	533	102	18	10.6	.413	802	549	99	17	10.5	1,155	52	19	10.9	386	54	19	10.7	755
Decayed heartwood																							
Decay	1	26	11.1	.332	350	4	26	10.0	.352	531	371	4	26	10.2	972	1	26	11.2	286	1	26	12.0	624

[1] Part II includes results from compression perpendicular to grain, hardness, shear parallel to grain, cleavage, and tension perpendicular to grain. Part I includes results from static bending, toughness, and compression parallel to grain.

[2] Specimens 1 by 2 by 6 inches loaded on 2-inch face.

[3] Specimens 1 by 2 inches, 4 inches to 6 inches long.

[4] Shear surface 2 inches long and 1 inch wide. One-eighth inch offset in shear tool.

[5] Cleaved surface 3 inches long and 1 inch wide.

[6] Tension surface 1 inch long and 1 inch wide.

[7] Average of two mutually perpendicular sides. In the majority of specimens, these sides were intermediate between radial and tangential.

[8] Specimens for cleavage and for tension perpendicular to grain were end-matched, and the same ring count used for both.

[9] Average of color group averages, weighted according to number of specimens in each group.

Table 3.--Variation by color groups of individual values of modulus of rupture of specimens of yellow-poplar

Color group	Specimens	Group average value	Maximum individual value	Minimum individual value
	Number	Pounds per square inch	Pounds per square inch	Pounds per square inch
Sapwood				
Unstained	40	9,070	11,620	5,960
Sap stain, light gray	22	9,800	13,530	6,980
Sap stain, medium gray	14	10,110	12,620	7,660
Sap stain, heavy gray	17	8,840	13,180	5,630
Discoloration, tan	11	10,980	12,920	9,100
Discoloration; tan, streaked	7	11,880	13,560	9,220
Heartwood				
Normal	40	10,710	14,580	7,220
Normal, streaked	36	9,780	14,450	6,100
Blue-butt; red, purple, gray	26	10,280	15,040	6,360
Blue-butt; brown	15	7,860	9,520	6,050
Decay	9	7,820	9,900	6,390

Table 4.--Averages of specific gravity values of yellow-poplar by rate-of-growth groups

1944 Study[1]						1936 Study[2]						1933 Study[3]			1914 Study[4]		
Sapwood			Heartwood			Old growth			Young growth								
Number of specimens	Average: Rings per inch	Average: Specific gravity	Number of specimens	Average: Rings per inch	Average: Specific gravity	Number of specimens	Average: Rings per inch	Average: Specific gravity	Number of specimens	Average: Rings per inch	Average: Specific gravity	Number of specimens	Average: Rings per inch	Average: Specific gravity	Number of specimens	Average: Rings per inch	Average: Specific gravity
9	7	0.444	6	3-1/2	0.367	24	7-1/2	0.352	49	3-1/2	0.379	42	3-1/2	0.433	20	6	0.330
19	10-1/2	.411	16	6-1/2	.380	37	12-1/2	.371	121	7-1/2	.397	133	7	.430	46	7-1/2	.356
21	14-1/2	.386	24	10-1/2	.405	38	17-1/2	.371	93	12-1/2	.401	97	10-1/2	.423	39	9-1/2	.377
24	18-1/2	.384	18	14	.393	40	22-1/2	.365	25	17-1/2	.388	56	15	.413	44	11-1/2	.386
12	22-1/2	.370	20	18-1/2	.378	22	27-1/2	.366	23	25	.393	42	19-1/2	.405	28	13-1/2	.384
20	28	.359	16	22-1/2	.373	20	32-1/2	.343				24	24	.377	59	15-1/2	.382
8	41	.334	10	27-1/2	.362	15	42	.328				32	30	.365	40	17-1/2	.382
			8	39-1/2	.361										22	19-1/2	.368
															19	21-1/2	.367
															14	23-1/2	.352
															8	29	.334

[1] Averages by rate of growth groups of specific gravity of individual specimens, adjusted to the basis of weight when oven dry and volume when green, by multiplying the available specific gravity values, based on weight and volume when oven dry, by the factor 0.88.

[2] Averages of specific gravity based on weight when oven dry and volume when green, as shown graphically in figure 4 of "Variations in the Wood of Yellow-poplar from the Southern Appalachian Region" by Benson H. Paul and Newell A. Norton, Proj. 259 of U. S. Forest Products Laboratory, 1936. The proportion of heartwood in this study is not accurately known, but is estimated at 80 percent.

[3] Averages of specific gravity based on weight when oven dry and volume when green, as shown graphically in chart 12 of "First Progress Report on Southern Hardwoods -- Specific Gravity, Rings per Inch, and Shrinkage", by E. M. Davis, Proj. L-252-3 of U. S. Forest Products Laboratory, 1933. The proportion of heartwood is unknown, but probably large (80 percent ±).

[4] Averages by rate of growth groups of specific gravity based on weight when oven-dry and volume when green, of individual specimens tested in static bending or compression parallel to grain, Forest Products Laboratory Shipment L-226. These specimens were composed of 80 percent heartwood and 20 percent sapwood.

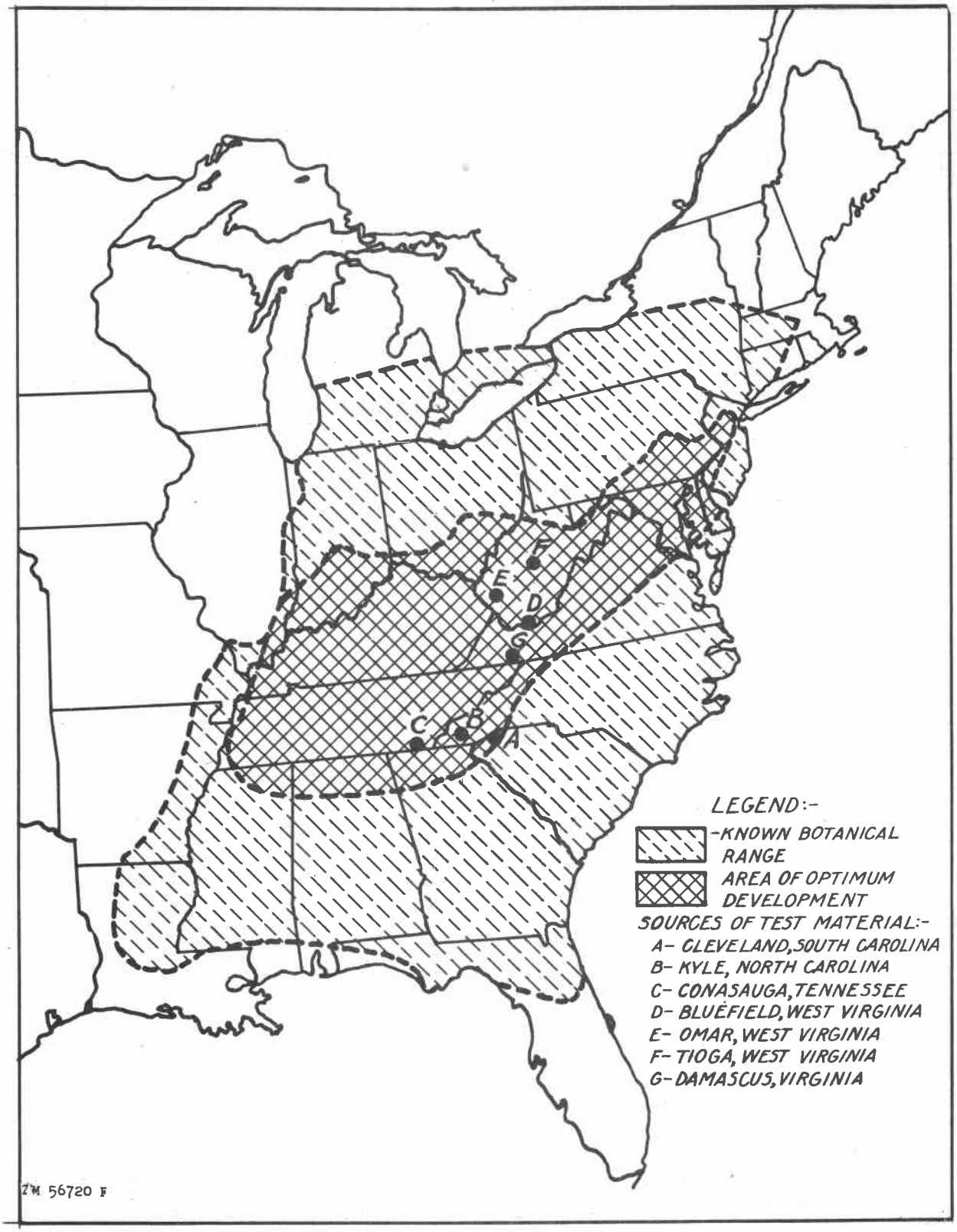


Figure 1.--Location of sources of test material with respect to the known botanical range and the area of optimum development of yellow-poplar.

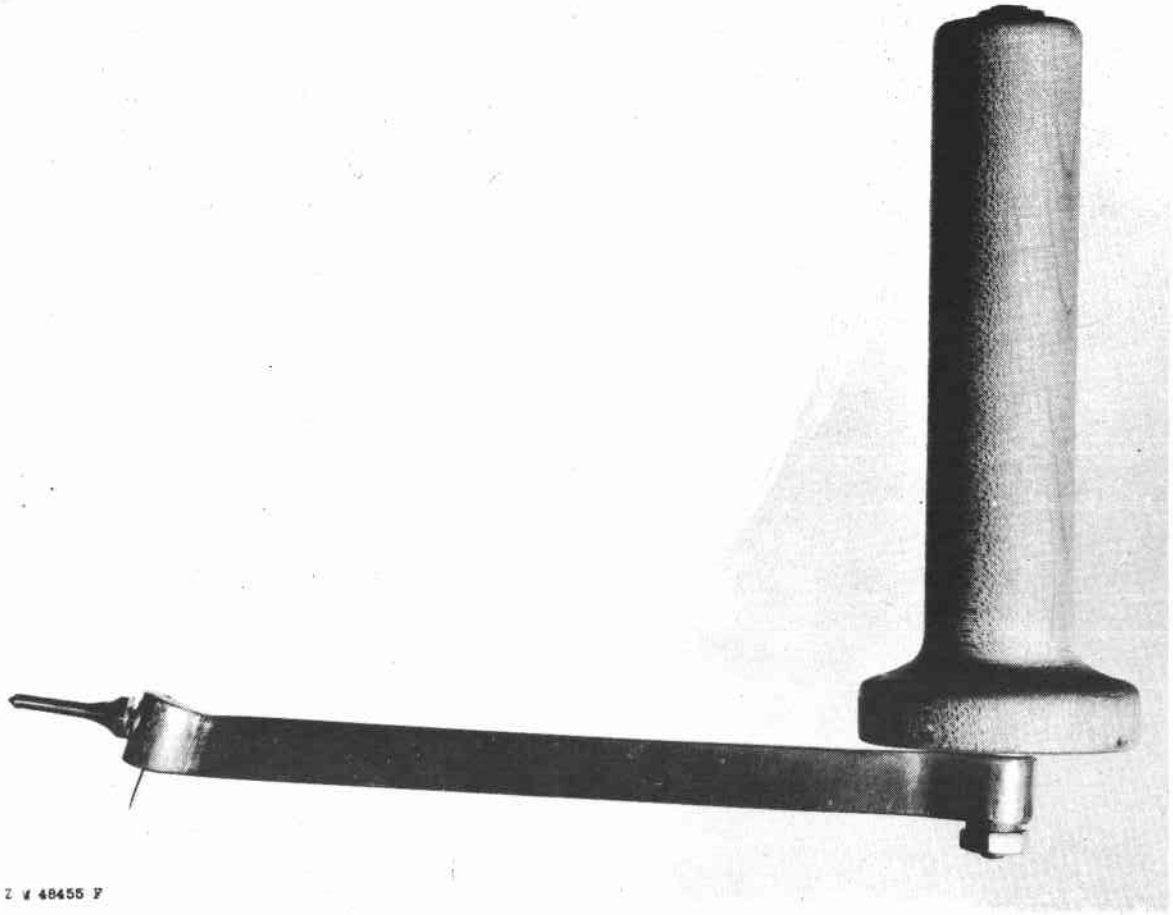


Figure 2.--Scribe for determining direction of grain.

