RELATIONSHIP BETWEEN SPECIFIC GRAVITY AND PERCENTAGE OF SUMMERWOOD IN WIDE-RINGED, SECOND-GROWTH DOUGLAS-FIR

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RELATIONSHIP BETWEEN SPECIFIC GRAVITY AND PERCENTAGE OF SUMMERWOOD IN WIDE-RINGED, SECOND-GROWTH DOUGLAS-FIR[1]

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Summary

For the sample of wide-ringed Douglas-fir discussed in this report, the relationship between specific gravity and percentage of summerwood is linear over a range of 16 to 60 percent summerwood content of the annual ring. The specific gravity of the summerwood and springwood portions of 96 dissected annual rings is also linearly related to the percentage of summerwood in the annual rings, so that the specific gravity of both increases with an increasing percentage of summerwood. The zero and 100 percent summerwood intercepts of the regression of specific gravity on percentage of summerwood of whole annual rings do not give valid estimates of the average specific gravity of springwood and summerwood.

[1] This report constituted part of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at the State University of New York College of Forestry, Syracuse, N. Y.

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

Introduction

The close relationship that exists between the specific gravity and strength properties of a piece of wood is well known. The significance of this relationship is that specific gravity is a criterion of the amount of wood substance present, although it does not give any indication of the constitution or the distribution of the wood substance. In Douglas-fir, the annual rings are divided into two distinct zones, the springwood, which is composed of large-diameter, thin-walled cells, and the summerwood, which is made up of small-diameter, thick-walled cells. Thus a high percentage of summerwood indicates a high ratio of cell wall to void space and, accordingly, a high specific gravity. Mork's definition of summerwood (1)[3] provides a standard for separating the two zones in the annual rings. Investigations of Douglas-fir at the Forest Products Laboratory have shown a high correlation between specific gravity and percentage of summerwood, on the basis of Mork's definition, with coefficients of correlation ranging from 0.85 to 0.95. Since the specific gravity of the summerwood itself varies with the origin of the sample, the relative proportions of summerwood and springwood cannot be used as a true criterion of the mechanical properties unless they are qualified by specific gravity.

The objectives of this work on wide-ringed Douglas-fir were (1) to examine the relationship between specific gravity and percentage of summerwood and (2) to determine whether the values that characterize the specific gravity of summerwood and springwood may be considered as constants or whether they are related to the percentage of summerwood in the annual rings.

Background Information

The relationship between summerwood percentage and specific gravity has been examined by a number of research workers, but perhaps the most significant contributions have been made by Trendelenburg, Turnbull, and Ylinen.

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[3] Underlined numbers in parentheses refer to the list of numbered references at the end of the report.

Trendelenburg (7) found that, for samples of the same ring width, a linear regression was obtained when specific gravity was plotted against percentage of summerwood. He hypothesized that extrapolation of the regression line to the points of intersection at zero and 100 percent summerwood gives the approximate specific gravity of springwood and summerwood, respectively. To test this hypothesis, Trendelenburg determined the average specific gravity of small specimens of springwood and summerwood of spruce, larch, fir, and Douglas-fir. He then compared the line obtained by joining the average specific gravity values for these springwood and summerwood specimens, plotted at zero and 100 percent summerwood, with plotted points for the same species based on large specimens that contained various proportions of summerwood, and found a satisfactory agreement. Trendelenburg also observed that wood from different origins was alined in similar regressions that did not necessarily coincide, which indicated that the same percentages of summerwood corresponded to different specific gravity values for material from different localities. From this he concluded that the thickness of the cell walls of summerwood and springwood differed according to the origin of the samples.

