ELASTIC PROPERTIES OF WOOD

The Young's Moduli, Moduli of Rigidity, and Poisson's Ratios of Balsa and Quipo

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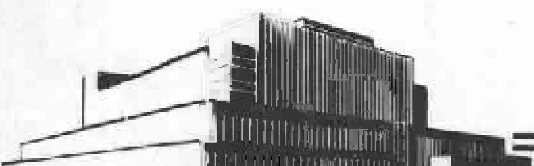

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

ELASTIC PROPERTIES OF WOOD[1]

The Young's Moduli, Moduli of Rigidity, and Poisson's Ratios of Balsa and Quipo[2]

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Summary

The values obtained for the Young's moduli, Poisson's ratios, and moduli of rigidity for balsa and quipo showed large variations for both species. This was to be expected from the wide range in density of these woods. The results for quipo may have been influenced by the presence of considerable decay, and the comparison with balsa was affected by a difference in moisture content of the two species at the time of test.

These tests, although based on a relatively small number of poorly matched specimens, indicated that the values of the Young's moduli and moduli of rigidity for both species increase with density, but that the

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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 issued in cooperation with the Army-Navy-Civil Committee on Aircraft Design Criteria. Original report published June 1945.

[2] This report is the first of a series of reports presenting the elastic properties of wood.

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

Poisson's ratios do not show a relationship with density. The ratios of the various elastic constants to E_L were reasonably uniform for all values of specific gravity for balsa, but showed considerable variation with density for quipo.

A comparison of the various elastic constants for the two species showed that neither balsa nor quipo gave consistently higher values.

Introduction

Balsa (Ochroma lagopus), because of its exceptionally light weight and insulating properties, has found increasing use as core material in "sandwich" construction for aircraft and for other war uses. Limitations in sources of supply of this wood, however, together with production and transportation problems have led to the consideration of other species of comparable density as substitute material.

One of the species considered is quipo (Cavanillesia platanifolia), also known as bongo. A report has been issued[4] covering the strength and related properties of balsa and quipo. The present report presents the results of tests to determine the elastic properties of these species.

The anisotropic nature of wood results in 12 elastic constants referred to the 3 mutually perpendicular principal axes of symmetry, longitudinal, radial, and tangential. These include three Young's moduli, three moduli of rigidity, and six Poisson's ratios.

Symbols and Definitions

The following definitions and symbols for the elastic constants are used in this report:

The longitudinal axis of wood (L) is defined as an axis of the material parallel to the grain; the radial axis (R) is perpendicular to the grain and

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[4] Wiepking, C. A., and Doyle, D. V., "Strength and Related Properties of Balsa and Quipo Woods," Forest Products Laboratory Report No. 1511, June 1944.

radial to the growth rings; and the tangential axis ($\underline{T}$) is perpendicular to the grain and tangential to the growth rings.

The term "axial," as used in this report, refers to the long axis of symmetry of the compression specimens, which is the direction in which the load is applied.

The term "lateral" indicates a direction perpendicular to the long axis, and parallel to one or the other of the short axes of symmetry of the specimen.

Young's Moduli

The three Young's moduli include $\underline{E_L}$, $\underline{E_R}$, and $\underline{E_T}$, which are the elastic moduli of wood in the longitudinal, radial, and tangential directions, respectively. These symbols, as used in this report, refer to the Young's moduli obtained from compression tests.

Poisson's Ratios

The symbol $\underline{\mu_{LR}}$ represents the numerical value of the ratio of the strain along the direction $\underline{R}$ to the strain along the direction $\underline{L}$ due to a stress parallel to the direction $\underline{L}$. The symbols $\underline{\mu_{LT}}$, $\underline{\mu_{RL}}$, $\underline{\mu_{RT}}$, $\underline{\mu_{TL}}$, and $\underline{\mu_{TR}}$ represent similar ratios.

It may be noted that the first letter of the subscript denotes the principal axis of the wood that is in the direction of the stress, and the second, the axis of the wood for which lateral deformation is determined.

Moduli of Rigidity

The three moduli of rigidity include $\underline{G_{LT}}$, $\underline{G_{LR}}$, and $\underline{G_{TR}}$, which are the moduli of rigidity associated with the shear strain corresponding to the $\underline{L}$ and $\underline{T}$, the $\underline{L}$ and $\underline{R}$, and the $\underline{T}$ and $\underline{R}$ axes, respectively. The two letters of the subscript may be interchanged without changing the meaning of $\underline{G}$.

The modulus of rigidity may also be referred to as the modulus of elasticity in shear or as the shear modulus.

Relationships Between Elastic Constants

The relationships between the several Young's moduli and Poisson's ratios may be expressed conveniently in the following equations:

$$\frac{\mu_{RL}}{E_R} = \frac{\mu_{LR}}{E_L} \; ; \qquad \frac{\mu_{TR}}{E_T} = \frac{\mu_{RT}}{E_R} \; ; \qquad \frac{\mu_{LT}}{E_L} = \frac{\mu_{TL}}{E_T}$$

It is frequently considered satisfactory to establish values for $\underline{\mu_{TL}}$ and $\underline{\mu_{RL}}$ by use of these equations from the four other larger and more readily established Poisson's ratios.

Development of Testing Technique

Young's Moduli

The determination of the Young's moduli requires only a simultaneous record of load and deformation. The technique for obtaining these data in compression tests is well established.

Poisson's Ratios

The technique required to evaluate Poisson's ratio is to measure the axial deformation resulting from an applied axial load and the corresponding lateral deformation along one of the principal axes. No difficulty is encountered with the measurement of axial deformations, as a specimen with uniform section can be observed over a suitable gage length by means of one of the common extensometers. Measurements in the lateral direction, however, present more of a problem, inasmuch as the strain is comparatively small and measurement must be made over a gage length that is no greater than the width or thickness of the specimen. Conditions of loading and requirements for proper stress distribution result in the use of specimens whose lateral dimensions are much smaller than their length. Because of the smaller lateral gage length, and due to the fact that the lateral strains are a fraction of the axial strains, it was difficult to determine the lateral strains with reasonable accuracy.

Measurements of Poisson's ratios for many engineering materials have been made over a period of years, and some values are quoted in reference books. Presumably some of the published ratios are approximate values resulting from direct measurements. One of the more exact techniques is that of Carrington[5] who measured the principal curvatures of the anticlastic neutral surface of beams when bent by couples applied to the ends. This method is accurate but difficult to apply, and it has definite limitations when applied to wood, particularly when stresses are in the radial and tangential directions.

Jenkin[6] reported Poisson's ratios for four species of wood tested during the first World War, but did not describe the methods used.

A technique, which will be described later, has been developed at the Forest Products Laboratory for evaluating Poisson's ratios in compression by direct simultaneous measurement of axial and lateral deformation with appropriate extensometers.

Modulus of Rigidity

The technique for the determination of the modulus of rigidity, as developed at the Forest Products Laboratory several years ago,[7] was followed in making these tests.

Description of Material

The material was selected from the stock of balsa and quipo wood that had been obtained previously for the determination of strength properties.[4] Decay and discoloration in the quipo was not visibly different than when it

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[5] Carrington, H., The Determination of Values of Young's Modulus and Poisson's Ratio by the Method of Flexure. Phil. Mag. I, VI, 41, S. 206-210, 1921.

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

[7] March, H. W., Kuenzi, E. W., and Kommers, W. J., "Method of Measuring the Shear Moduli in Wood," Forest Products Laboratory Report No. 1301, June 1942.

reached the Laboratory. Some checking had occurred in both species during storage.

The available material was in board form, ranging from 1 to 2 inches in thickness. It was in a dry condition, having been loosely piled in the Laboratory for approximately 9 months. Specimens were cut from the dry lumber and were then conditioned at 70° F. and 64 percent relative humidity until they reached an apparent constant weight.

Tests to determine the values of Young's modulus and Poisson's ratio were made on 27 balsa and 25 quipo specimens in the longitudinal direction, and from 13 to 20 specimens in the radial and tangential directions. The number of specimens for moduli-of-rigidity tests varied from 9 to 18 in the 3 orientations of grain for each species.

Marking and Matching

The material available for both balsa and quipo was inadequate to provide direct matching of specimens, which would require a block of material approximately 9 inches in its least dimension and with a minimum of ring curvature. Specimens were, therefore, selected on a density basis with an attempt to secure distribution from 5-1/2 to 11-1/2 pounds per cubic foot. Effort was made to secure straight-grained material reasonably free of defects and with a minimum of ring curvature.

Compression prisms, 2 by 2 by 8 inches, were cut to provide specimens oriented in the direction of each of the principal axes of elastic symmetry. The compression specimens with the long axis in the longitudinal direction were cut from the ends of the static-bending specimens previously used in determining values of the bending strength.[4] For the majority of compression specimens with the long axis in the radial or tangential directions it was necessary to glue together adjacent pieces from the same stick in order to obtain the required size and to avoid excessive ring curvature.

Figure 1 illustrates the several types of compression prisms, both in solid and glued forms (prisms of Sitka spruce are shown because of the clearly visible growth rings). In preparing the glued tangential and radial specimens of balsa and quipo, it was not always possible to use four blocks of equal size as illustrated in figure 1.

Figure 2 shows the three types of shear plates oriented as they occur in a tree (plates of Douglas-fir are pictured because of the clearly visible growth rings). In the preparation of plates for balsa and quipo, it was found necessary to glue adjacent pieces in order to provide the proper size and to minimize ring curvature. The specimens were 8 by 8 by 1/4 inch, and a 1- by 8- by 1/4-inch moisture section was cut in conjunction with a majority of the test specimens to provide data on the moisture content and specific gravity without destroying the test piece.

Test Methods

Young's Moduli and Poisson's Ratios

In the tests to determine values of Young's moduli and Poisson's ratios, simultaneous measurements of axial compression and lateral expansion were taken while the specimens were compressed in the direction of their length.

The axial compression was measured with a Lamb's roller extensometer over a central 6-inch gage length. This instrument consists of two principal units clamped to opposite vertical faces of the specimen by means of tie rods. Each of these units consists of two parallel hardened steel plates, each with one knife edge in contact with the specimen arranged so that the distance between knife edges is 6 inches. Between these plates a hardened steel roller is inserted so that as the specimen shortens, the plates move in relation to one another, giving the roller a small rotary movement that is proportional to the axial deformation. The angular movement of a mirror attached to each roller is measured by successive readings of the image of a vertical curved scale through a telescope provided with a cross hair. In figure 3, showing the test set-up, the vertical Lamb's roller is attached to the near and the hidden faces of a Sitka spruce specimen. The vertical scale (visible in the background to the left of the specimen) is curved to a radius such that the distance from the mirror facing the scale to any point on the scale is approximately constant. For these tests the distance was such that a difference of 1 millimeter on the scale represented a deformation of 0.0001 inch. Readings were taken to the nearest half millimeter, or 0.00005 inch.