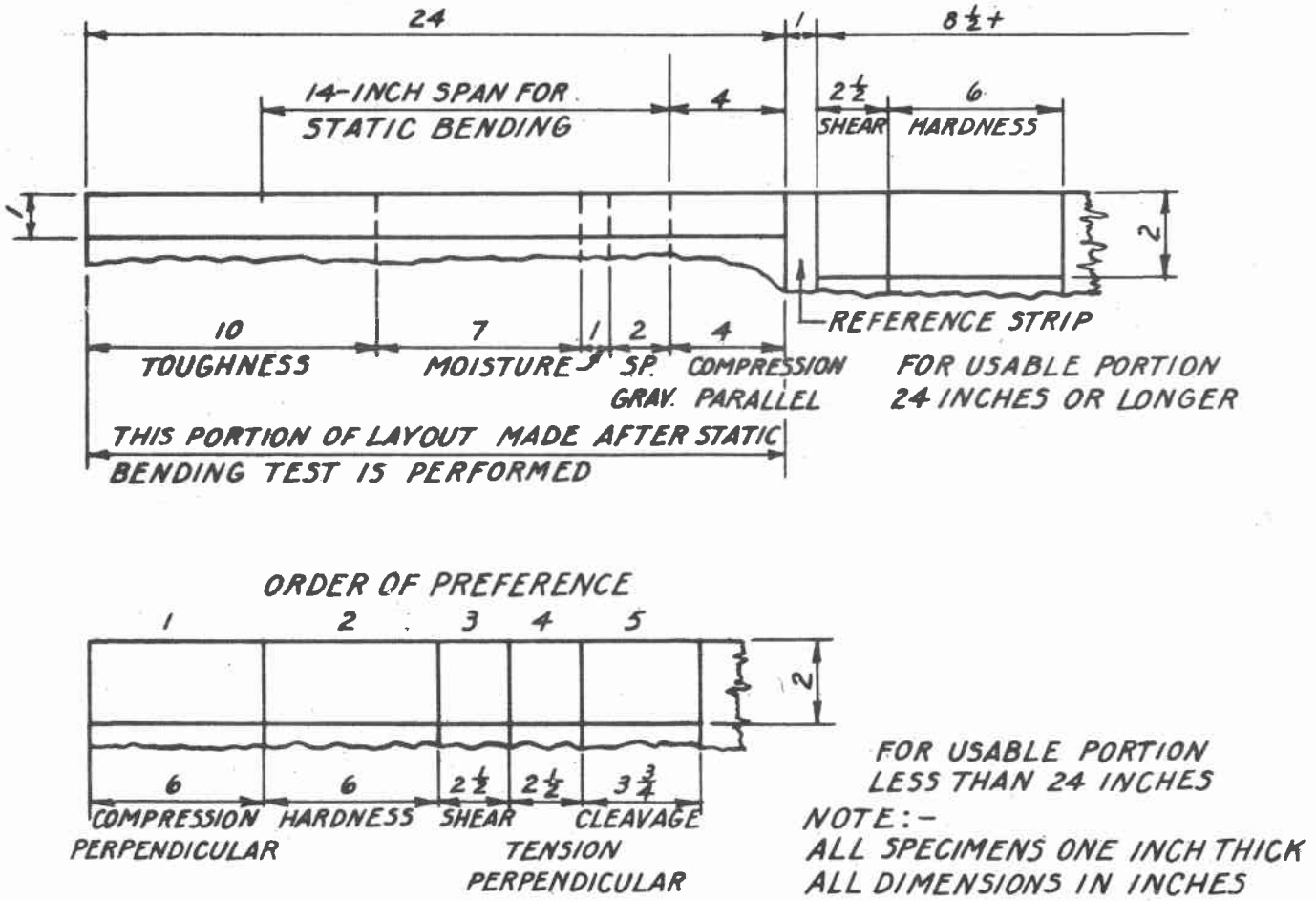


Figure 3.--Layout of specimens in sapwood.

Z M 56721 F

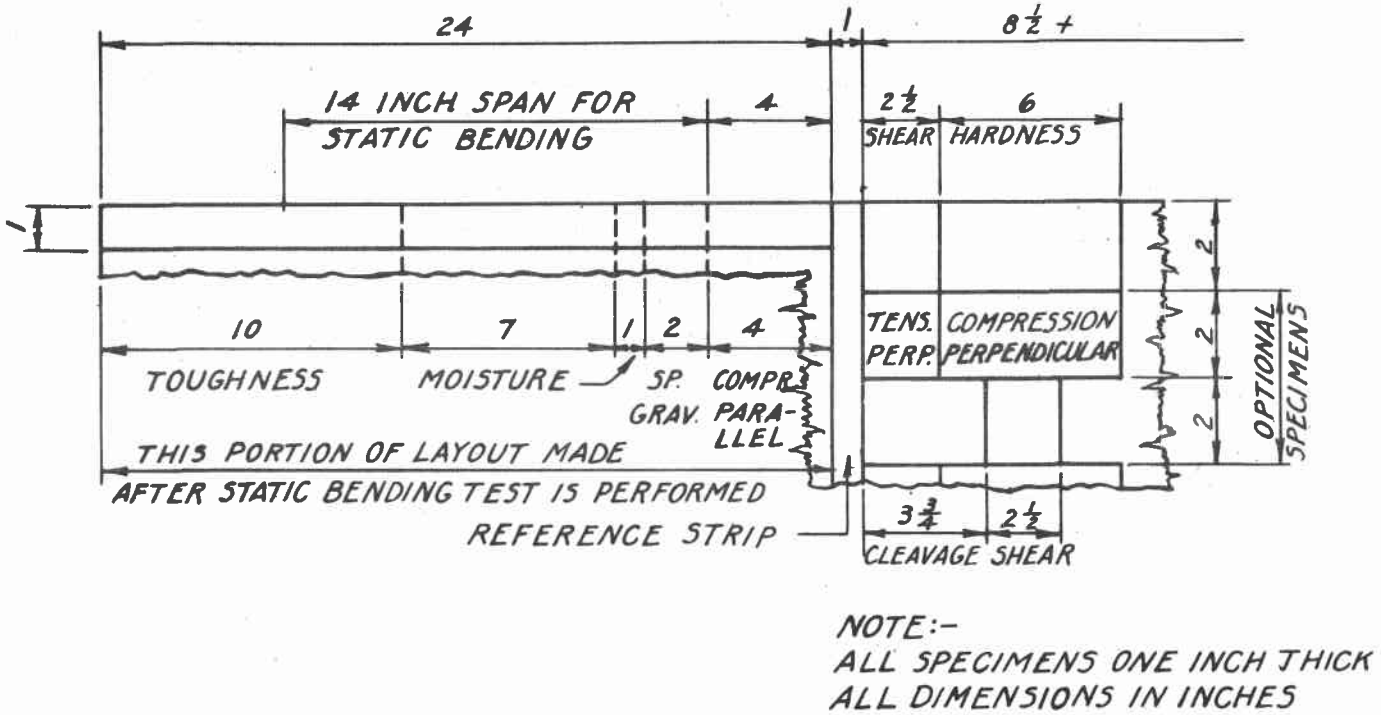


Figure 4.--Layout of specimens in discolored heartwood.

Z M 56722 F

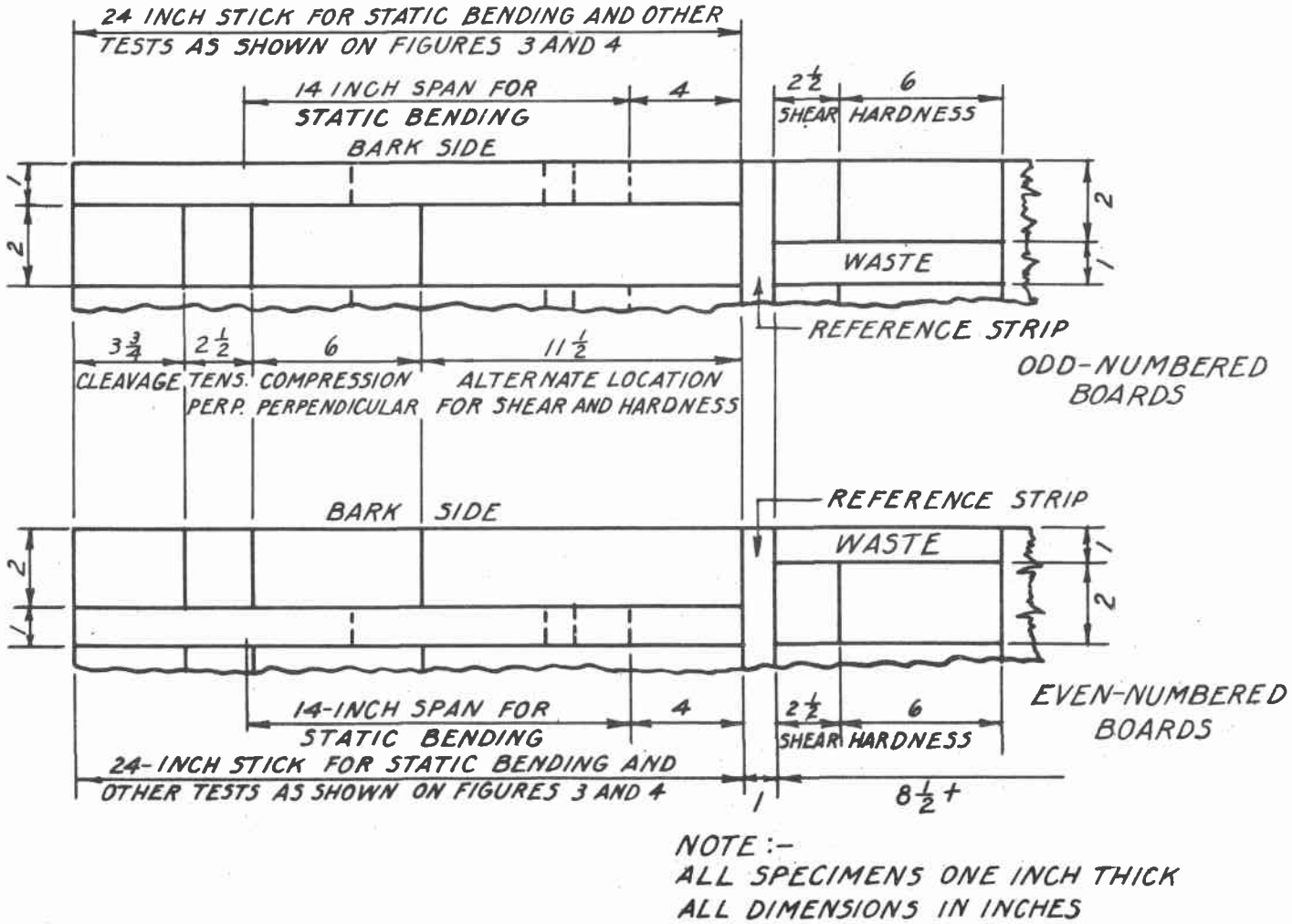
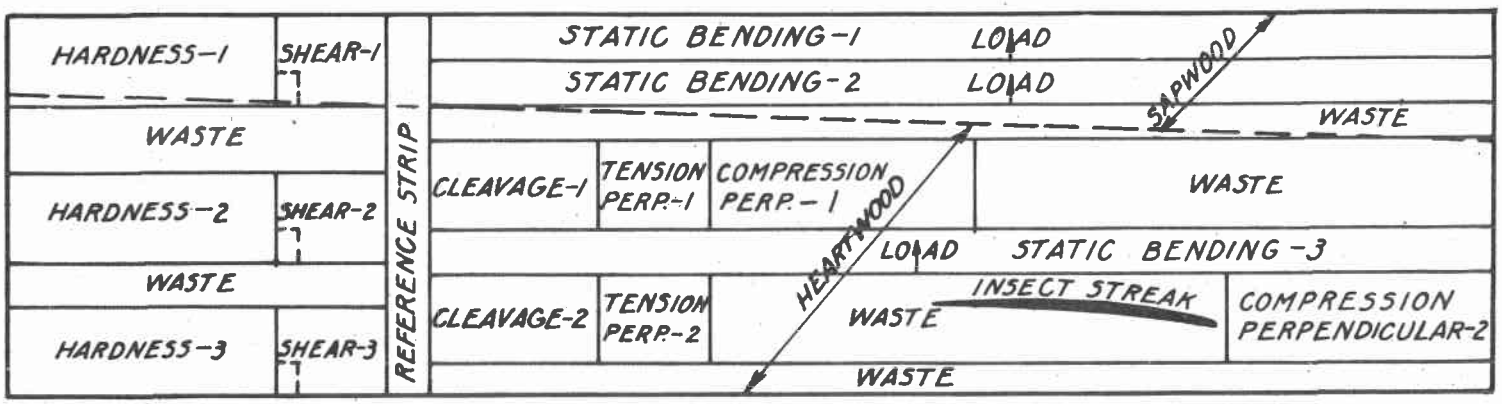
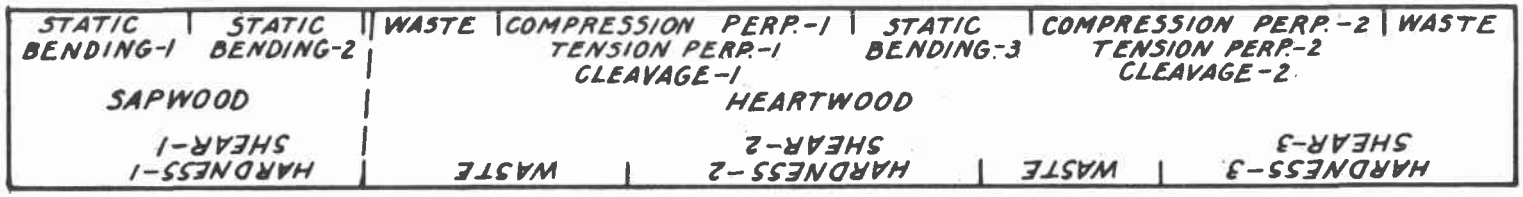