Turnbull (8) pointed out that the assumption that "wood density is a reflection of the ratio existing between the widths of summerwood and springwood zones of the annual rings in any piece of wood" presupposes a constant specific gravity for each of the two types of tissue. To test the validity of the assumption, Turnbull took 30 samples from different heights and radial positions in 3 stems of South African grown Pinus taeda. He divided the specimens into two groups, light and heavy, and determined the mean specific gravity and summerwood percentage of each group. From the data so obtained, Turnbull calculated the specific gravity of springwood "by equating the ratio between the mean general specific gravity of the two groups against that between their respective summerwood percentages," so that in simplified form, using summerwood ratio rather than summerwood percentage:

$$\frac{W_1 - P(1 - X_1)}{W_2 - P(1 - X_2)} = \frac{X_1}{X_2} \qquad (1)$$

and

$$P = \frac{W_1X_2 - W_2X_1}{X_2 - X_1} \tag{2}$$

where W is the general specific gravity of the whole wood, P is the specific gravity of springwood, X is the summerwood ratio or the ratio of summerwood width to ring width, and the subscripts 1 and 2 indicate the material from the 2 groups. Substituting the numerical value obtained for P in the following general equation,

$$W = SX + P(1 - X) \tag{3}$$

where S is the specific gravity of summerwood, he obtained

$$S = \frac{W - P(1 - X)}{X} \tag{4}$$

Turnbull's values for S and P, when applied to all 30 specimens, satisfied the equation to such an extent that the mean error between the calculated and observed values did not exceed 3 percent, with a maximum error of 8.6 percent. This applied only to sapwood.

Ylinen (10) gave a formula for the density of a piece of wood and its percentage of summerwood that may be expressed as follows:

$$W = P + (S - P)X \tag{5}$$

when all determinations are made at the same moisture content. The equation is in the form Y = a + bX and is a rearrangement of the same general equation (3) given by Turnbull. Ylinen pointed out that the above formula is linear in X provided that the specific gravity of summerwood and springwood is regarded as constant. Ylinen determined experimentally the average specific gravity of small samples of Finnish pine springwood and summerwood and substituted the values in equation (5). He then compared the straight line with plots of specific gravity as a function of summerwood ratio for 41 samples and found that the straight line corresponded quite closely with the test points.

From the foregoing discussion, the general consensus seems to be that the zero and 100 percent intercepts of the regression of specific gravity on percentage of summerwood give valid estimates of the average specific gravity of springwood and summerwood, respectively. This theory could have wide application in technical studies of wood. Regression analyses based on the specific gravity and summerwood percentage of samples of wood that contain several annual rings would eliminate the tedious measurements of dissected rings that are now necessary to evaluate the growth-strength relations of coniferous woods.

Under certain conditions, however, the relationship between specific gravity and percentage of summerwood may be curvilinear. Ylinen (10) indicated that if there is a functional relation between P, S, and X, then formula (5) should be written in such a form that

$$P = f(X) \text{ and } S = g(X), \text{ and, therefore,}$$

$$W = P(X) + [S(X) - P(X)]\, X \qquad (6)$$

which is no longer linear in X.

Trendelenburg (7) found that for spruce the calculated regressions for wood with broad annual rings lay somewhat below those for wood with narrower rings. Thus he was able to explain the curved regression lines that occurred when all samples were plotted together: the wide-ringed samples predominated at the lower summerwood percentages, while at the higher percentages the narrow-ringed samples predominated, with a resultant greater increase in specific gravity at the higher percentages of summerwood.

Turnbull (9) also went further in his development of formulas to express the relationship between specific gravity and percentage of summerwood. He found that, over a very wide range of specific gravity values for *Pinus taeda*, the relationship was curvilinear, and "specific gravity of *Pinus taeda* varies directly with the logarithm of the square root of percentage summerwood, and inversely with the springwood percentage." The formulas he gave are in the form:

$$W = \frac{\log\sqrt{X}}{Q} \qquad (7)$$

or

$$W = \frac{1}{R(100 \quad X)} \qquad (8)$$

where X is the percentage of summerwood, W is the general specific gravity of the specimen, and Q and R are specific gravity coefficients. To determine the constants Q and R for the two geographical locations under consideration (Kluitjes Kraal and Jessivale), Turnbull solved the above equation by substituting for W the average general specific gravity and for X the average percentage of summerwood corresponding to W, for material from each location. He concluded that, "given distinct summerwood zones, it is now possible to determine very closely by inspection the specific gravity of small specimens of pine timber, once the seasonal specific gravity for the locality concerned is known. . ."