The lateral expansion was measured with a Lamb's roller lateral extensometer modified and rebuilt to eliminate nonparallelism in the working parts. Figure 4 shows the instrument attached to a section of a longitudinal specimen of Sitka spruce in position to measure the tangential expansion. This instrument employs the same optical-lever principle as the other extensometer, with mirrors (C) mounted on the ends of vertical steel rollers. As the specimen expands, it pushes against a spring-held movable plunger (A), causing it to slide in relation to the housing frame (B). The relative motion produces a rotation of the rollers and mirrors (C) proportional to the expansion. The angular rotation of the mirrors is measured by successive readings of the image of a curved horizontal scale through a second telescope. The lateral extensometer is suspended by a system of pulleys, line, and lead counterweights as shown in figure 3 and bears against circular steel buttons. The buttons (E) are intended to distribute the spring pressure over an area sufficient to eliminate surface indentation, and they provide supports for the extensometer through conical holes drilled in the adjustable bearing block (G) and the movable plunger (A).

Arrangements at the left end of the outer frame provide for adjustment of the instrument to specimens of various sizes by means of clamp screws (H), which hold the cross member in proper position on the tie rods (J). The attachment to the specimen at the left is through an adjustable block (G), which may be moved by means of a screw and nut (K) to give the entire frame a setting at which the mirrors are in a favorable position.

The rollers in this instrument have a diameter of 0.02865 inch. With the proper scale distance from the mirror, 1 millimeter on the horizontal scale represents a movement of 0.00001 inch, and closer readings may be approximated by interpolation.

The Lamb's lateral extensometer as received from the manufacturer contained a slightly tapered plunger and other variations of the parts, which indicated that the contact surfaces were not plane and parallel. In rebuilding the instrument, it was considered desirable to substitute two dummy rollers (D) for the two ball-bearing plunger supports, which required accurately machined grooves in the outer faces of the plunger and the inner faces of the housing frame. A pair of coil springs were mounted within two hollow cylinders (L) to apply pressure to the rollers and hold the working unit in line. These springs operate against a contact block (M) within the housing frame. Microscopic examination of the original rollers revealed scratches and other surface irregularities, and they were replaced by new rollers made from piano wire polished in a lathe. Visual inspection under the microscope indicated a highly polished scratch-free surface on the new rollers, and high-precision optical measurement tests showed the greatest variation in any measured diameter to be 0.00005 inch. The original spring against which the plunger operates exerted a pressure of 4 pounds upon the specimen. Although contact buttons were used to distribute this pressure, it was considered desirable to reduce it further by using a 2-pound spring.

Specimens for obtaining the values of the Young's moduli and Poisson's ratios were compressed at an average rate of head movement of 0.012 inch per minute and unloaded at approximately the same rate. A spherical bearing block of the self-aligning type was used. Loads were increased until significant deformations had been obtained, but the maximum in each run was held well within the proportional limit of the wood. The test loads for individual specimens were varied according to the density. The majority of longitudinal specimens were loaded to 250 or 500 pounds per square inch, while radial and tangential specimens were run to a load of 12.5 to 50 pounds per square inch.

The vertical and horizontal extensometers were both applied to the specimen, as shown in figure 3, so that simultaneous readings could be taken during each run. The vertical instrument was centered on one pair of opposite faces, leaving a 1-inch section of the specimen beyond the gage points at each end. The horizontal instrument was attached to the other pair of faces, with the contact buttons set on the vertical center line of such faces at a level 1 inch above the center of the specimen. This arrangement was necessary to secure clearance between the two extensometers.

Readings of both instruments were taken at frequent uniform intervals during the loading of each specimen. A final reading was taken after the load had been reduced to its initial value. The load-deformation curves were generally plotted directly during the run. Thus a curve representing the relationship between load and axial deformation in a 6-inch gage length was obtained simultaneously with a curve representing loads and lateral deformation in approximately a 2-inch gage length. For an acceptable test, it was required that the plotted points formed practically straight lines and that the final readings checked the initial values within 1 millimeter on the scales.

Two runs were generally taken at each setting. If the two sets of data were in good agreement, as indicated by like slopes of corresponding curves, the data were considered satisfactory. When discrepancies occurred, however, additional runs were made until the data for two runs showed agreement. The average of the acceptable runs provided one value of Young's modulus and one Poisson's ratio. The instruments were then interchanged, and by a similar procedure another value of Young's modulus and the value of Poisson's ratio in the other of the two lateral directions were obtained.

The specimens were then returned to the humidity room, and after being reconditioned were subjected to a test procedure identical with the foregoing. The average of the acceptable runs from this series provided a second value of Young's modulus and of Poisson's ratio for each of the two sets of faces.

The two independent sets of values thus obtained were compared, and further reruns were made for those properties in which the data were not in reasonable agreement. For properties where two independent determinations were satisfactory and for those tests in which two of three determinations agreed, but the other value was decidedly not in agreement, the average of two sets was taken as representing the specimen for that particular attachment. In some tests where three determinations were made, it was not possible to eliminate one value as being inconsistent with the other two, and the three values were then averaged to represent the specimen.

All specimens were weighed upon removal from the conditioning room at the beginning of a test, and after completion of the readings. It was not possible to conduct tests under controlled temperature and relative humidity conditions, but the change in weight during the tests was small and was not considered significant. The average of the two weights was used in computing the moisture content.

All specimens were tested to failure after satisfactory data had been obtained for the Young's moduli and Poisson's ratios.

Moduli of Rigidity

In tests to determine the moduli of rigidity, the 8- by 8- by 1/4-inch plates were loaded at a uniform rate of head movement of 0.0408 inch per minute. The technique employed was in accordance with standard procedure as developed by the Laboratory.[7]

The "plate shear" apparatus commonly employed in tests to determine the modulus of rigidity is shown in figure 5. This type of equipment is not sufficiently sensitive to be used successfully with materials having a low modulus of rigidity. A special apparatus (fig. 6) utilizing identical principles of operation, but constructed of lightweight materials, was built and used for all G_{RT} tests and for low-density specimens in the G_{LR} and G_{LT} groups. Readings were taken at frequent uniform intervals during the application of load, and a load-deflection curve was plotted during the run. The specimen was rotated horizontally 90° at each successive run until a total of four runs was completed.

Computations

Young's Moduli

The values of the Young's moduli were computed from the load-compression curves by using the average slope of two or more lines in the series of runs for each position of the vertical Lamb's roller. The equation used was

$$E = \frac{6P}{A\, e_V}$$

where E = Young's modulus in pounds per square inch,

P = arbitrary load (pounds) at which the axial deformation (e_V) in a 6-inch gage length was taken from the curve,

A = loaded area of specimen in square inches,

and e_V = axial deformation in inches corresponding to load P.

Poisson's Ratio

Poisson's ratio for each testing position was computed from the load-expansion curves obtained from the lateral extensometer. The equation used was

$$\mu = \frac{\epsilon_H}{\epsilon_V}$$

where ϵ_H and ϵ_V were the lateral and axial strains (inches per inch) corresponding to the load P (pounds). The equations for these strains were:

$$\epsilon_H = \frac{e_H}{\text{width of specimen in direction of expansion (inches)}}$$

$$\epsilon_v = \frac{e_v}{6}$$

where e_H and e_v were the total lateral and axial deformations (in inches) taken from the respective curves at load P.

Modulus of Rigidity

The values of the modulus of rigidity were computed[7] from the load-deformation curves as follows:

$$G = \frac{3u^2}{2h^3} \frac{P}{w}$$

where u = distance from center of plate to point of deflection measurements (inches)

h = thickness of specimen (inches)

P = applied load (pounds)

w = average deformation (inches)

Explanation of Tables and Figures

Tables 1 to 4, inclusive, list the average values of the Young's moduli, Poisson's ratios, and moduli of rigidity of balsa and quipo wood, obtained from tests on groups of specimens, classified according to density. In each of tables 1 to 3 values of E are given for each pair of opposite faces to which the compressometer was attached to read axial deformation.

The ratios of the various other elastic moduli to E_L, for the classified densities, are presented in table 5. The upper portion of each table presents the values for balsa, and the lower portion the values for similar specimens of quipo.

Density Range (column 1 in tables 1 to 5)

The density ranges listed in column 1 of tables 1 to 5 provide for grouping of specimens in intervals of 1 pound per cubic foot within the range of 5-1/2 to 11-1/2 pounds per cubic foot. Additional groups were provided for those specimens whose density fell outside the extremes of this range.

Number of Specimens (column 2 in tables 1 to 3 and columns 2, 6, and 10 of table 4)

In the second column of tables 1 to 3 and in columns 2, 6, and 10 of table 4 are listed the number of specimens whose density fell within the range listed in column 1.

Specific Gravity (column 3 in tables 1 to 3 and columns 3, 7, and 11 in table 4)

Values of specific gravity, based on weight when ovendry and volume at test, were determined from the weights of the ovendried specimens after failure, and measurements of specimens before test.

Moisture Content (column 4, in tables 1 to 3 and columns 4, 8, and 12 in table 4)

The moisture content at the time of test was determined by subtracting the weight when ovendry from the average of the weights taken before and after test, and dividing by the weight when ovendry. The determination of the values of the moisture content of each of the Young's-modulus specimens was made on the entire specimen after it had been run to failure. The value of the moisture content of the modulus-of-rigidity specimens was determined from 1-inch sections cut in conjunction with the plates and conditioned in the same manner until test.

Stress at Proportional Limit (column 5 in tables 1 to 3)

Column 5 in tables 1 to 3, ,inclusive, lists the stress at proportional limit. These values were determined from the load-deflection curves obtained when the specimens were run to failure.

Crushing Strength (column 6 in tables 1 to 3)

The maximum crushing-strength values, obtained from longitudinal specimens, are listed in column 6, table 1. Column 6 in tables 2 and 3 lists the values of stress at 1/10-inch compression for radial and tangential specimens.

Young's Moduli (columns 7 to 9 in tables 1 to 3) (figs. 7 to 9)

Tables 1, 2, and 3 list the average values of Young's modulus in the longitudinal, radial, and tangential directions, respectively. The average of the two or three independent determinations made on a particular face, which was taken as the $\underline{E}$ of the specimens for that attachment, is listed in columns 7 and 8. The values shown in these columns were averaged to give the mean value of $\underline{E}$ for the specimen listed in column 9.

The relationship between specific gravity and $\underline{E_L}$ for both species is shown in figure 7. Empirical curves of the straight-line type ($y = mx + b$) were determined by the method of least squares.