Figure 5.--Layout of specimens in normal heartwood.

Z M 56723 F



PLAN OF BOARD QUARTER SIZE



MARKINGS ON REFERENCE STRIP - FULL SIZE

Figure 6.--Layout of specimens on typical board.
(Board B-20)

Z M 56724 F

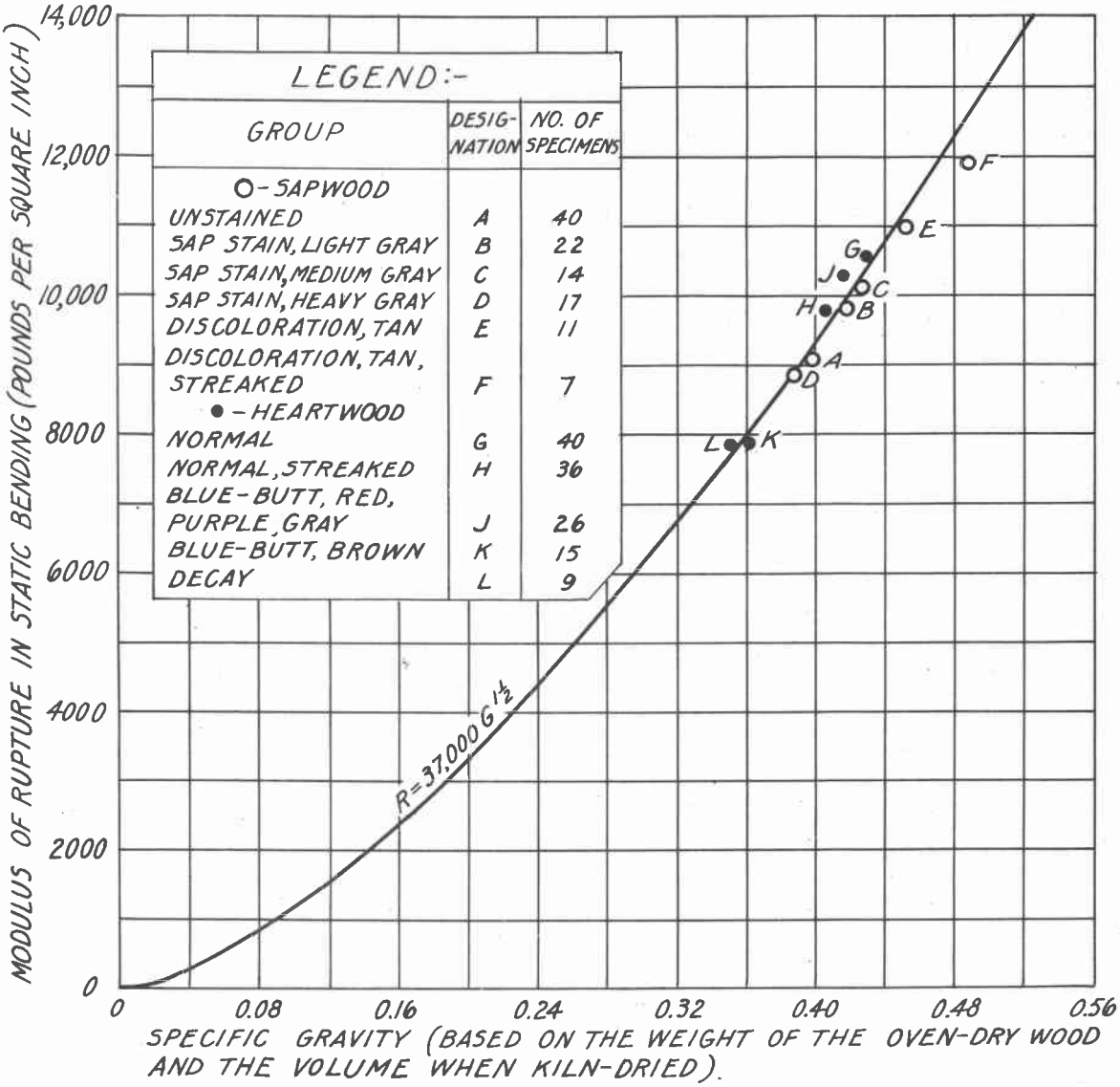


Figure 7.--Relation of modulus of rupture to specific gravity of yellow-poplar of various colorations.

Z M 56725 F

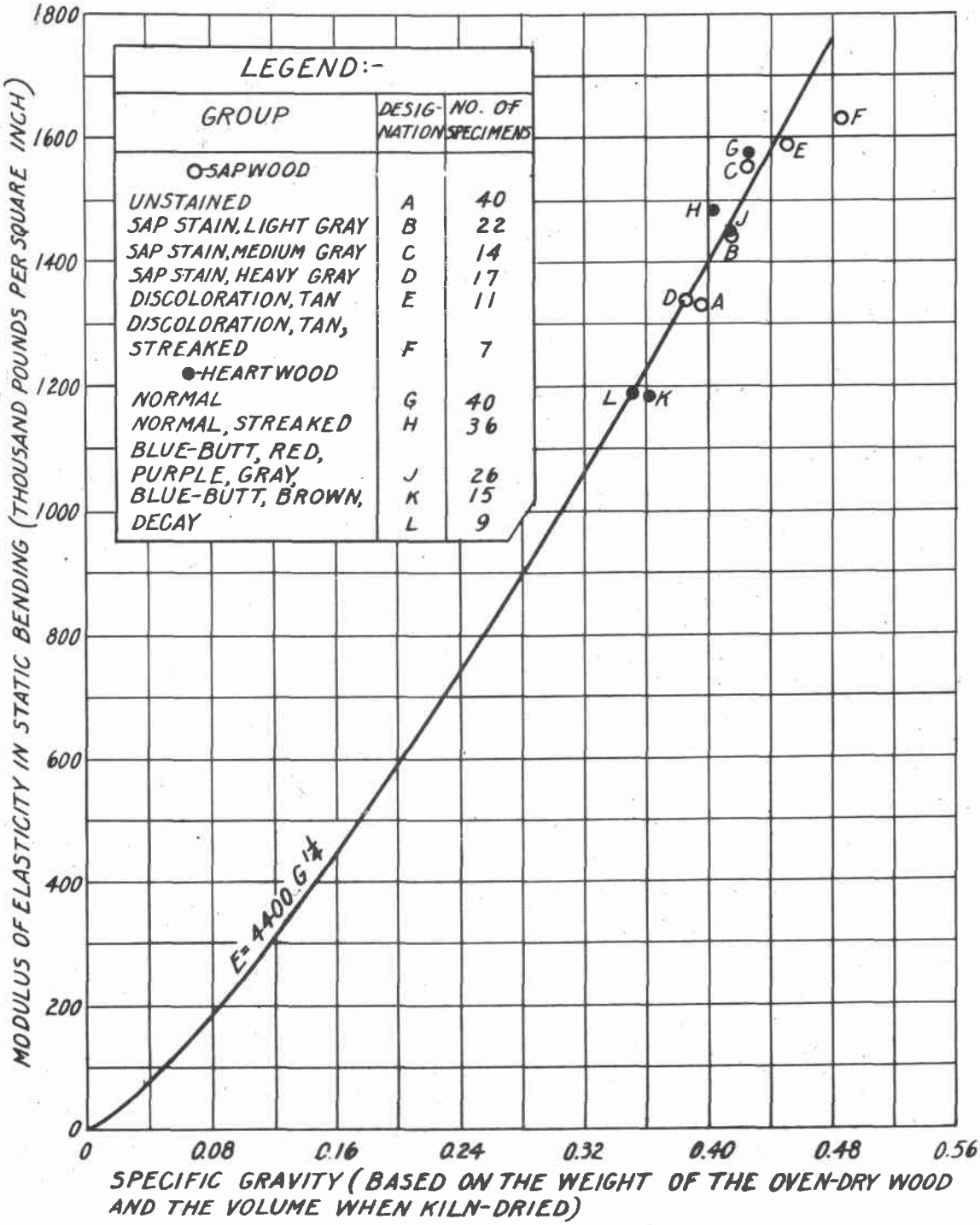


Figure 8.--Relation of modulus of elasticity in static bending to specific gravity of yellow-poplar of various colorations.