Material and Procedures

The Douglas-fir wood used in this study came from 16 butt logs selected from a special sample of wide-ringed Douglas-fir (3). The first 35 to 40 annual rings in each log were segregated into inner, intermediate, and outer zones, and 2 annual rings were selected at random from each zone in each log (4) to give a total of 96 annual rings. From each annual ring, 3 consecutive samples were obtained. The first sample contained springwood only, the second was comprised of the complete annual ring, and the third contained summerwood only, for a total of 288 test specimens. The method of dissecting the annual rings into their component parts has been described (4).

Summerwood percentage determinations were made microscopically on the 96 samples of complete annual rings by the standard Forest Products Laboratory method for growth-quality studies (3). Specific gravity determinations were made on the 288 specimens by the maximum-moisture method of Keylwerth (2). Keylwerth's method requires the assumption of a constant for the specific gravity of cell wall substance. Since the specific gravity of cell wall substance was not determined directly for the springwood and summerwood of this sample of wide-ringed Douglas-fir, the average value of 1.53 obtained by Stamm (6) for all woods tested by the water displacement method, was used throughout.

Results and Discussion

The frequency distribution of the specific gravity values of 96 springwood and 96 summerwood specimens is shown in figure 1. The average specific gravity of springwood is 0.266, with a range of 0.218 to 0.328, and the average specific gravity of summerwood is 0.735, with a range of 0.594 to 0.895. The absence of any overlap indicates that the methods employed in dissection and definition of the summerwood and springwood were successful in separating the annual rings into 2 distinct portions. The percentage of summerwood in the dissected annual rings ranged from 15.9 to 62.2 percent, with an average of 33.1 percent, while ring width ranged from 0.094 to 0.471 inch, with an average of 0.261 inch or 3.8 rings per inch. Table 1 gives the means, standard deviations, and coefficients of variation of specific gravity, percentage of summerwood, and ring width.

The specific gravity values for springwood, summerwood, and the complete annual rings were plotted against the percentage of summerwood as determined for each annual ring before dissection (fig. 2). Since a definite trend of increasing specific gravity with increasing percentage of summerwood for both portions and the whole annual ring was indicated by the plots, the linear regressions of specific gravity on percentage of summerwood for the annual ring components were calculated from the data by the method of least squares. These regressions are shown in figure 2 by the broken lines that have been extrapolated to show the intercepts at zero and 100 percent summerwood. In all cases correlation coefficients were significant at the 1 percent level (table 2), which indicates that there is a significant linear relationship between specific gravity and percentage of summerwood, not only for complete annual rings, but also for the dissected springwood and summerwood components of the annual rings.

Since it was observed that the specific gravity of both springwood and summerwood are related to the percentage of summerwood in this sample of Douglas-fir, the hypothesis that, for complete annual rings, the intercepts of the specific gravity-percentage summerwood regression at zero and 100 percent summerwood are valid estimates of the average specific gravity of springwood and summerwood does not hold because the hypothesis assumes that the specific gravity of the annual ring components is constant. The specific gravity values obtained for the intercepts and averages are as follows:

Average specific gravity of springwood	0.266
Zero percent summerwood intercept of the regression of complete annual rings	0.180
Difference	0.086
Average specific gravity of summerwood	0.735
100 percent summerwood intercept of the regression of complete annual rings	0.878
Difference	-0.143

The differences indicate that the regression intercepts underestimate the average specific gravity of springwood by 32 percent and overestimate the average specific gravity of summerwood by 19 percent.

A study of the least squares lines calculated independently for the growth ring components (fig. 2) suggests an alternative hypothesis: The regressions for complete annual rings and for springwood coincide at zero percent summerwood, while the regressions for complete annual rings and for summerwood coincide at 100 percent summerwood. The intercepts of these regressions at zero and 100 percent summerwood are as follows:

Intercepts at zero percent summerwood	
Complete annual rings	0.180
Springwood	0.205
Difference	-0.025

Intercepts at 100 percent summerwood	
Complete annual rings	0.878
Summerwood	1.006
Difference	-0.128

Although the comparison of the intercepts at 100 percent summerwood is not so conclusive as that of the intercepts at zero percent summerwood, it should be noted that the extrapolation of the regressions beyond the range of the data to zero percent summerwood is small in comparison with the extrapolation of the regressions to 100 percent summerwood. The latter intercepts, therefore, would not be expected to have the same accuracy as the former.