Figures 8 and 9 show the specific-gravity-$\underline{E_R}$ and specific-gravity-$\underline{E_T}$ relationships, respectively, for both species, including curves determined by the method of least squares.

Poisson's Ratio (columns 10 and 11 in tables 1 to 3) (figs. 10 to 15)

The average values of Poisson's ratio for balsa and quipo for specimens within the several density ranges are shown in columns 10 and 11 of tables 1 to 3, inclusive. Values for individual specimens are plotted against specific gravity in figures 10 to 15, inclusive.

Moduli of Rigidity (columns 5, 9, and 13 in table 4) (figs. 16, 17, and 18)

Average values of the moduli of rigidity, obtained from groups of balsa and quipo specimens classified according to density, and associated with the three mutually perpendicular planes, are listed in columns 5, 9, and 13 of table 4. The individual values are plotted in figures 16, 17, and 18. The relationship between the moduli of rigidity and specific gravity is shown in these graphs, in which the trend is indicated by empirical curves of the straight-line type determined by the method of least squares.

Relationship of the Elastic Moduli to E_L (table 5)

The values listed in table 5 are the ratios of the various other elastic moduli to $\underline{E_L}$ for the selected density groups. They were established by dividing the average $\underline{E_R}$, $\underline{E_T}$, and $\underline{G}$ values for each density group (tables 2, 3, and 4) by the average $\underline{E_L}$ values of corresponding density (table 1).

Analysis of Results

In planning this study of the elastic moduli of balsa and quipo woods, certain limitations were encountered. These included the supply and condition of the available material and the amount of time required to conduct the tests. The sampling of the woods was not extensive, as the available material was inadequate in size to permit direct matching of specimens, and it was often necessary to build up specimens by gluing together pieces of similar character. Checks, decay, and other defects and the direction of rings, also limited the selection of specimens. The testing procedure required several runs on each specimen before comparable results could be accepted with confidence.

In making comparisons between the two species, consideration should be given to the decay of the quipo wood caused by improper seasoning after cutting. This condition presumably was the major cause of variation in the test results for this species. No specimens of balsa were used that contained apparent compression failures, but it is possible that undetected failures were present in some specimens. Worm holes present in some of the balsa specimens were small and apparently did not significantly affect the test results.

In comparing the values of balsa and quipo within comparable density ranges, consideration must also be given the number of tests conducted in each range, as the average values from a small number of tests will be less reliable than those obtained from a greater number.

The effect of using specimens for some of the radial and tangential tests that were built up by gluing together two or more pieces is not known. It is believed that the effect of the glue may be partially or entirely offset by an improvement in the uniformity of the specimens. The use of glued specimens resulted in less ring curvature for tangential specimens and in less variation in growth conditions for radial specimens. It is believed that the values obtained from tests on glued specimens were consistent with those obtained for solid specimens.

The average moisture content for quipo specimens was from 0.5 to 2.3 percent higher than for balsa. This difference is presumed to result from variations in the original seasoning of the materials, since both species were brought to constant weight before test under identical conditions (70° F. - 64 percent relative humidity).

No attempt was made to adjust values to a common moisture content. Previous research has shown that for most properties of wood a reduction in moisture content results in an increase in strength. Such tests have shown a moderate increase in values of $\underline{E_L}$ with decrease in moisture, but little specific information is available with respect to the effect of moisture on $\underline{E_T}$, $\underline{E_R}$, the moduli of rigidity, or Poisson's ratios. Since the quipo in these tests contained, on the average, somewhat more moisture than the balsa, the values obtained for the two species are not strictly comparable.

An examination of the data in table 1 shows that, for both balsa and quipo, the average results for $\underline{E_L}$ were almost exactly the same when strain measurements were made on either set of faces. For $\underline{E_R}$ (table 2) and $\underline{E_T}$ (table 3) the differences in average values, while somewhat larger than for $\underline{E_L}$, cannot be considered significant, particularly when it is noted that, for individual specimens, neither attachment produced consistently higher results.

A consideration of figures 7 to 9 indicates a definite trend toward increase of Young's modulus with specific gravity for each of the three types of specimen, particularly for those having their long axis in the longitudinal direction. It should also be noted that the values obtained for $\underline{E_L}$ are in close agreement with those obtained in compression-parallel-to-grain tests previously reported.[4]

For comparable specific gravities, the values of E_L for balsa were approximately double those for quipo, but for E_R and E_T the quipo gave higher values than balsa.

Tables 1 to 3 and figures 10 to 15 show that no specific relationship can be established between Poisson's ratios and specific gravity from the test data. A variation of as much as 400 percent may be observed between values for a particular plane, and both high and low values for Poisson's ratios are associated with all specific gravities. The order of magnitude of the values of the six Poisson's ratios differed for the two species, μ_{RT} showing the highest average values for balsa, while μ_{LT} was the highest average values for quipo. For both species, however, the tangential expansion exceeded the radial when the compression was in the longitudinal direction, and the tangential or radial expansion greatly exceeded the longitudinal for compression in the radial or tangential directions.

These data indicate that each species and each specimen within a species has its own value for Poisson's ratio for each of the six orientations of grain. The proportion of fast and slow growth, straightness of grain, ring curvature, and accuracy of specimen construction are probably instrumental in influencing the values of Poisson's ratio.

In most mathematical calculations involving the use of Poisson's ratios it is to be expected that the final result will be affected but little by rather large differences in the value used. Consequently, use of an average value for the several ratios is considered suitable for most design calculations.

The ratios of the various elastic constants to E_L listed according to density groups in table 5 show a comparison both for density groups and species. Due to differences in specific gravity, moisture content, and number of specimens within groups, the elastic values establishing the ratios are not strictly comparable. This results in an inconsistency of ratios among groups. Elastic ratios to be used in computations can probably be determined more accurately by choosing values from the curves (figs. 7, 8, 9, 16, 17, and 18) for like specific gravities.

The small Poisson's ratios (μ_{RL} and μ_{TL}) as determined from tests are, in most instances, higher for each of the selected density groups than those determined from the relationships involving the ratios of Young's moduli (E_R/E_L and E_T/E_L) and the larger Poisson's ratios (μ_{LR} and μ_{LT}). No explanation for this difference is apparent.

Conclusions

The values obtained for the Young's moduli, Poisson's ratios, and moduli of rigidity exhibited large variations for both balsa and quipo, as would be expected from the wide density range typical of these woods. Density variations occurred not only among planks, representing an unknown number of trees, but also within individual pieces.

In considering the results from the quipo tests and in comparing this material with balsa, consideration should be given to the fact that the quipo contained a considerable amount of discoloration and decay, and that these specimens contained from 0.5 to 2.3 percent more moisture at time of test than the balsa. No attempt was made to adjust the test values for these factors, as no data were available upon which adjustment could be based.

The following conclusions from this study were based upon a relatively small number of poorly matched specimens, and must be considered as indicative only:

1. The Young's moduli and moduli of rigidity for balsa and quipo increased with density.

2. The Poisson's ratios for both species showed no relationship to density. The average values obtained from tests are considered sufficiently accurate for most calculations involving Poisson's ratios.

3. For like densities or for average values neither balsa nor quipo showed consistently higher results for comparable properties. The average ratios of the other elastic constants to E_L, however, were considerably greater for quipo than for balsa.

4. The ratios of the various other elastic constants to E_L for balsa were reasonably uniform for all specific gravities. This was not true of several of the ratios for quipo.

Table 1.--Average Young's moduli and Poisson's ratios of balsa and quipo in compression parallel to grain (longitudinal)

Density range	Number of specimens	Specific gravity	Moisture content	Stress at proportional limit	Maximum crushing strength	E_L LT[1]	E_L LR[2]	E_L Average	Poisson's ratio μ_{LT}[1]	Poisson's ratio μ_{LR}[2]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Lb. per cu. ft.	Number		Percent	Lb. per sq. in.	Lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.	1,000 lb. per sq. in.		
BALSA										
Under 5-1/2	1	0.079	9.0	....	751	292	277	284	0.447	0.177
5-1/2 to 6-1/2	4	.095	9.5	409	900	332	332	332	.471	.237
6-1/2 to 7-1/2	5	.111	9.4	677	1,195	375	383	379	.452	.228
7-1/2 to 8-1/2	3	.130	9.2	697	1,532	585	558	572	.457	.241
8-1/2 to 9-1/2	4	.141	9.5	1,264	1,599	585	596	590	.451	.248
9-1/2 to 10-1/2	4	.158	9.5	1,411	2,032	645	659	652	.478	.218
10-1/2 to 11-1/2	4	.170	9.6	1,872	2,166	754	766	760	.607	.228
Over 11-1/2	2	.186	9.6	2,204	2,558	828	799	814	.530	.206
Average	....	.135	9.5	1,143	1,601	550	551	550	.488	.229
QUIPO										
Under 5-1/2	5	.084	12.1	225	478	102	103	102	.579	.198
5-1/2 to 6-1/2	4	.096	11.2	267	610	144	144	144	.651	.227
6-1/2 to 7-1/2	2	.110	12.0	274	804	180	190	185	.520	.203
7-1/2 to 8-1/2	4	.128	12.0	555	979	250	250	250	.662	.222
8-1/2 to 9-1/2	5	.142	11.8	474	1,052	291	289	290	.783	.231
9-1/2 to 10-1/2	2	.156	11.2	532	1,332	368	362	365	.660	.199
10-1/2 to 11-1/2	2	.178	11.8	709	1,326	364	364	364	.802	.210
Over 11-1/2	1	.199	11.4	677	1,652	518	547	532	.632	.239
Average	....	.126	11.8	428	921	235	236	235	.666	.216

[1]Axial compressometer attached to LT faces of specimen.

[2]Axial compressometer attached to LR faces of specimen.