Z M 56726 F

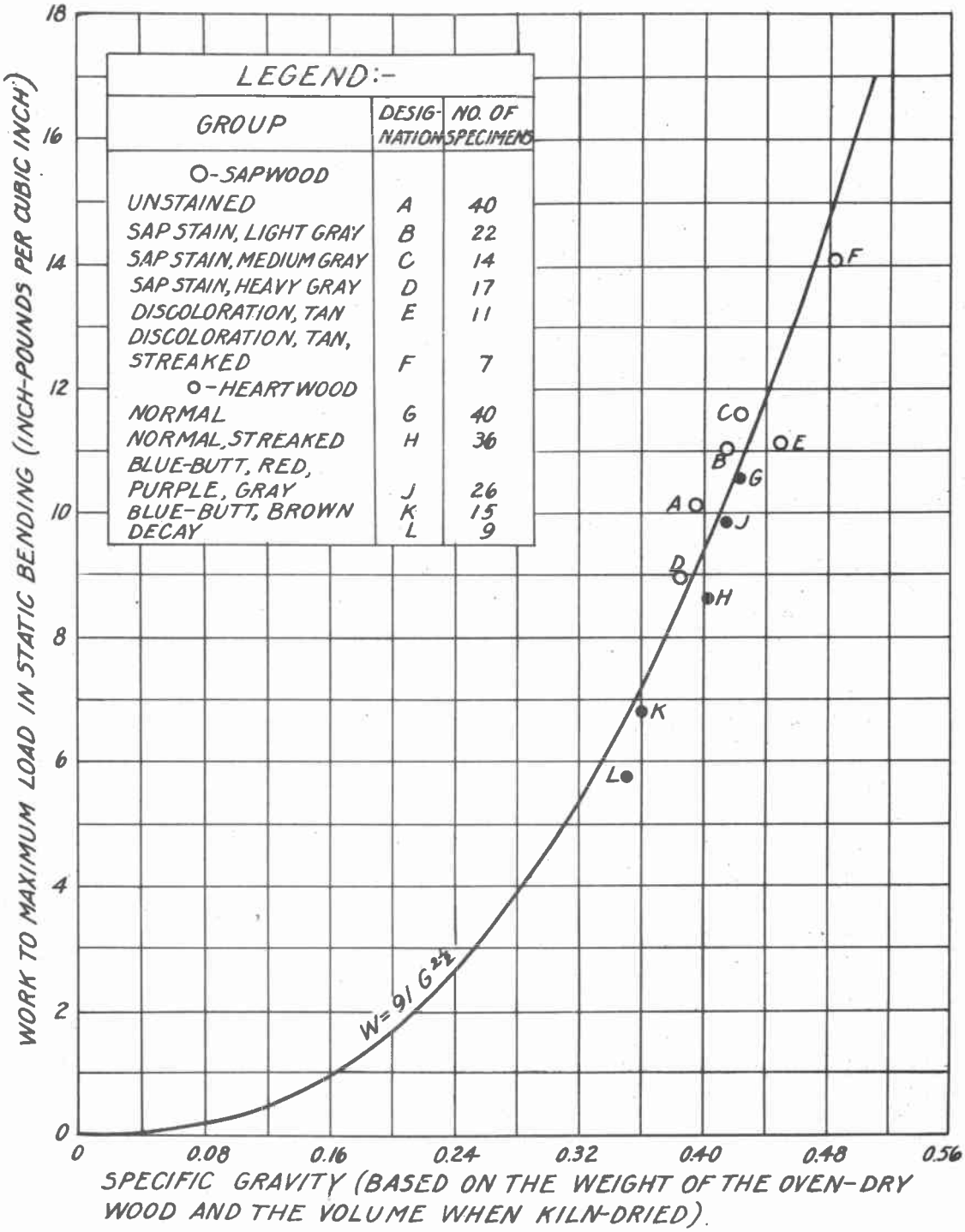


Figure 9.--Relation of work to maximum load to specific gravity of yellow-poplar of various colorations.

Z M 56727 F

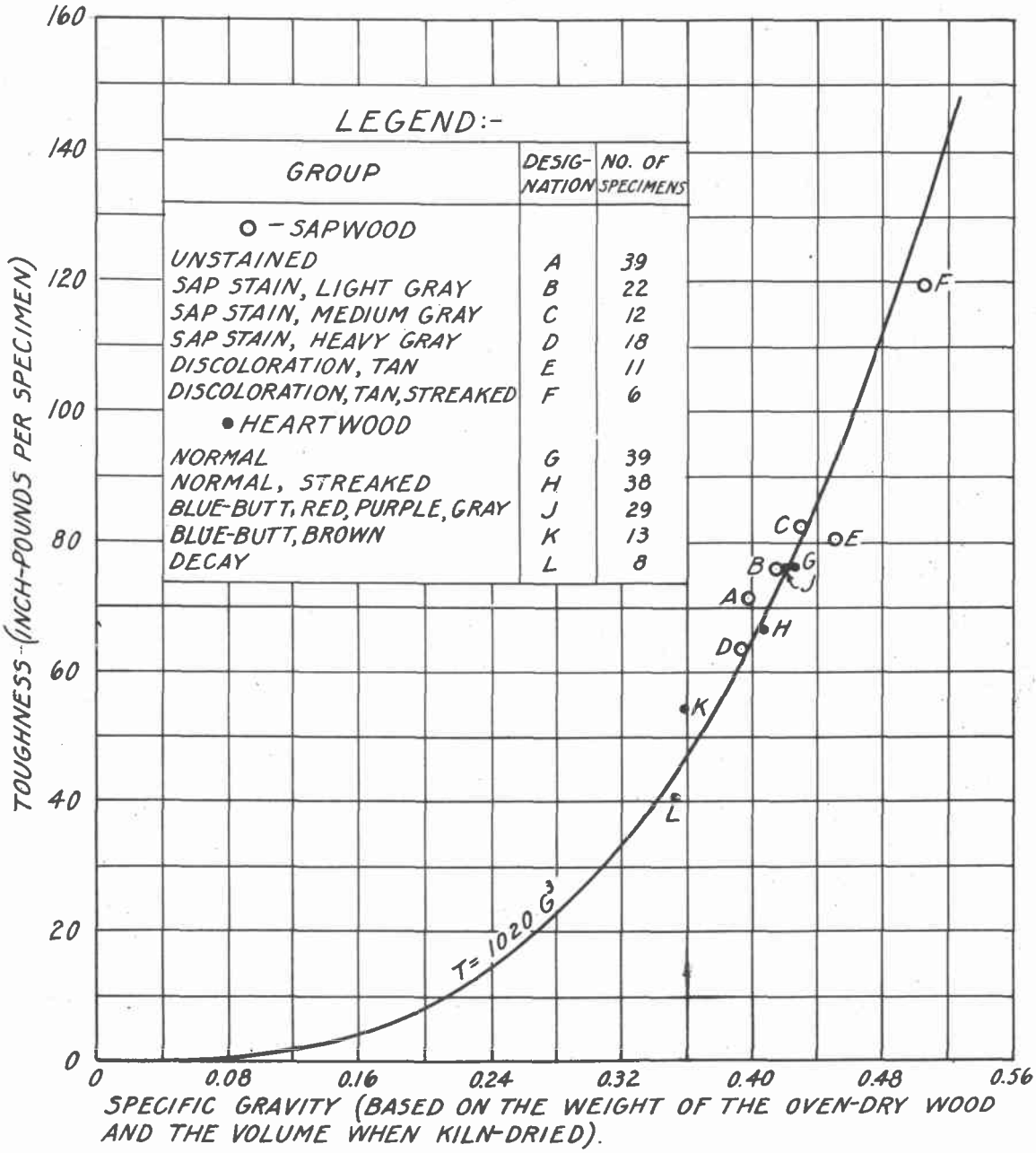


Figure 10.--Relation of toughness to specific gravity of yellow-poplar of various colorations.

Z M 56728 F

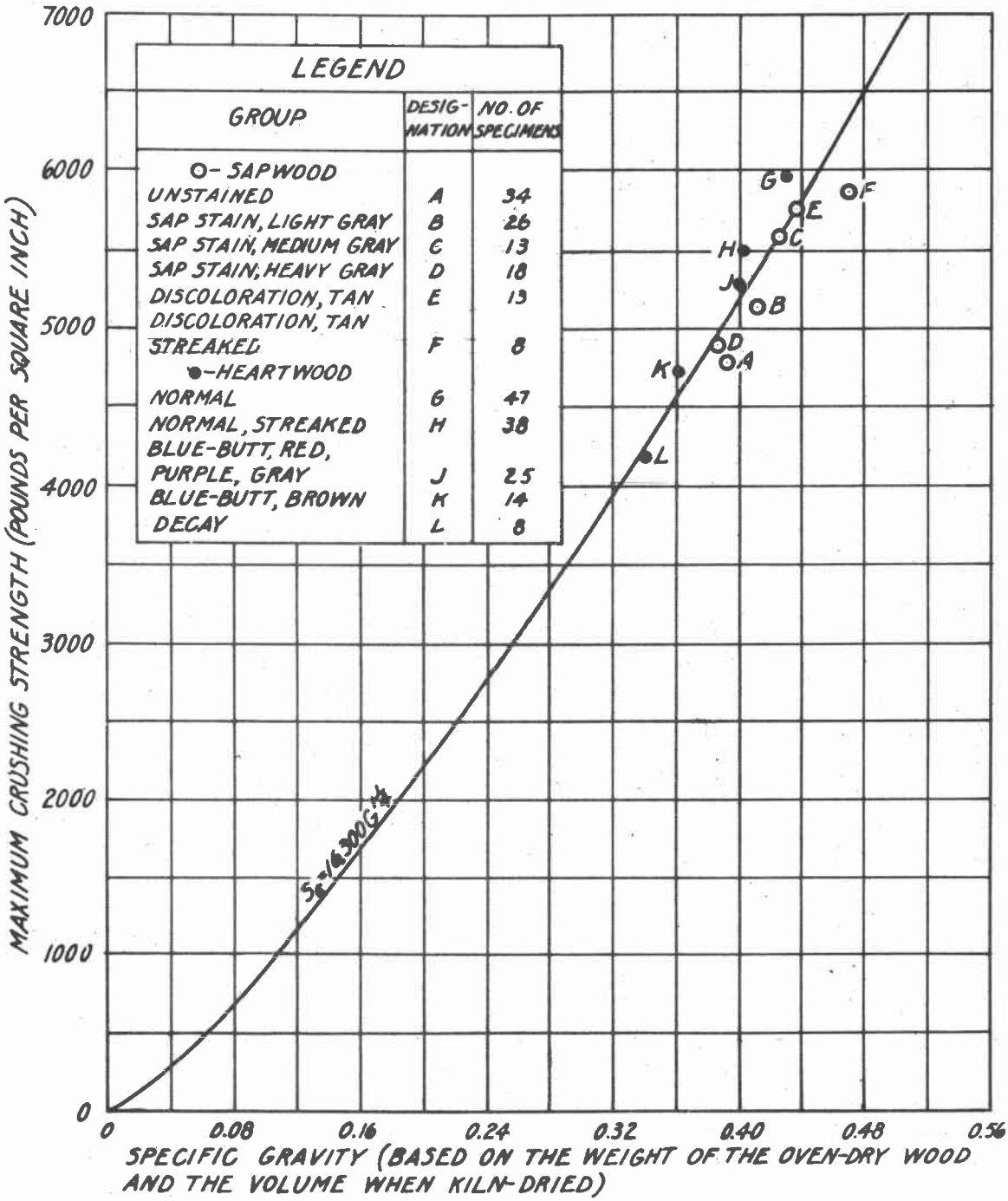


Figure 11.--Relation of maximum crushing strength in compression parallel to grain to specific gravity of yellow-poplar of various colorations.

Z M 56729 F

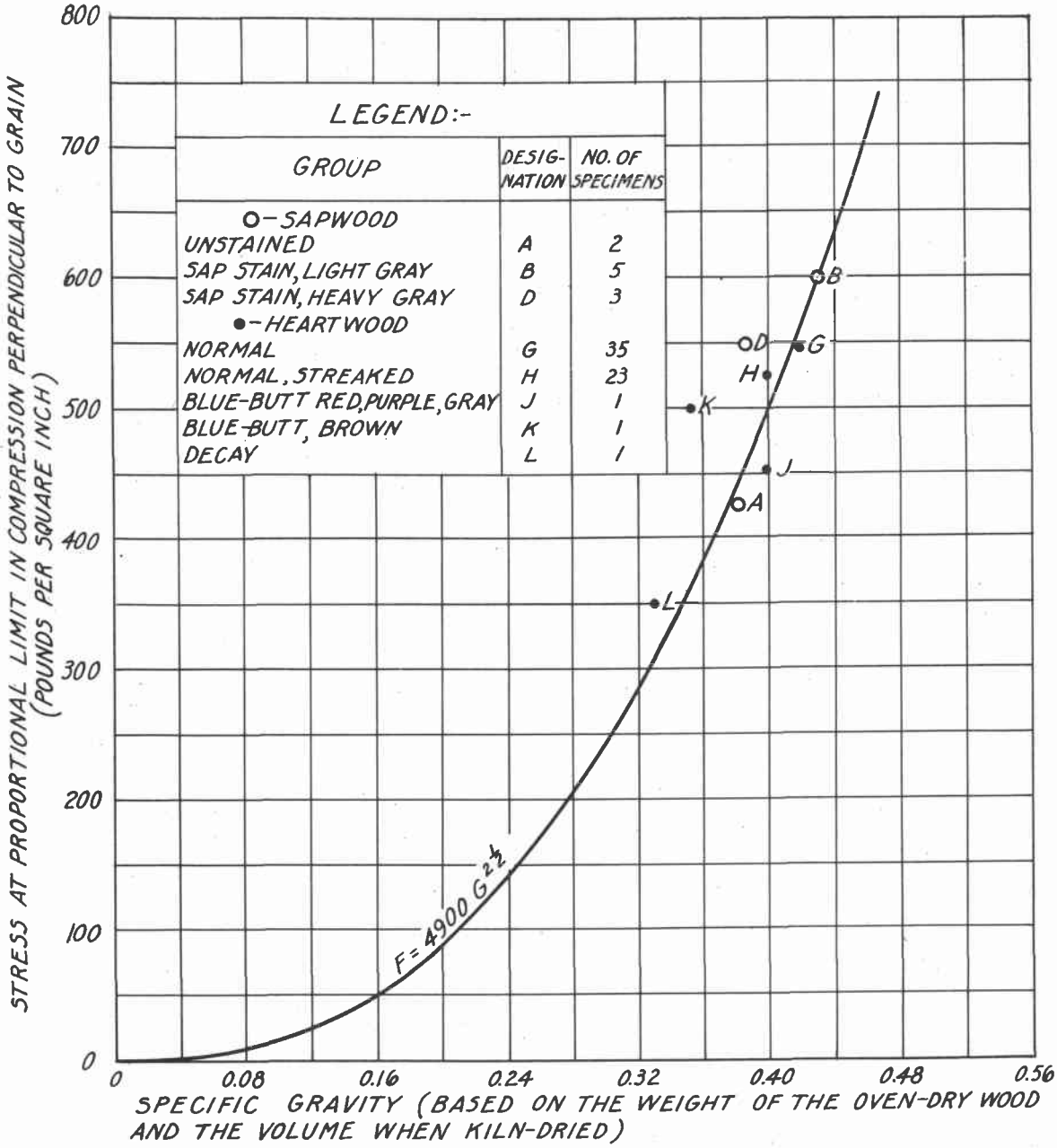


Figure 12.--Relation of stress at proportional limit in compression perpendicular to grain to specific gravity of yellow-poplar of various colorations.