To further develop the concept of this new hypothesis, it is necessary to reconsider Ylinen's statement (10) concerning formula (5). Ylinen states that the equation $W = P + (S - P)X$, which is in the form $Y = a + bX$, is linear only as long as P and S are not dependent on X. In this equation, W is the specific gravity of whole wood, P is the specific gravity of springwood, S is the specific gravity of summerwood, and X is the ratio of summerwood width to ring width. It appears from the data that both P and S are linearly dependent on X such that $P = a_1 + b_1 X$ and $S = a_2 + b_2 X$, so that the general equation becomes:

$$W = (a_1 + b_1 X) + [(a_2 + b_2 X) - (a_1 + b_1 X)] X \qquad (9)$$

which is no longer linear in X. The only condition under which equation (9) could be linear with respect to X is if $b_1 = b_2$. Then

$$W = (a_1 + b_1 X) + [(a_2 + b_1 X) - (a_1 + b_1 X)] X$$

$$= a_1 + (b_1 - a_1 + a_2) X$$

The correlation coefficient obtained experimentally for the regression of complete annual rings ($r = 0.944$) indicates that the relationship is linear, and, if the regressions for the springwood and summerwood portions of the annual rings are also linear, then $b_1 = b_2$. Here again, the high correlation coefficients obtained experimentally for the components of the annual rings (table 2) perhaps justify the assumption that the regressions are linear, and the assumption that $b_1 = b_2$ seems more justifiable than that $b_1 = b_2 = 0$. It would seem reasonable that the specific gravity of an annual ring that is composed of springwood only would be given by the intercept of the regression of springwood specific gravity on percentage of summerwood at zero percent summerwood. That is, $W = a_1$ at zero percent summerwood. Conversely, it would seem reasonable that a growth ring composed entirely of summerwood would have a specific gravity approximating the 100 percent summerwood intercept of the regression of summerwood specific gravity on percentage of summerwood. That is, $W = a_2 + b_2$ where the ratio of summerwood width to ring width is 1.

Therefore, to obtain the three linear regressions that best represented the data simultaneously (so that knowing the summerwood ratio in the annual ring and the specific gravity of springwood and summerwood for that ratio, the specific gravity of the ring could be calculated), b_1 was set equal to b_2. Normal equations were developed by using the method of least squares and the theoretical regressions derived from substitution in the normal equations have been indicated in figure 2 by the solid lines. Imposition of the above restriction gave linear regressions that appear to fit the data satisfactorily, especially with regard to complete annual rings and springwood. The fit of the theoretical regression for summerwood is the least satisfactory.

In view of the above analysis, it is interesting to know the agreement between the actual and calculated specific gravity values for complete annual rings. Therefore, the general specific gravity of the complete ring, $\underline{W_1}$, was reconstituted from its component parts, where $\underline{P_1}$ is the specific gravity of the springwood portion of the ring determined after dissection, S_1 is the specific gravity of the summerwood portion, and X_1 is the percentage of summerwood determined from measurement of the complete annual ring. The formula used was:

$$W_1 = \frac{P_1 (100 - X_1) + S_1 X_1}{100}$$

The computed specific gravity values for 96 annual rings obtained from application of the above formula were compared with the observed specific gravity values for complete annual rings and are shown in figure 3. In this figure, the observed specific gravity values for the rings were plotted against the calculated specific gravity values, and the linear regression through the points was calculated by the method of least squares. The regression equation so obtained was:

$$Y = 0.0019 + 1.025X$$

with a correlation coefficient of $r = 0.983$ and a standard error of estimate of $s_{y.x} = 0.0130$. The broken line in figure 3 is the least squares line calculated from the data, and the solid line represents the theoretically identical values for calculated and observed specific gravity. The two lines diverge slightly as specific gravity increases, but no significant difference was found between either the intercepts or the slopes of the regressions when a *t*-test was made. Although not significant, the divergence of the computed and theoretical regressions may be explained in part by the method of obtaining the observed specific gravity. The formula used for determining specific gravity on the green volume basis by the maximum-moisture method (4) is:

$$\text{Specific gravity} = \frac{1}{M_{max} + \frac{1}{1.53}}$$

where M_{max} is the maximum moisture content in grams of water per gram of ovendry wood, and 1.53 is the average specific gravity of cell wall substance as determined by Stamm (5). It has been shown (4) that when the value for the maximum moisture content approaches the reciprocal of the specific gravity of cell wall substance, which it does in the case of summerwood, the error in the assumed value for the specific gravity of cell wall substance is magnified in respect to the specific gravity of the test specimen. For springwood or complete annual rings, where the maximum moisture content is considerably larger than the reciprocal of the specific gravity of cell wall substance, any error in the assumed value for the specific gravity of cell wall substance is diminished in respect to the specific gravity of the test specimen. For instance, the reciprocal of 1.53 is approximately 0.65. For summerwood specific gravity values in the range of 0.7, the maximum moisture content is approximately 0.8 gram of water per gram of ovendry wood, while for summerwood specific gravity values in the range of 0.8, the maximum moisture content is approximately 0.6 gram of water per gram of ovendry wood. Therefore, within the summerwood itself the error associated with the determination of the specific gravity increases as specific gravity increases. The errors inherent in the summerwood specific gravity values determined by the maximum-moisture method, together with the fact that the specimens with the higher specific gravity values had the narrower rings and were more difficult to dissect, tend to make the computed specific gravity values for complete annual rings slightly larger than the observed values (fig. 3).

Conclusions

1. For wide-ringed Douglas-fir, the relationship between the specific gravity of whole annual rings and percentage of summerwood is linear over a range of summerwood percentages of 16 to 60 percent.

2. The specific gravity of both the springwood and the summerwood components of the annual ring appears to be related to the percentage of summerwood in the ring in such a way that the specific gravity of both increases linearly with increasing percentages of summerwood.

3. The specific gravity values obtained from the zero and 100 percent summerwood intercepts of the regression of specific gravity of whole annual rings on percentage of summerwood do not give valid estimates of the average specific gravity of springwood and summerwood. The following theory, substantiated by the data for this sample of Douglas-fir, is suggested: The relationship between the three regressions, (1) for whole annual rings, (2) for springwood, and (3) for summerwood is such that the regression for whole annual rings and that for springwood intersect at zero percent summerwood, while the regression for whole annual rings and that for summerwood intersect at 100 percent summerwood.

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Table 1. --Specific gravity, percentage of summerwood, and ring width of 96 annual rings of Douglas-fir and the specific gravity of their springwood and summerwood portions

Statistic	Complete annual ring	Springwood	Summerwood
Specific gravity			
Mean	0.411	0.266	0.735
Standard deviation	.067	.027	.064
Coefficient of variation	16.302	10.150	8.707
Summerwood percent			
Mean	33.08		
Standard deviation	9.03		
Coefficient of variation	27.30		
Ring width (inch)			
Mean	.261		
Standard deviation	.078		
Coefficient of variation	29.885		

Table 2. --Linear regressions, correlation coefficients, and standard errors of estimate that express the relationship between specific gravity and percentage of summerwood for 96 complete annual rings of Douglas-fir and their springwood and summerwood portions

Portion of ring	Regression equation	Correlation coefficient	Standard error of estimate
Complete annual rings	Y = 0.1795 + 0.006988X	[1]0.943	0.0224
Springwood	Y = 0.2053 + 0.001826X	[1].601	.0221
Summerwood	Y = 0.6016 + 0.004045X	[1].575	.0522

[1]Significance of correlation coefficient (r) according to Snedecor (5), page 149: $r_{0.05}$ = 0.205 for 90 degrees of freedom
$r_{0.01}$ = 0.267 for 90 degrees of freedom