Table 2.--Average Young's moduli and Poisson's ratios of balsa and quipo in compression perpendicular to grain (radial)

Density range	Number of specimens	Specific gravity	Moisture content	Stress at proportional limit	Stress at 0.1 inch compression	E_R RT[1]	E_R RL[2]	E_R Average	Poisson's ratio μ_{RT}[1]	Poisson's ratio μ_{RL}[2]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Lb.per cu.ft.	Number		Percent	Lb. per sq. in.	Lb.per sq.in.	Lb.per sq.in.	Lb.per sq.in.	Lb.per sq.in.		
BALSA										
Under 5-1/2	3	0.075	9.5	20	....	14,690	13,880	14,280	0.712	0.0180
5-1/2 to 6-1/2	3	.093	9.9	21	72	12,930	14,320	13,620	.590	.0163
6-1/2 to 7-1/2	1	.107	9.3	40	90	17,640	18,840	18,240	.653	.0167
7-1/2 to 8-1/2	2	.134	9.7	30	....	23,880	24,700	24,290	.486	.0160
8-1/2 to 9-1/2	None	....	....	....	....	....	....	....	....	....
9-1/2 to 10-1/2	2	.162	9.1	50	....	31,080	31,920	31,500	.752	.0140
10-1/2 to 11-1/2	1	.175	8.8	60	138	28,700	30,350	29,520	.470	.0184
Over 11-1/2	3	.195	8.9	43	166	44,530	44,690	44,610	.826	.0254
Average	....	.131	9.4	34	101	24,850	25,410	25,130	.665	.0183
QUIPO										
Under 5-1/2	1	.085	9.1	114	154	31,600	31,100	31,350	.363	.0742
5-1/2 to 6-1/2	2	.089	10.2	63	156	32,200	32,400	32,300	.547	.0818
6-1/2 to 7-1/2	1	.106	11.1	50	200	41,800	33,100	37,450	.380	.0344
7-1/2 to 8-1/2	1	.132	11.0	75	....	36,400	34,000	35,200	.489	.0437
8-1/2 to 9-1/2	6	.147	10.8	84	176	42,900	44,100	43,500	.457	.0432
9-1/2 to 10-1/2	3	.158	11.7	89	216	52,300	53,000	52,650	.487	.0349
10-1/2 to 11-1/2	3	.173	11.4	73	202	47,400	48,300	47,850	.435	.0417
Over 11-1/2	None	....	....	....	....	....	....	....	....	....
Average	....	.140	11.0	80	162	43,010	43,040	43,020	.455	.0474

[1]Axial compressometer attached to RT faces of specimen.

[2]Axial compressometer attached to RL faces of specimen.

Table 3.--Average Young's moduli and Poisson's ratios of balsa and quipo in compression perpendicular to grain (tangential)

Density range	Number of specimens	Specific gravity	Moisture content	Stress at proportional limit	Stress at 0.1 inch compression	E_T TR[1]	E_T TL[2]	E_T Average	Poisson's ratio μ_{TR}[1]	Poisson's ratio μ_{TL}[2]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Lb.per cu.ft.	Number		Percent	Lb. per sq. in.	Lb.per sq.in.	Lb.per sq.in.	Lb.per sq.in.	Lb.per sq.in.		
BALSA										
Under 5-1/2	6	0.072	9.4	15	30	3,120	3,040	3,080	0.150	0.0085
5-1/2 to 6-1/2	None	....	....	....	....	....	....	....	....	....
6-1/2 to 7-1/2	2	.106	8.8	22	70	7,660	7,760	7,710	.312	.0094
7-1/2 to 8-1/2	2	.124	8.7	19	54	6,180	6,320	6,250	.200	.0080
8-1/2 to 9-1/2	5	.142	9.5	30	77	8,610	8,700	8,660	.285	.0086
9-1/2 to 10-1/2	2	.160	9.0	35	102	12,880	12,550	12,720	.266	.0119
10-1/2 to 11-1/2	None	....	....	....	....	....	....	....	....	....
Over 11-1/2	3	.200	9.1	28	125	16,630	15,560	16,100	.249	.0104
Average	....	.126	9.2	24	69	8,260	8,080	8,170	.231	.0092
QUIPO										
Under 5-1/2	None	....	....	....	....	....	....	....	....	....
5-1/2 to 6-1/2	1	.103	11.2	13	53	6,880	6,870	6,880	.0597	.0267
6-1/2 to 7-1/2	1	.119	11.3	20	64	9,240	10,010	9,620	.131	.0394
7-1/2 to 8-1/2	1	.123	10.3	17	64	10,400	10,500	10,450	.118	.0272
8-1/2 to 9-1/2	6	.147	10.6	22	78	12,840	13,000	12,920	.131	.0292
9-1/2 to 10-1/2	1	.167	11.3	16	83	13,780	13,100	13,440	.115	.0291
10-1/2 to 11-1/2	1	.169	10.7	20	84	12,100	15,000	13,550	.137	.0383
Over 11-1/2	1	.187	11.4	40	143	22,600	23,700	23,150	.190	.0389
Average	....	.146	10.8	22	80	12,670	12,790	12,730	.128	.0323

[1] Axial compressometer attached to TR faces of specimen.

[2] Axial compressometer attached to TL faces of specimen.

Table 4.--Average moduli of rigidity of balsa and quipo

Density range	Number of specimens	Specific gravity	Moisture content	G_{LR}	Number of specimens	Specific gravity	Moisture content	G_{LT}	Number of specimens	Specific gravity	Moisture content	G_{RT}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Lb. per cu. ft.	Number		Percent	Lb. per sq. in.	Number		Percent	Lb. per sq. in.	Number		Percent	Lb. per sq. in.
BALSA												
Under 5-1/2	None	......	.....	....	None	....	.....	....	2	0.084	9.3	1,400
5-1/2 to 6-1/2	2	0.100	9.2	17,000	2	0.095	9.3	15,300	2	.094	9.3	2,260
6-1/2 to 7-1/2	3	.110	8.9	22,300	1	.116	9.2	17,400	None	....	.....	......
7-1/2 to 8-1/2	2	.133	9.2	26,800	1	.125	8.1	14,100	1	.128	8.9	2,380
8-1/2 to 9-1/2	4	.144	8.4	28,200	4	.141	9.7	16,700	1	.137	9.2	2,480
9-1/2 to 10-1/2	3	.159	9.2	36,400	2	.158	9.1	18,400	1	.153	9.3	3,030
10-1/2 to 11-1/2	2	.180	9.2	41,800	1	.170	9.8	30,900	None	....	.....	......
Over 11-1/2	1	.192	8.1	40,000	3	.196	9.3	30,300	2	.207	9.5	5,310
Average	......	.141	8.9	29,400	......	.148	9.3	20,500	......	.132	9.3	2,870
QUIPO												
Under 5-1/2	1	.079	8.7	15,600	1	.077	11.4	7,000	1	.084	7.7	5,470
5-1/2 to 6-1/2	7	.096	9.4	16,500	2	.091	9.1	7,540	None	....	.....	......
6-1/2 to 7-1/2	3	.113	10.3	17,600	2	.113	9.6	9,380	2	.108	10.8	6,600
7-1/2 to 8-1/2	None	......	.....	....	2	.134	10.3	14,000	1	.130	10.0	6,150
8-1/2 to 9-1/2	2	.146	10.9	20,400	7	.147	9.8	13,500	1	.138	9.5	5,440
9-1/2 to 10-1/2	1	.152	10.7	26,100	2	.158	10.5	14,800	2	.160	10.4	7,980
10-1/2 to 11-1/2	2	.170	10.0	29,500	2	.178	9.3	19,600	3	.173	10.2	9,870
Over 11-1/2	None	......	.....	....	None	....	.....	....	None	....	.....	......
Average	......	.117	9.9	19,300	......	.137	9.9	12,900	......	.141	10.0	7,580

Table 5.--Ratios of values of Young's modulus and moduli of rigidity for balsa and quipo

Density range	$\frac{E_T}{E_L}$	$\frac{E_R}{E_L}$	$\frac{G_{LR}}{E_L}$	$\frac{G_{LT}}{E_L}$	$\frac{G_{RT}}{E_L}$
(1)	(2)	(3)	(4)	(5)	(6)
Lb. per cu. ft.					
			BALSA		
Under 5-1/2	0.0108	0.0503	....	....	0.0049
5-1/2 to 6-1/2	....	.0410	0.0512	0.0461	.0068
6-1/2 to 7-1/2	.0203	.0481	.0588	.0459	....
7-1/2 to 8-1/2	.0109	.0425	.0469	.0247	.0042
8-1/2 to 9-1/2	.0147	....	.0478	.0283	.0042
9-1/2 to 10-1/2	.0195	.0483	.0558	.0282	.0046
10-1/2 to 11-1/2	....	.0388	.0550	.0407	....
Over 11-1/2	.0198	.0548	.0491	.0372	.0065
Average	.0149	.0457	.0535	.0373	.0052
			QUIPO		
Under 5-1/2	....	.307	.1529	.0686	.0536
5-1/2 to 6-1/2	.0478	.224	.1146	.0524	....
6-1/2 to 7-1/2	.0520	.202	.0951	.0507	.0357
7-1/2 to 8-1/2	.0418	.141	....	.0560	.0246
8-1/2 to 9-1/2	.0445	.150	.0703	.0466	.0188
9-1/2 to 10-1/2	.0368	.144	.0715	.0405	.0219
10-1/2 to 11-1/2	.0372	.132	.0810	.0538	.0271
Over 11-1/2	.0433	....	....	....	....
Average	.0548	.182	.0818	.0547	.0321

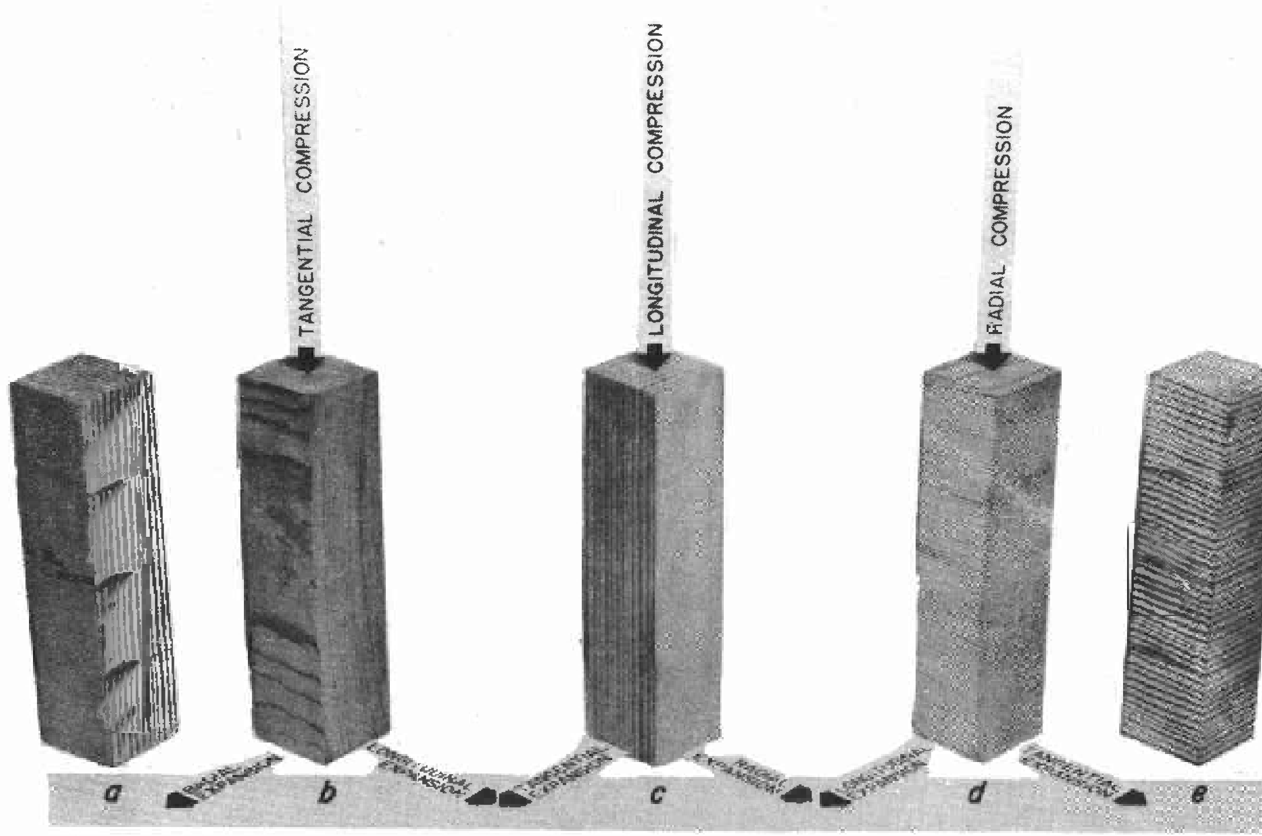

Figure 1.--Representative specimens for tests to determine Poisson's ratio; (a) glued tangential, (b) solid tangential, (c) longitudinal, (d) solid radial, and (e) glued radial.