Z M 56730 F

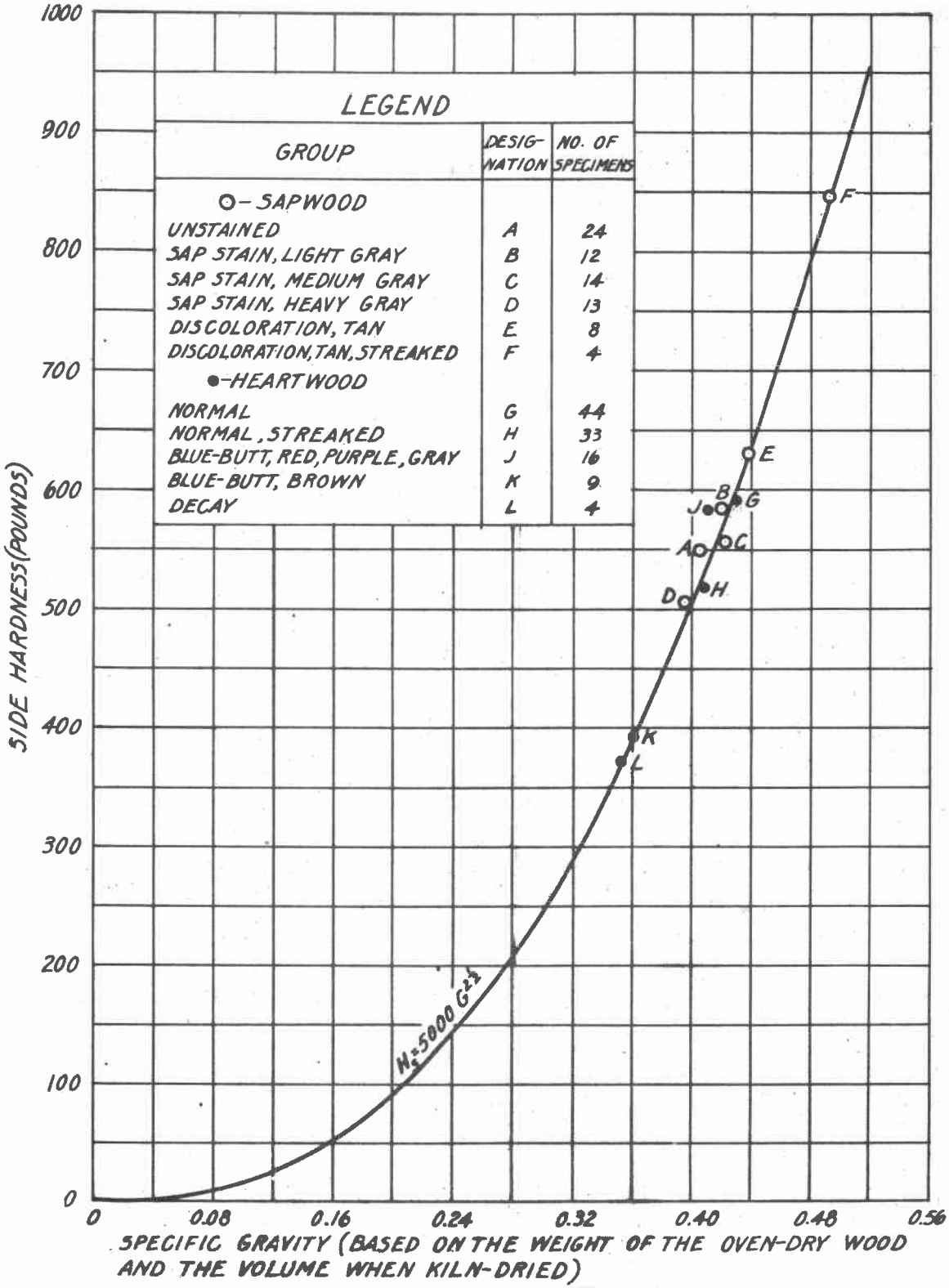


Figure 13.--Relation of side hardness to specific gravity of yellow-poplar of various colorations.

Z M 56731 F

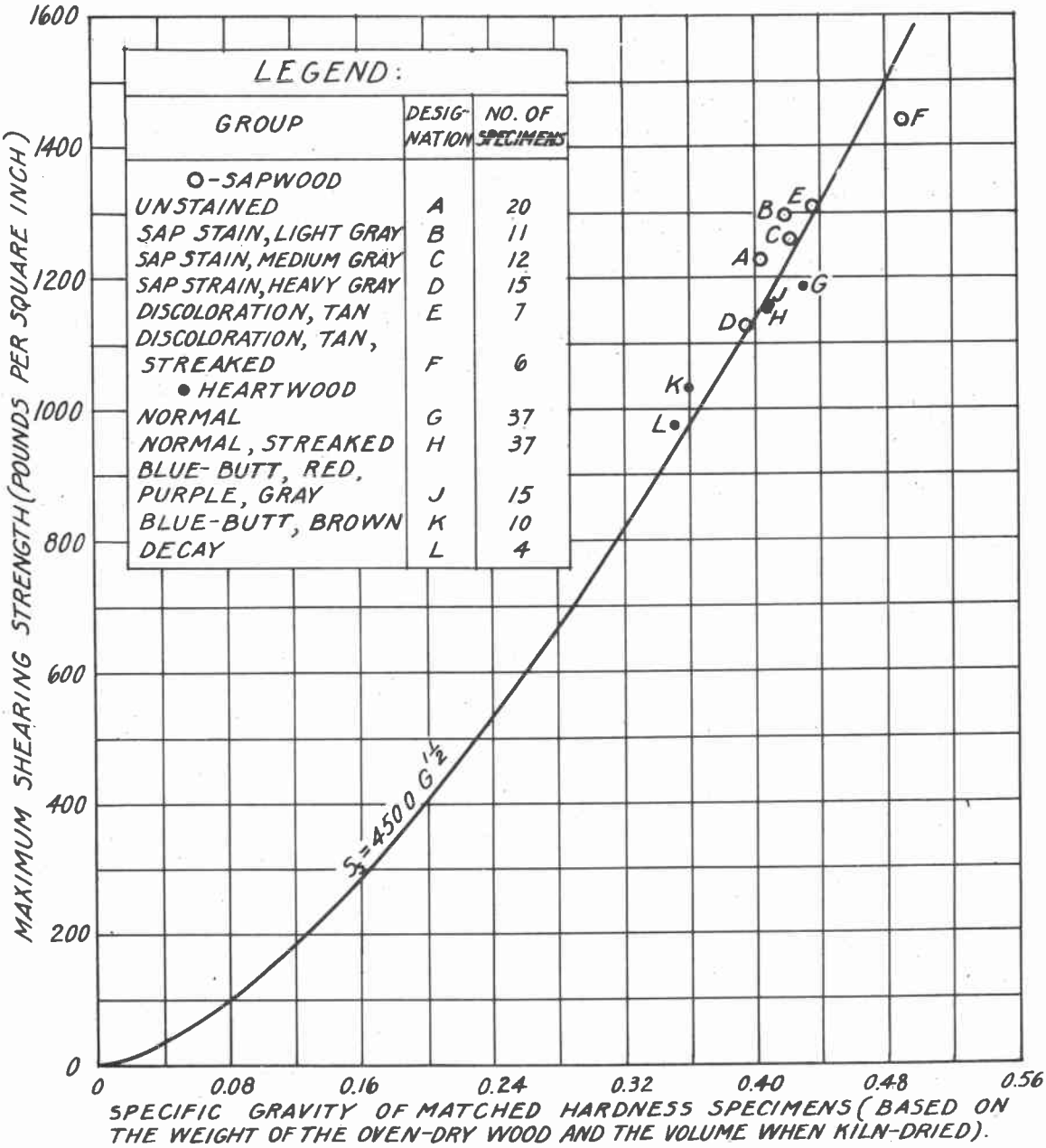


Figure 14.--Relation of maximum shearing strength to specific gravity of yellow-poplar of various colorations.

Z M 56732 F

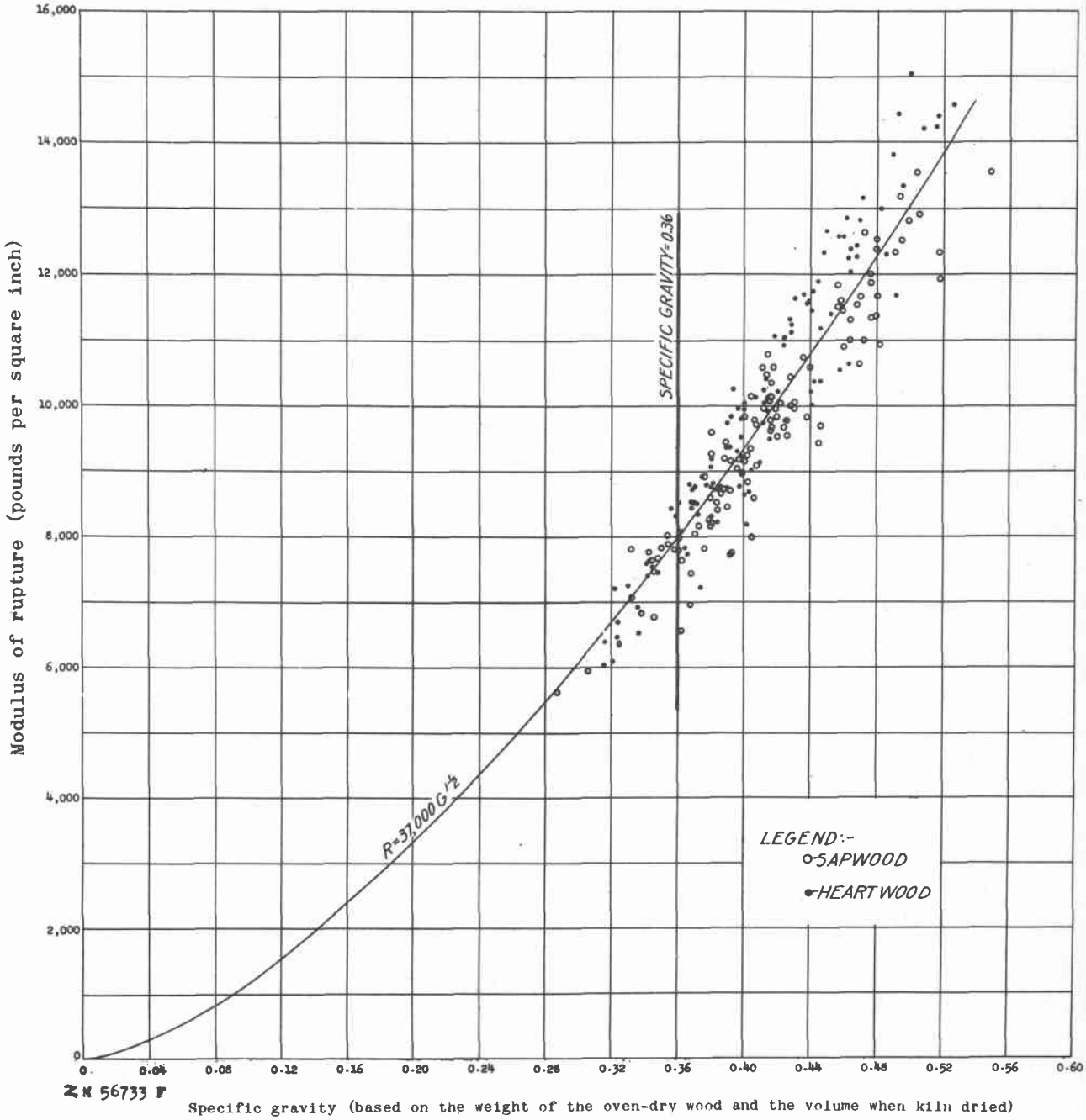


Figure 15.--Relation of modulus of rupture to specific gravity of yellow-poplar.