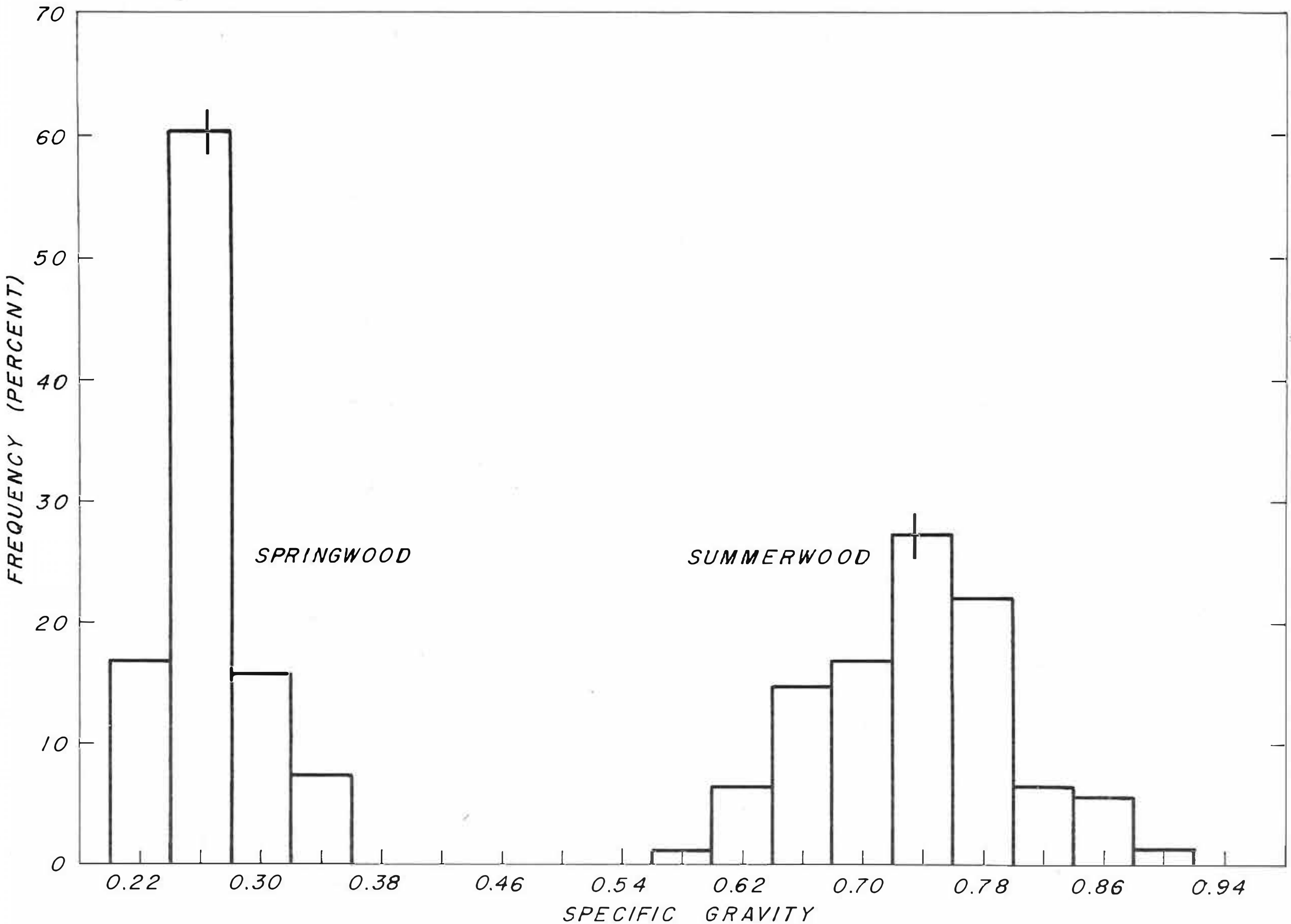

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Figure 1. --Frequency distribution of specific gravity values of 96 summerwood and 96 springwood samples.