Z M 61096 F

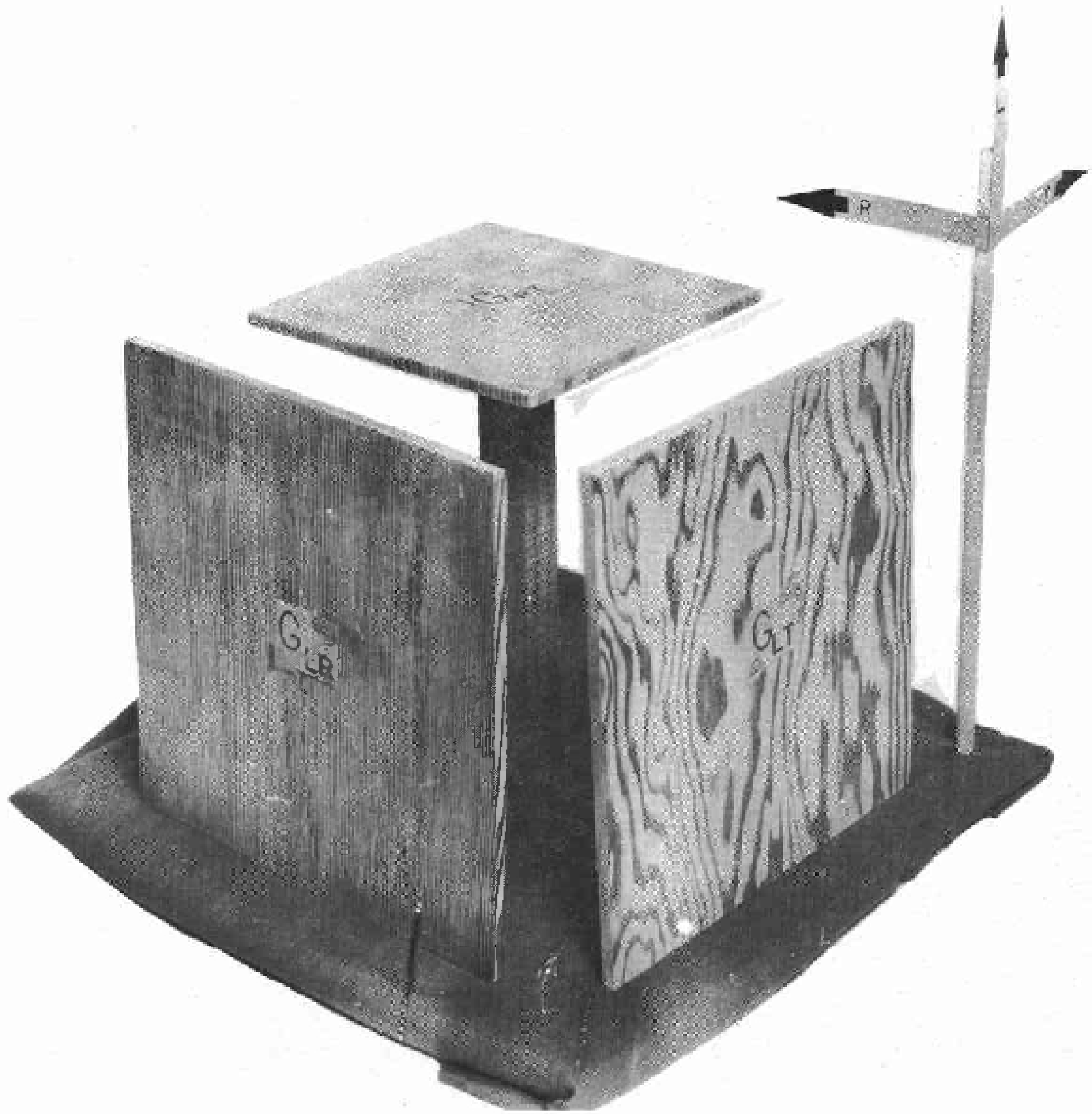

Figure 2.--Representative specimens for tests to determine the shear modulus.

Z M 59509 F

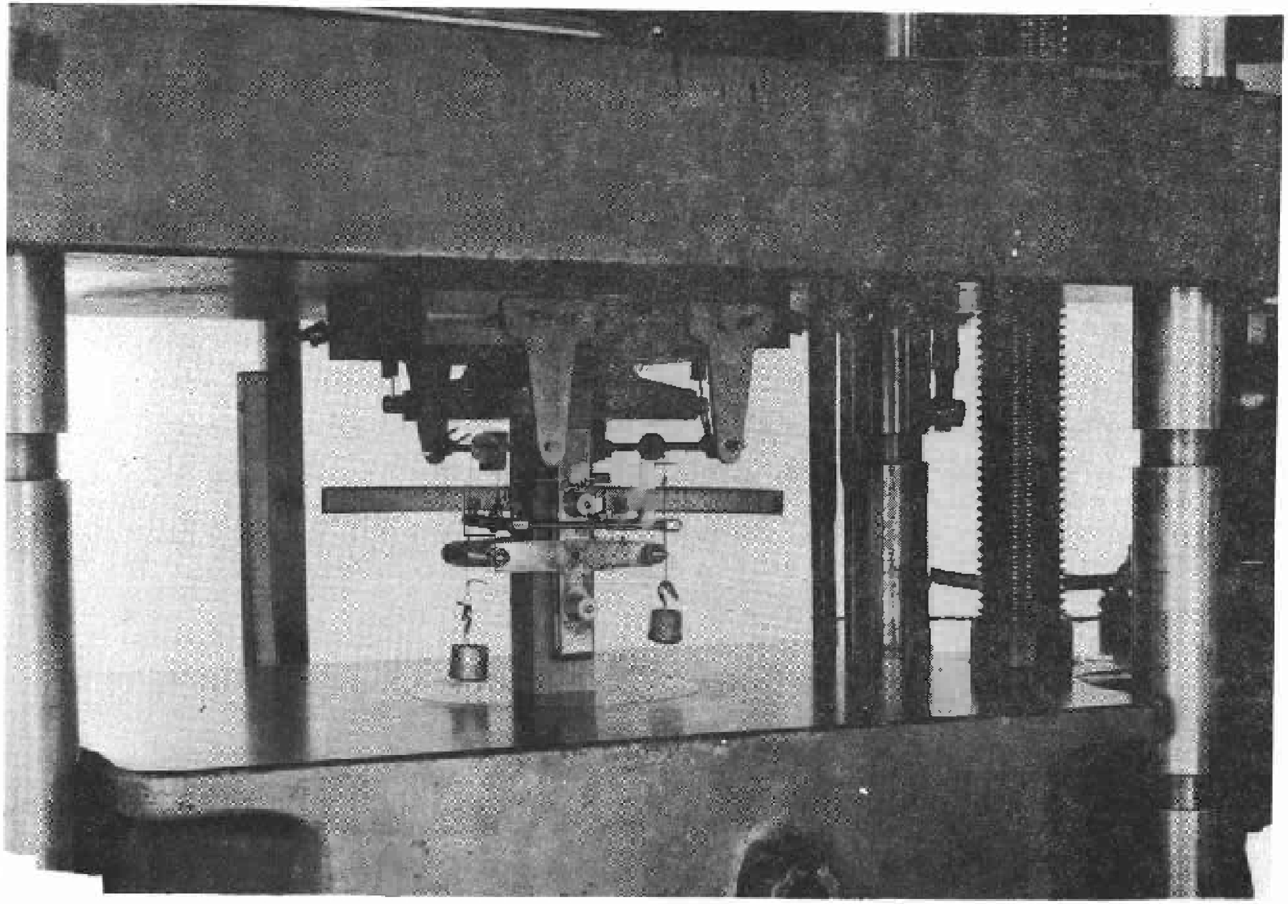

Figure 3.--Method of measuring Young's moduli and Poisson's ratios, showing axial and lateral extensometers, and scales for measuring deformation.