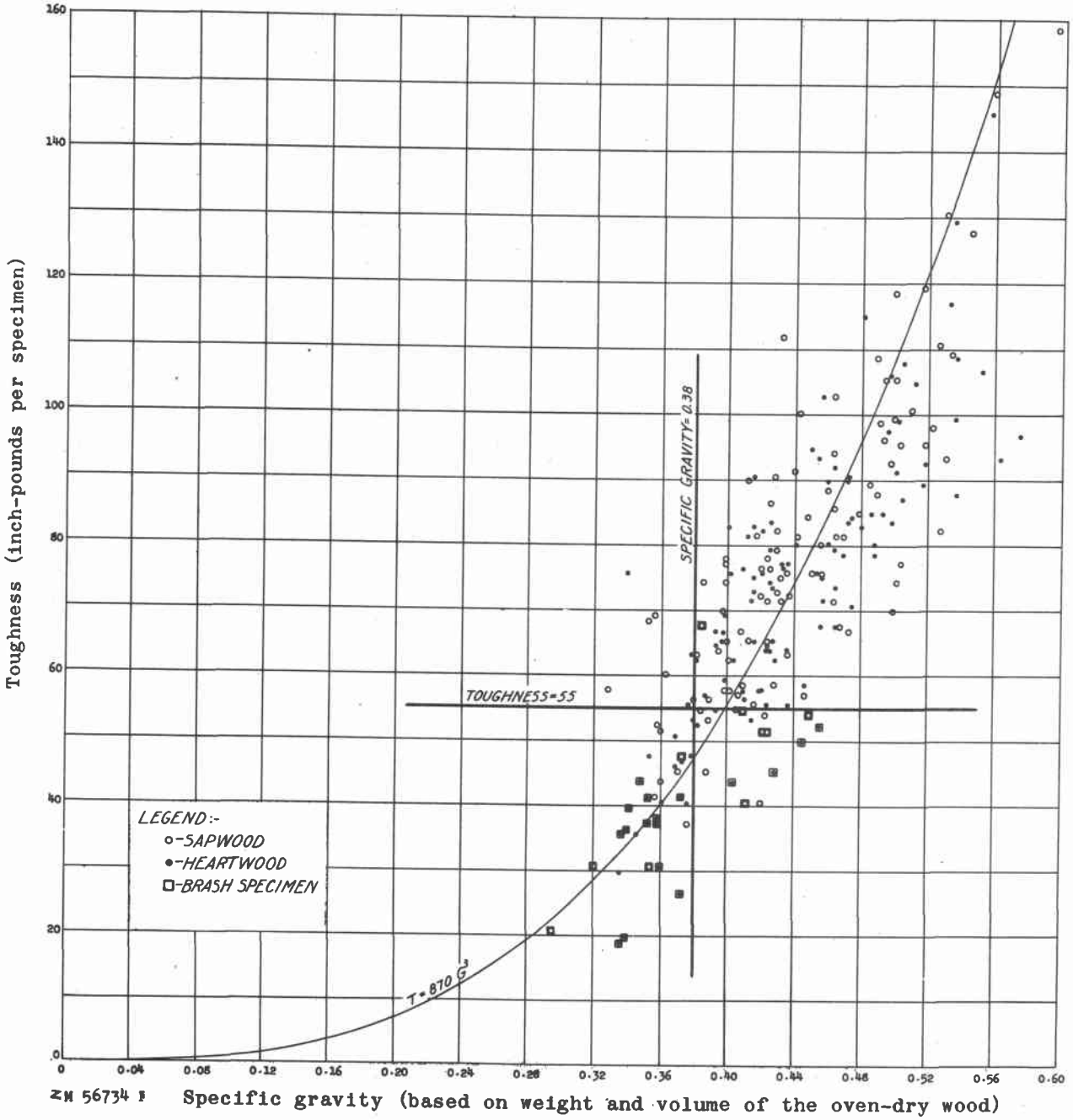


Figure 16.--Relation of toughness to specific gravity of yellow-poplar.

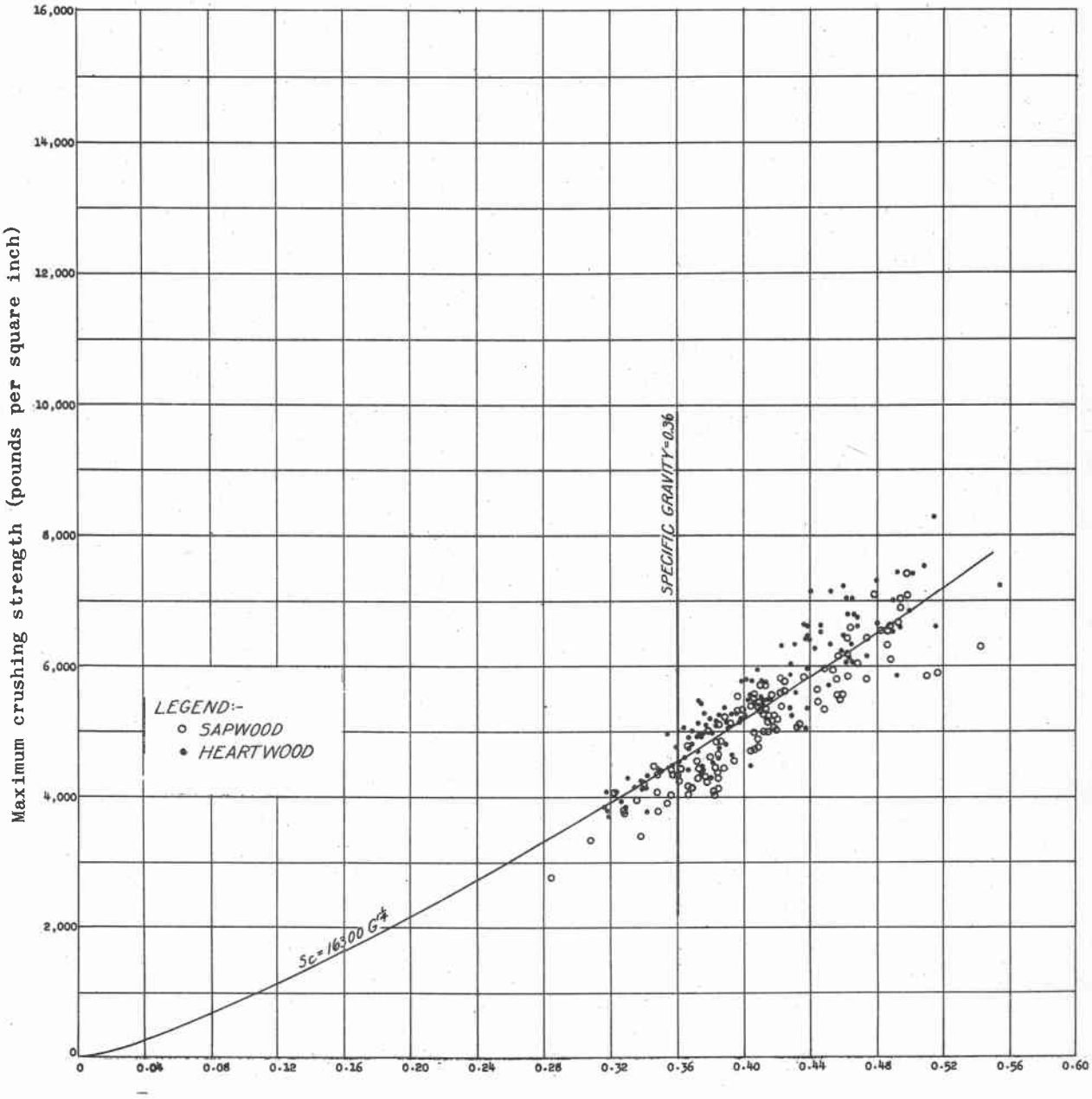


Figure 17.--Relation of maximum crushing strength to specific gravity of yellow-poplar.

ZM 56735

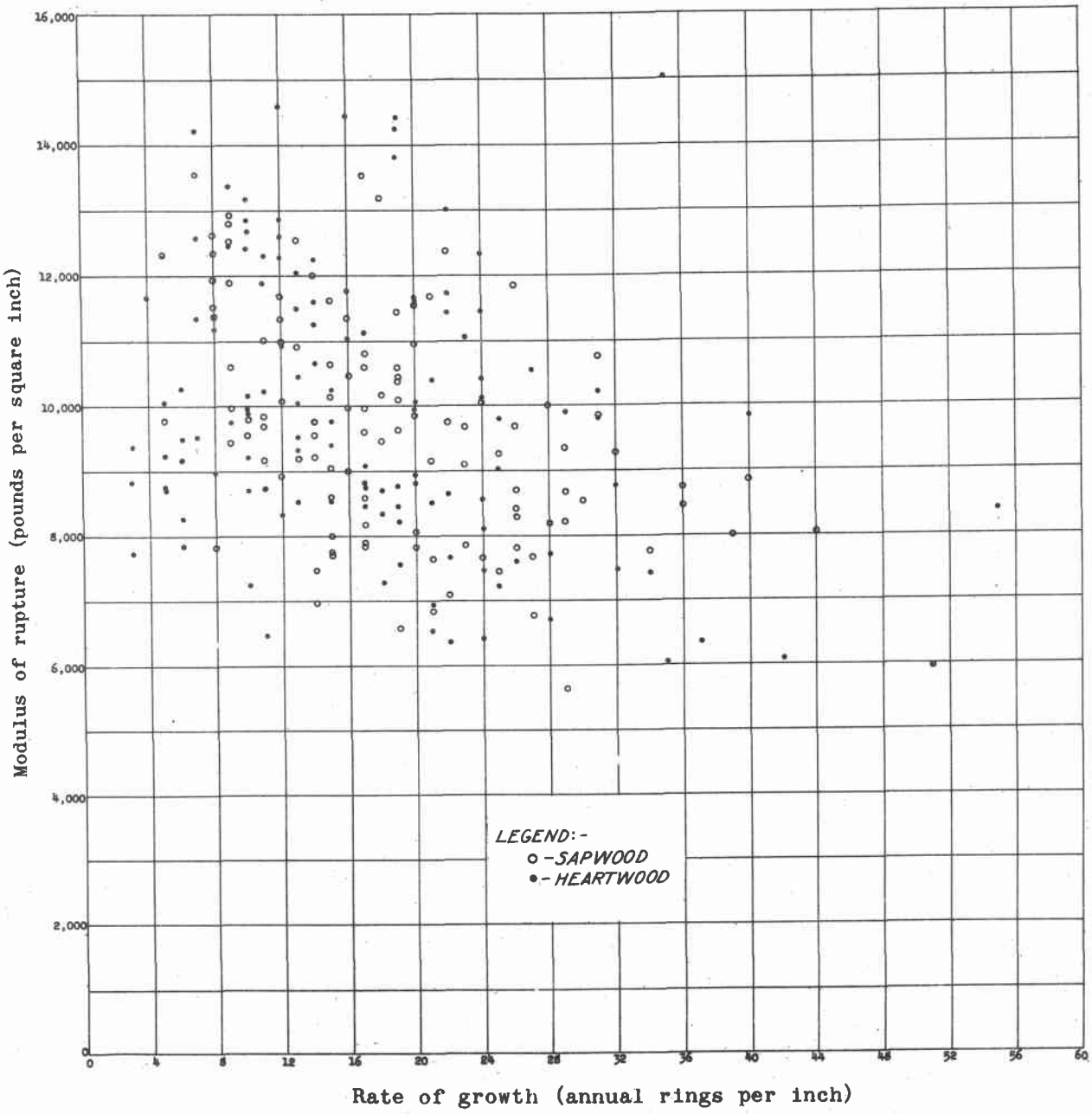


Figure 18.--Relation of modulus of rupture to rate of growth of yellow-poplar.