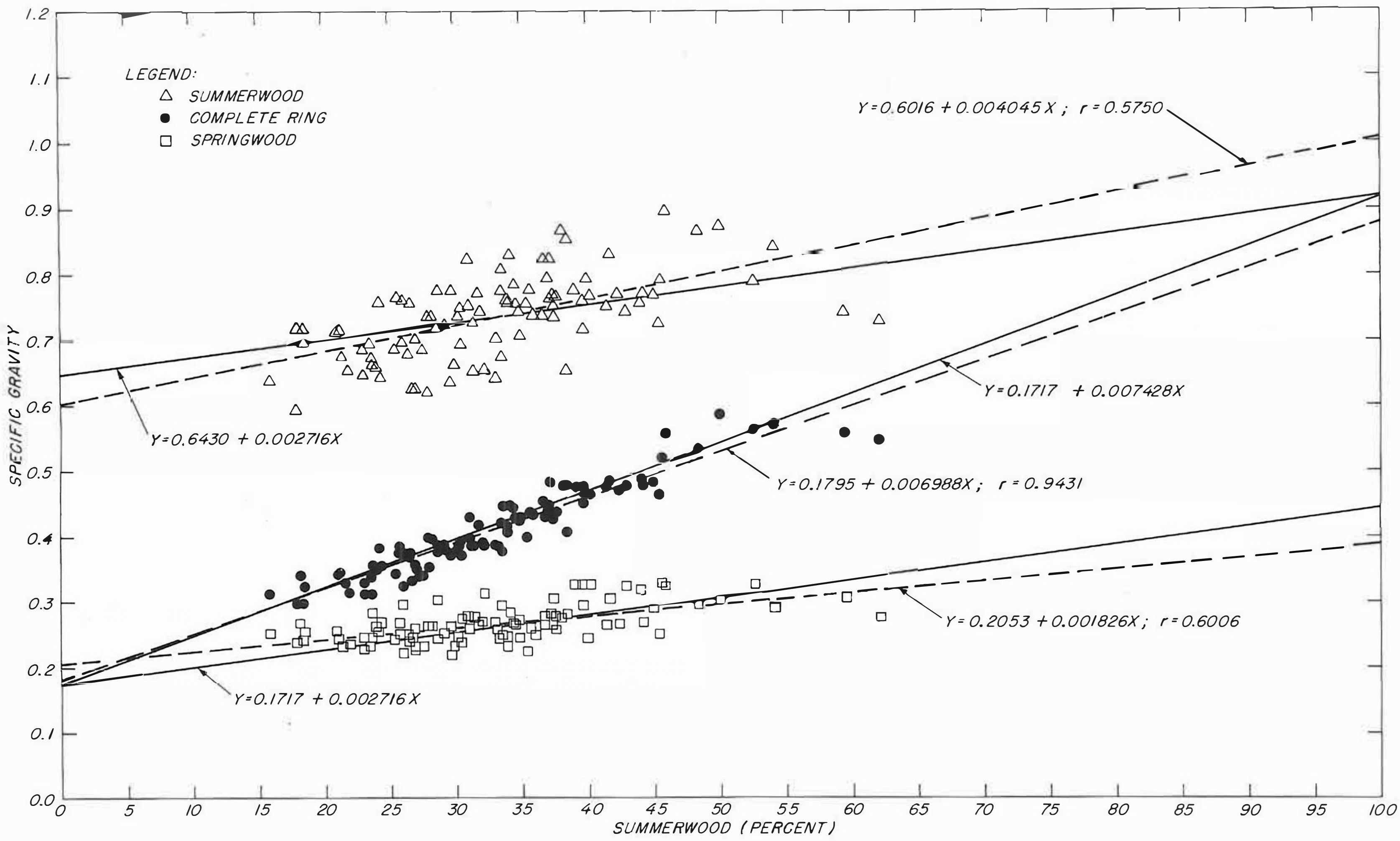

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Figure 2.--Variation in the specific gravity of complete annual rings, and of the springwood and summerwood portions of the rings, with percentage of summerwood. The broken lines are the least squares lines calculated from the data. These lines have been extrapolated to zero and 100 percent summerwood for comparison with the solid theoretical lines that also were calculated, with certain restrictions, from the data.