Z M 60812 F

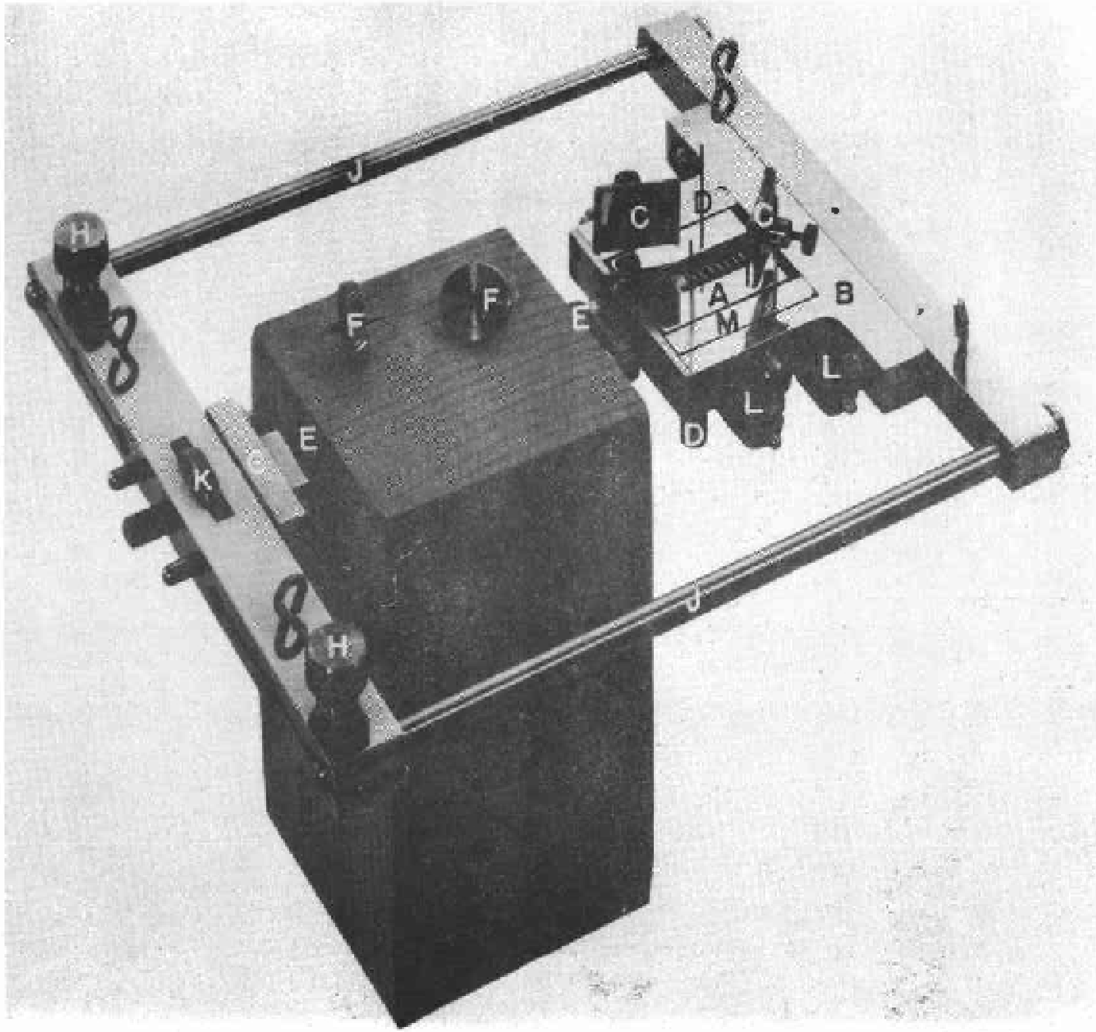

Figure 4.--Details of lateral extensometer used in tests to determine Poisson's ratio. (A) movable plunger, (B) housing frame, (C) mirrors mounted on steel rollers, (D) dummy rollers, (E) contact buttons in place, (F) extra contact buttons, (G) adjustable bearing block, (H) clamp screws, (J) tie rods, (K) adjusting nut, (L) hollow spring enclosures, (M) movable contact block.

Z M 63751 F

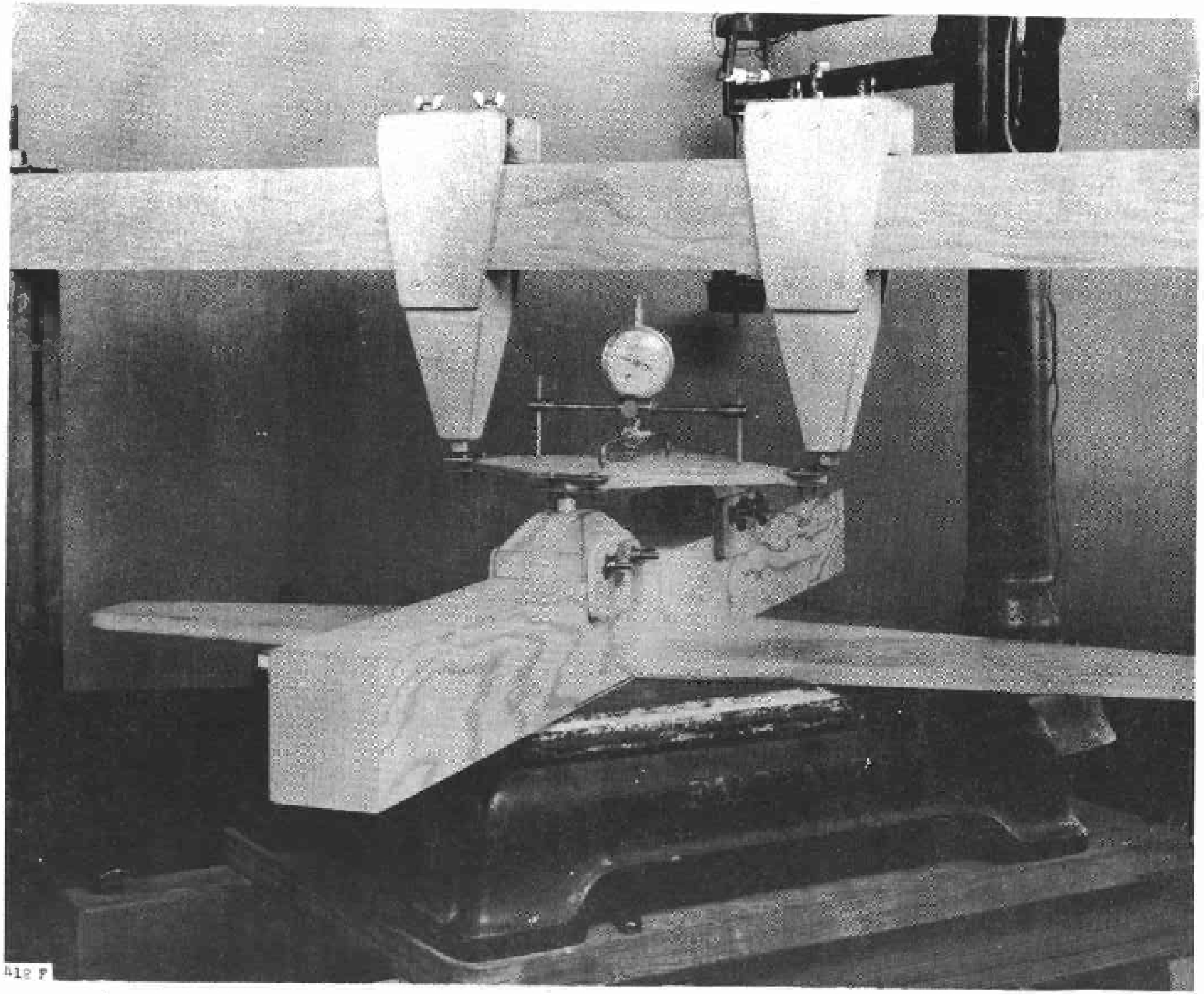

Figure 5.--Standard plate shear apparatus for measuring modulus of rigidity.
Z M 62326 F

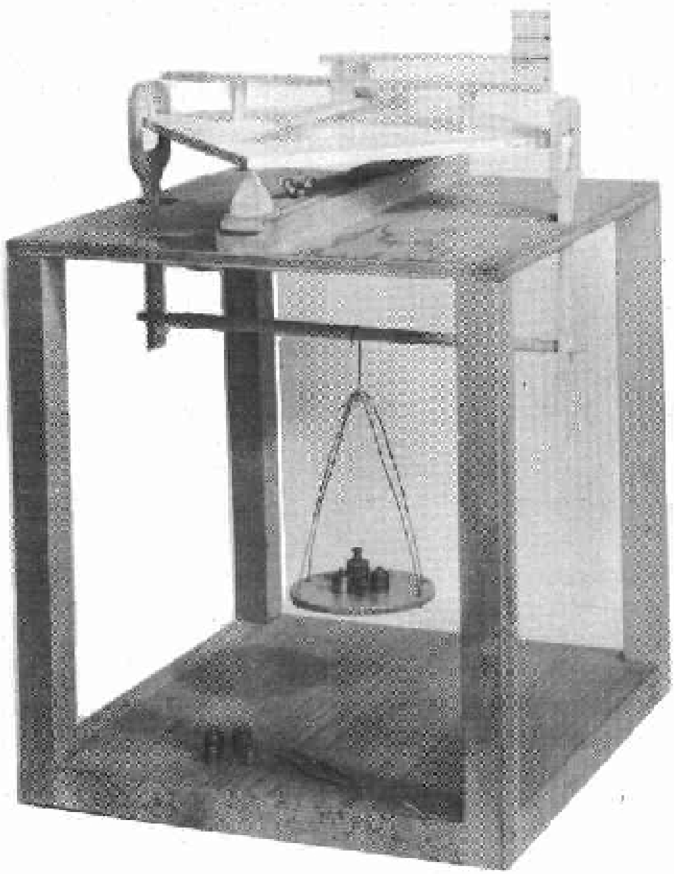

Figure 6.--Special plate shear apparatus used for materials having a low modulus of rigidity.
Z M 62327 F