ZN 56736 F

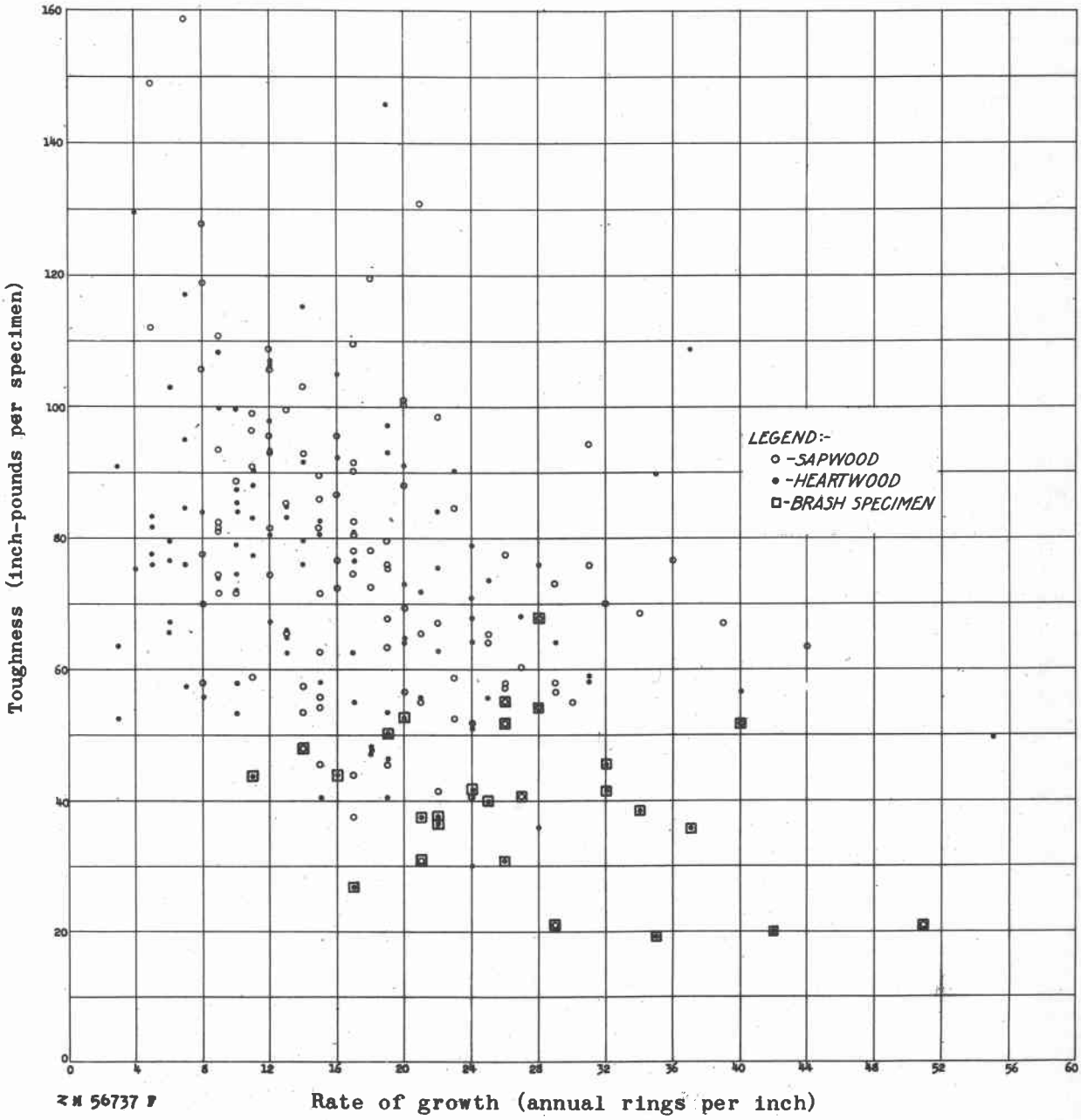


Figure 19.--Relation of toughness to rate of growth of yellow-poplar.

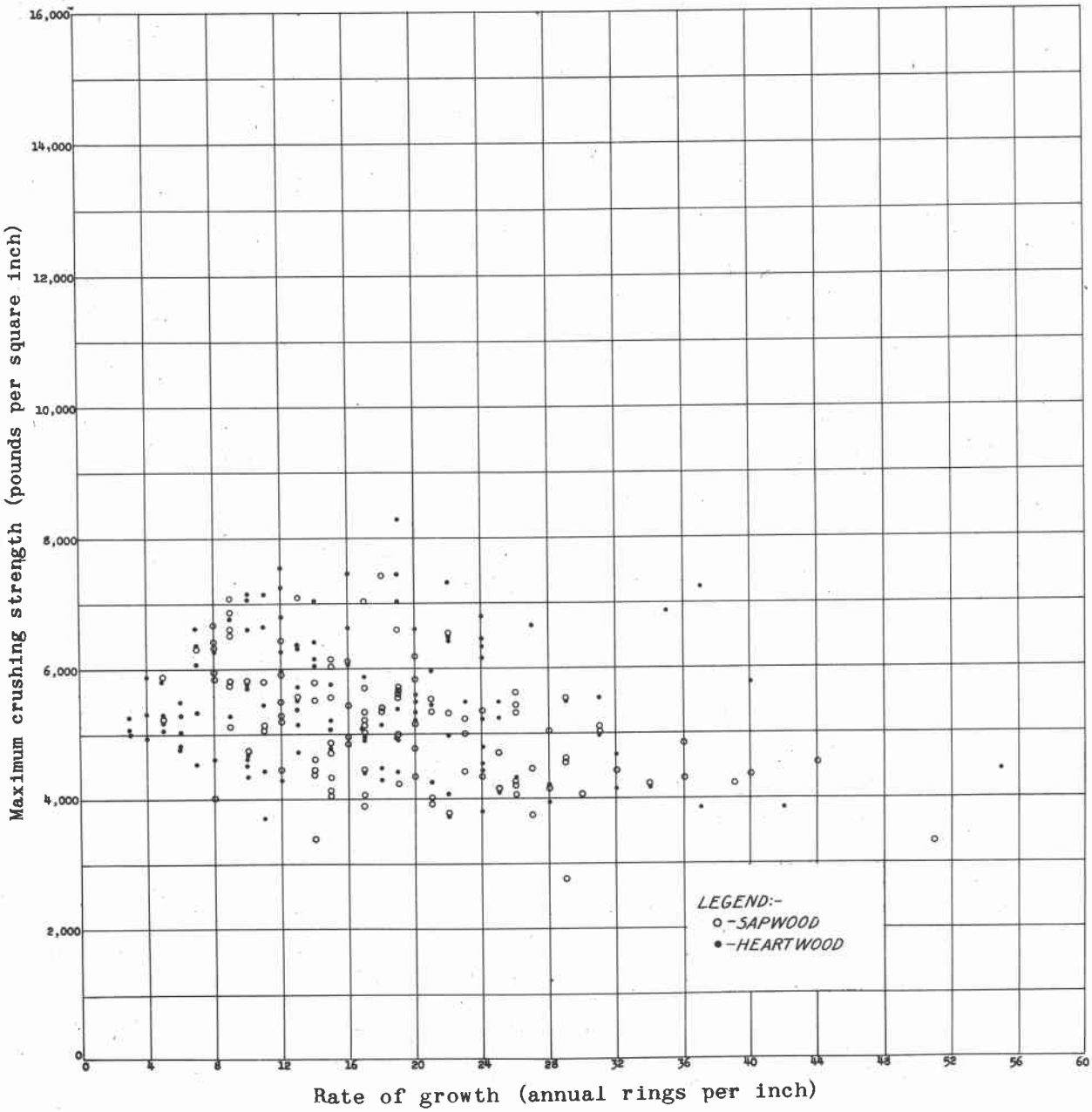


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Figure 20.--Relation of maximum crushing strength to rate of growth of yellow-poplar.

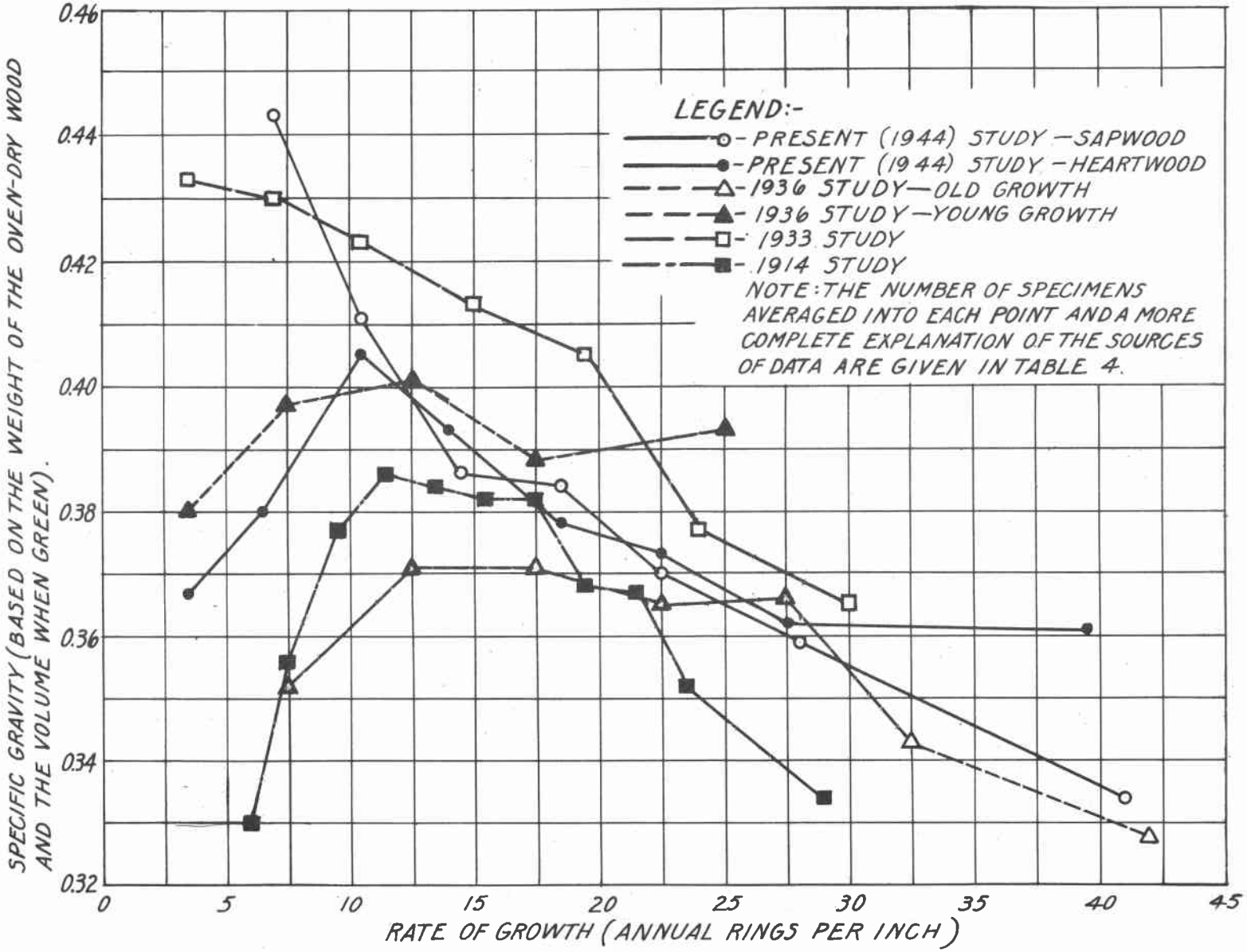

Figure 21.--Relation of specific gravity to rate of growth of yellow-poplar.