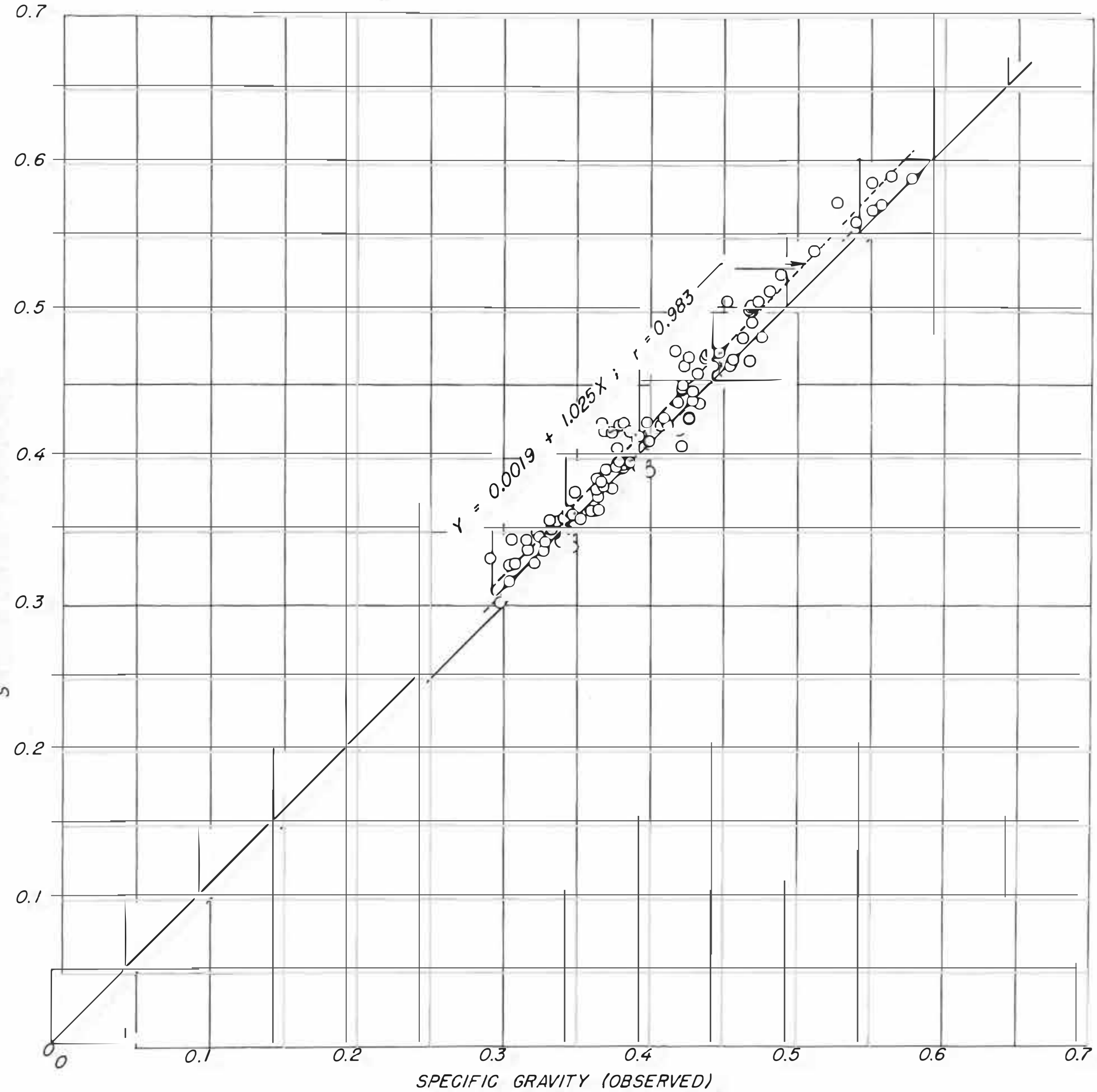

Figure 3. --Comparison of calculated and observed specific gravity values of 96 complete annual rings. The calculated specific gravity values were obtained from the percentage and specific gravity of individually determined springwood and summerwood portions of the complete annual ring. The broken line is the least squares line calculated from the data, while the solid line represents the theoretically identical values for calculated and observed specific gravity.

Z M 105 424