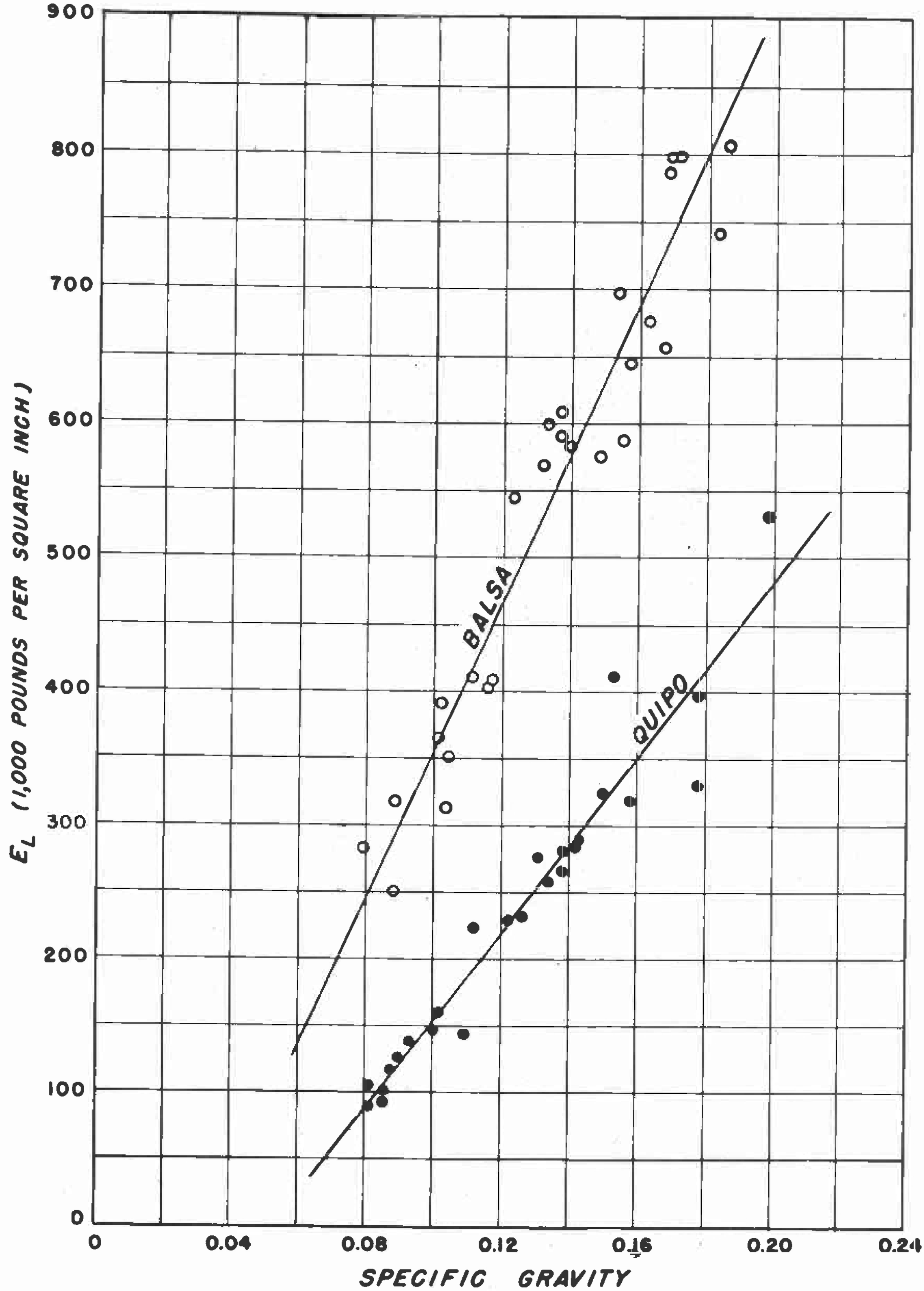

Figure 7.--Relation of modulus of elasticity in the longitudinal direction (E_L) with specific gravity for balsa and quipo.

Z M 61098 F

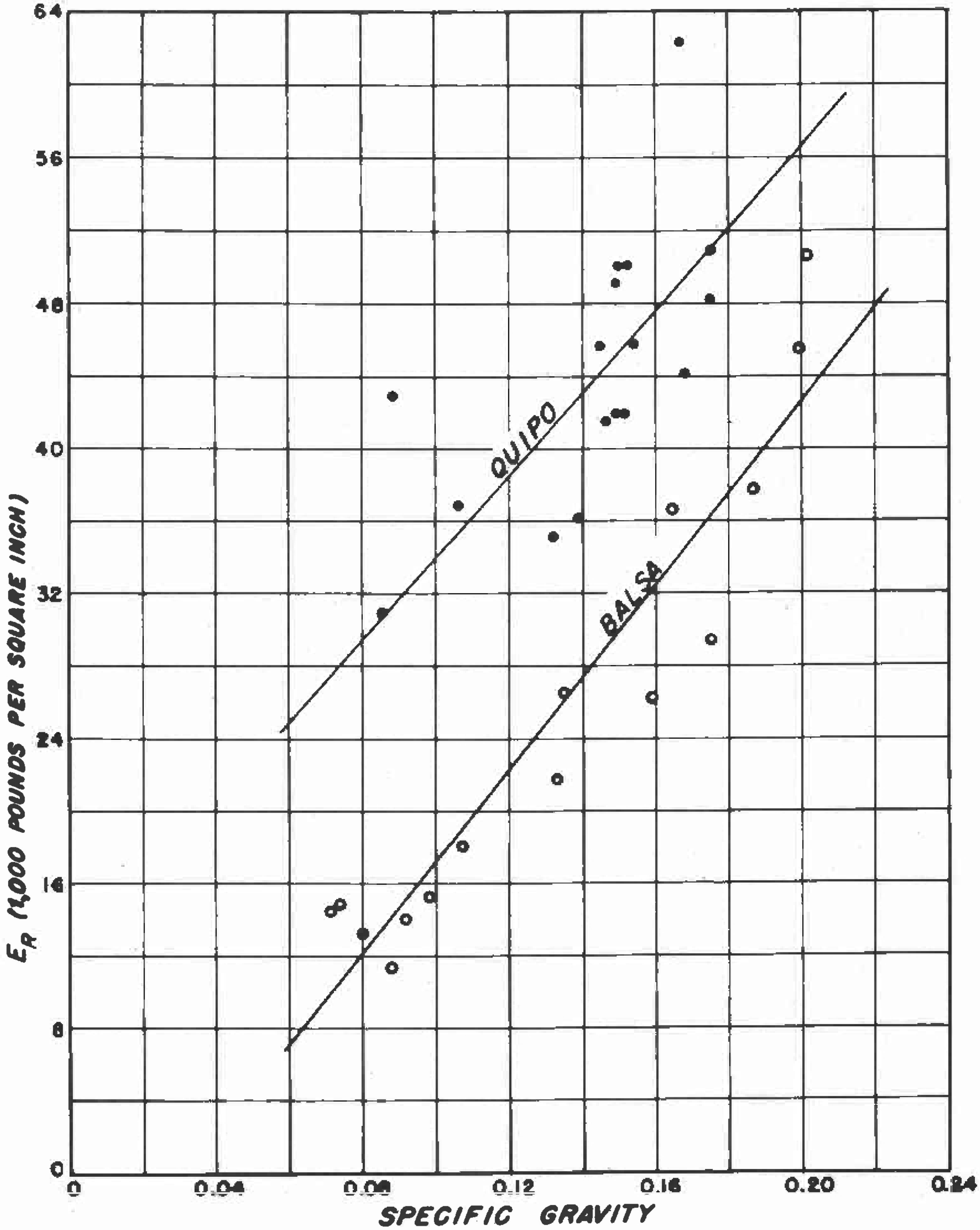

Figure 8.--Relation of modulus of elasticity in the radial direction (E_R) with specific gravity for balsa and quipo.

Z M 61099 F

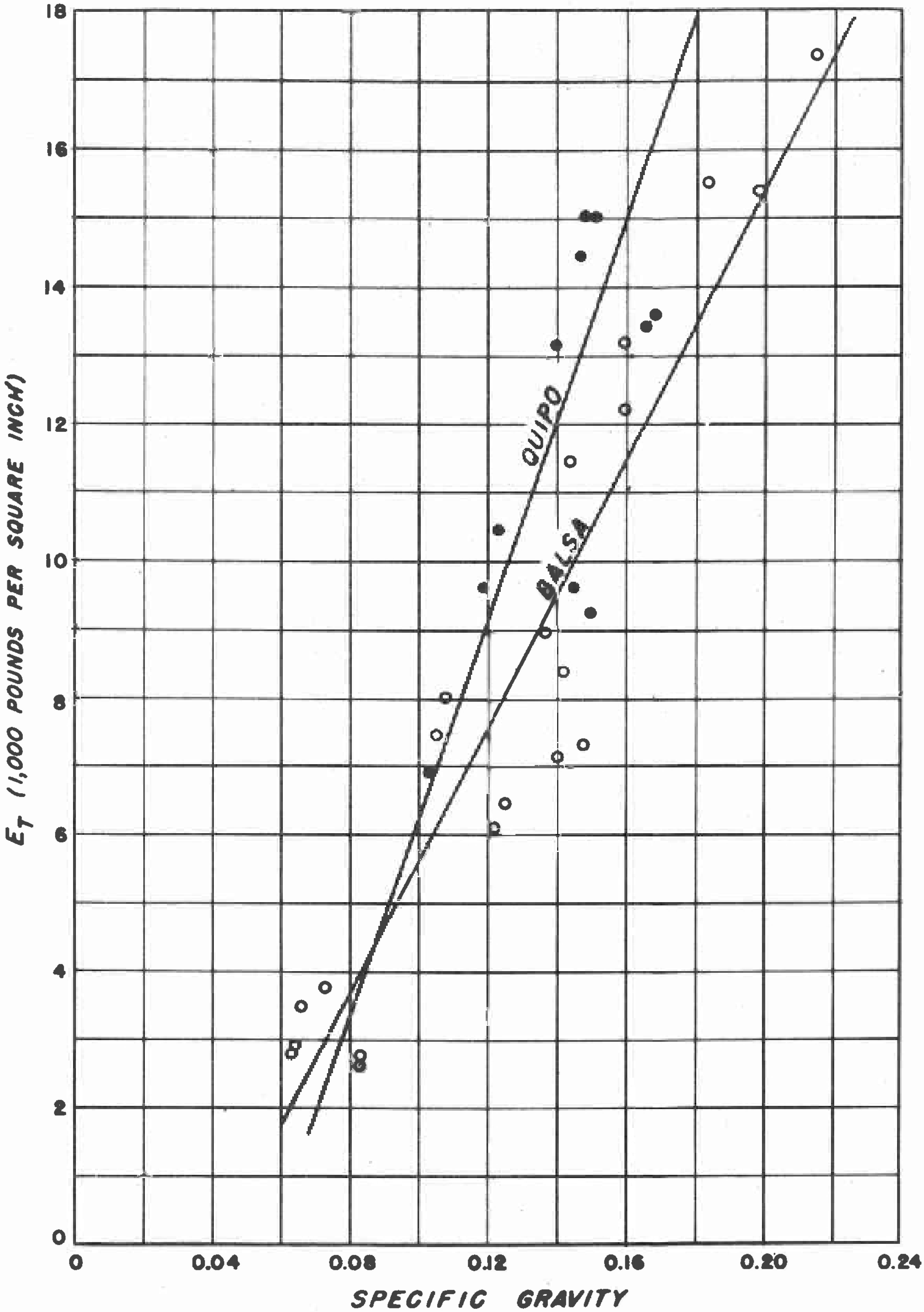

Figure 9.--Relation of modulus of elasticity in the tangential direction (E_T) with specific gravity for balsa and quipo.