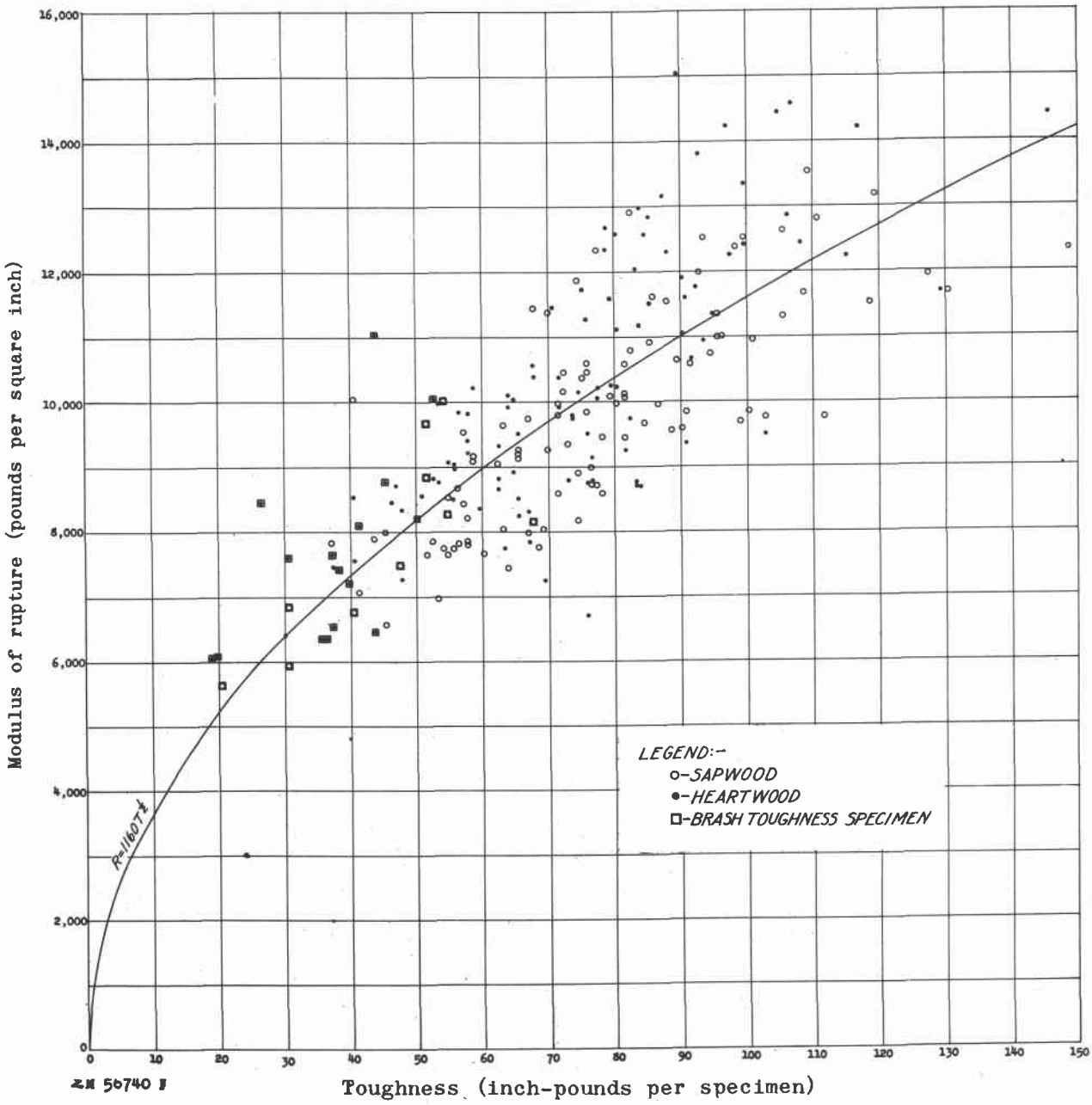

Figure 22.--Relation of modulus of rupture to toughness for individual yellow-poplar specimens.

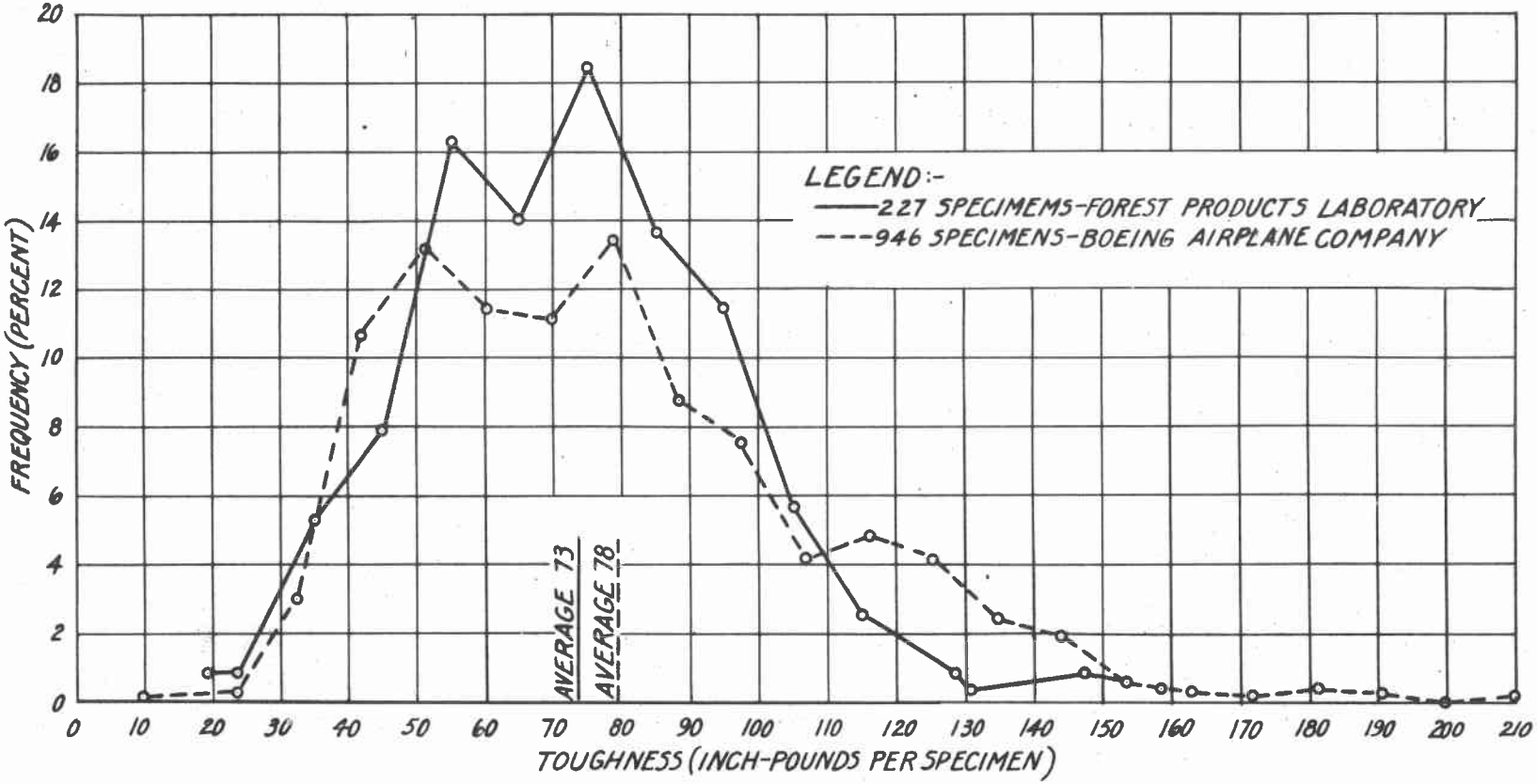

Figure 23.--Frequency distribution of yellow-poplar specimens at approximately 10 percent moisture content.

Z M 56741 F

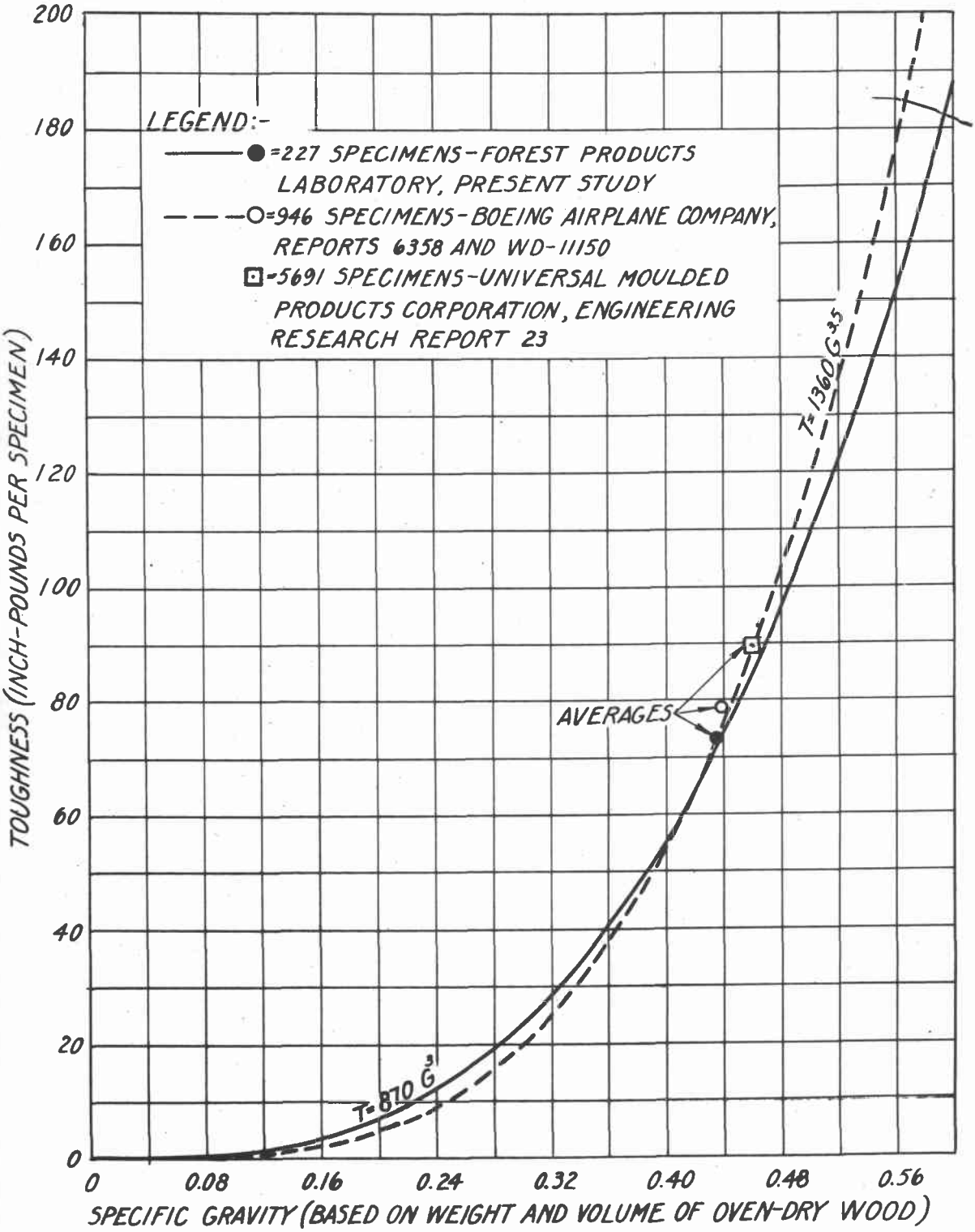

Figure 24.--Comparison of specific gravity-toughness relationship of yellow-poplar from various sources.

Z M 56742 F