Z M 61100 F

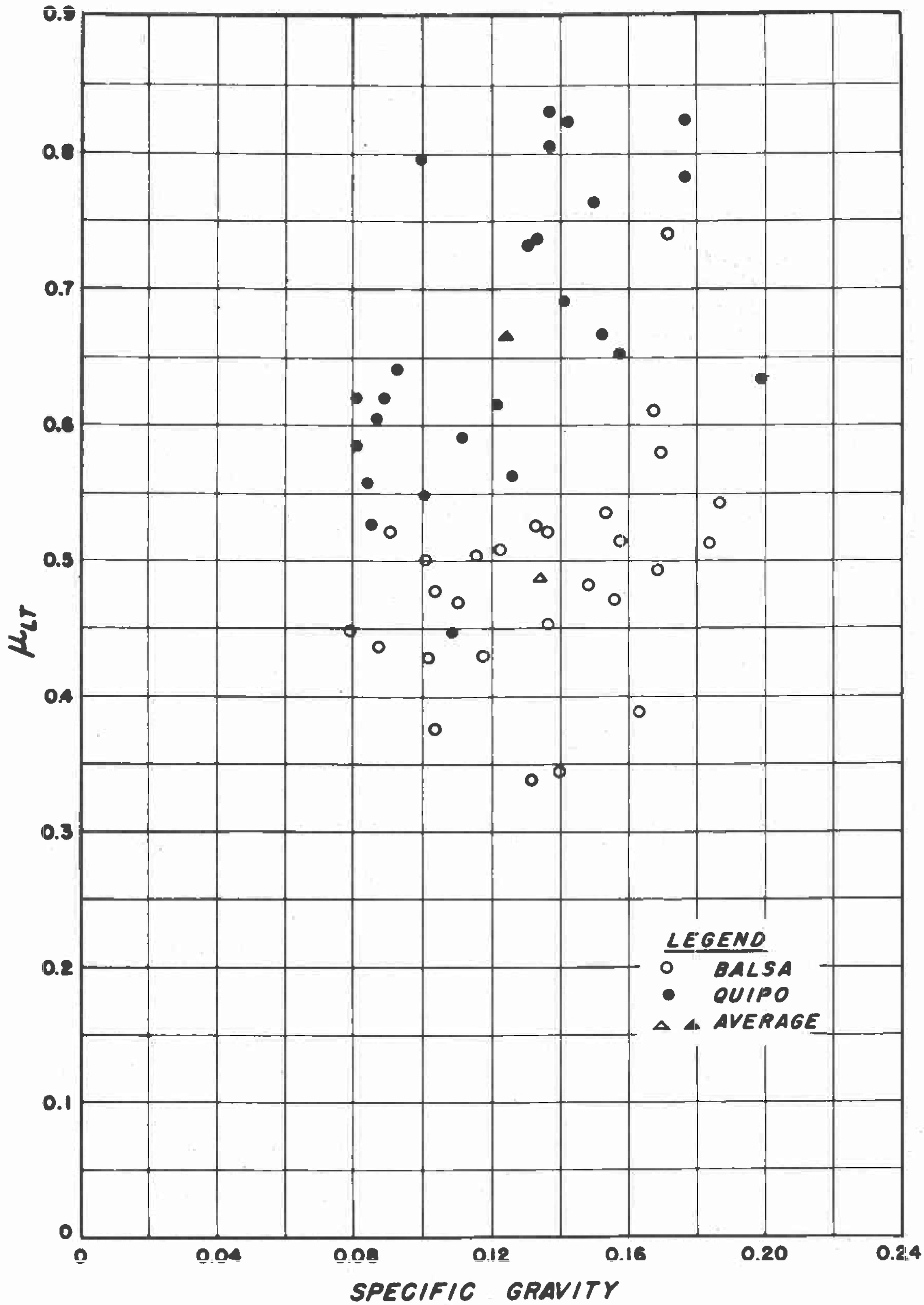

Figure 10.--Poisson's ratio (μ_{LT}) plotted against specific gravity for balsa and quipo.

Z M 61101 F

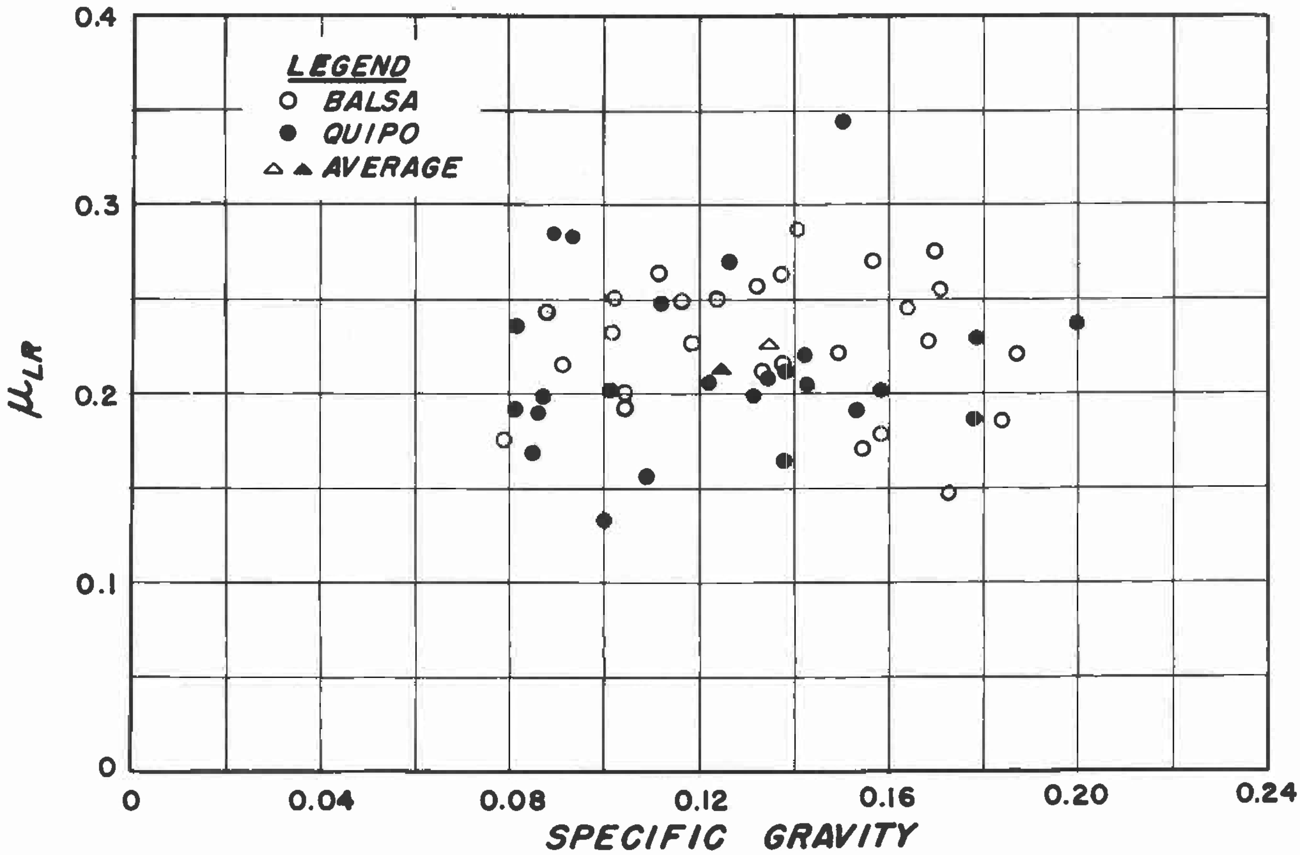

Figure 11.--Poisson's ratio (μ_{LR}) plotted against specific gravity for balsa and quipo.

Z M 61102 F

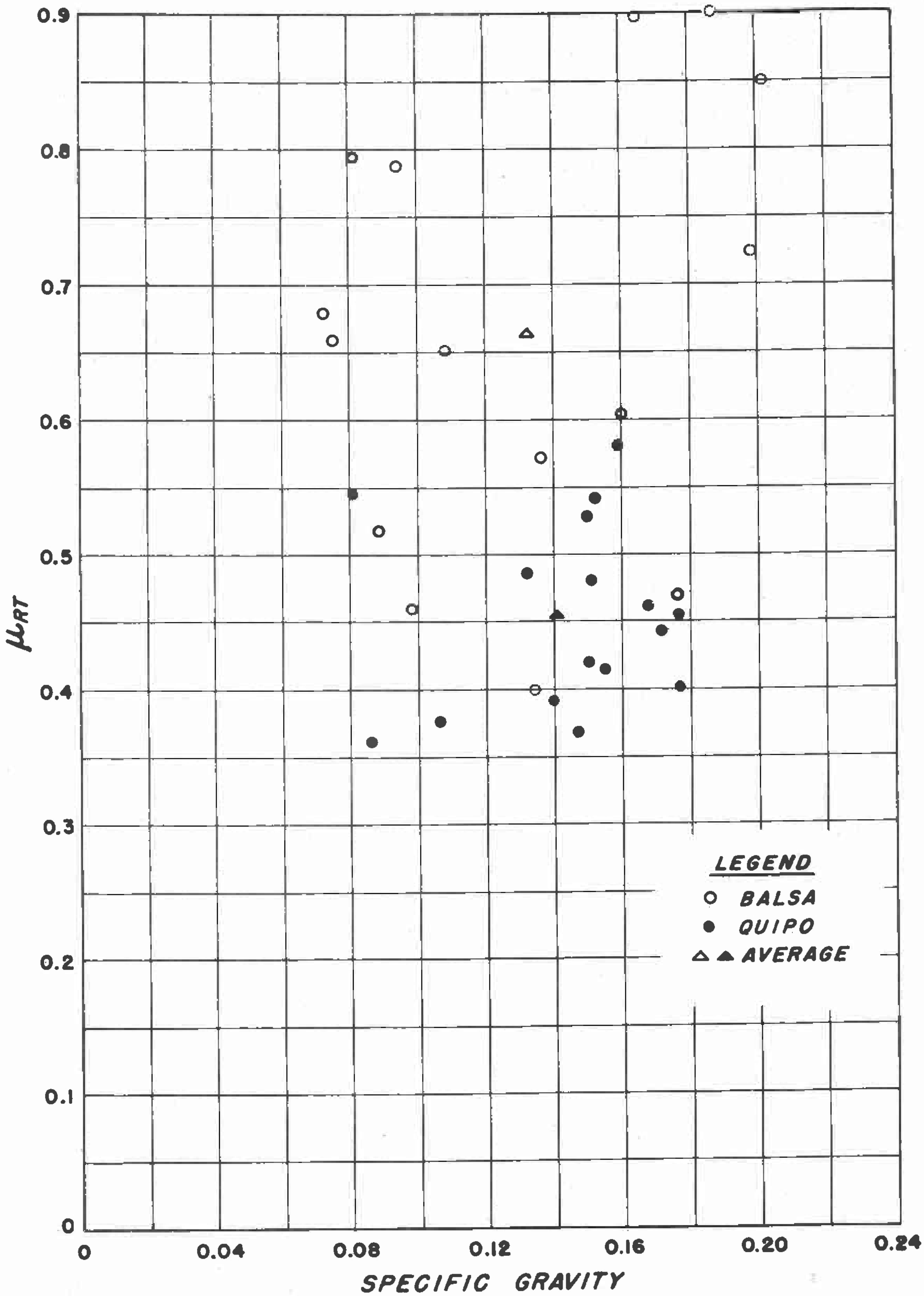

Figure 12.--Poisson's ratio (μ_{RT}) plotted against specific gravity for balsa and quipo.

Z M 61103 F

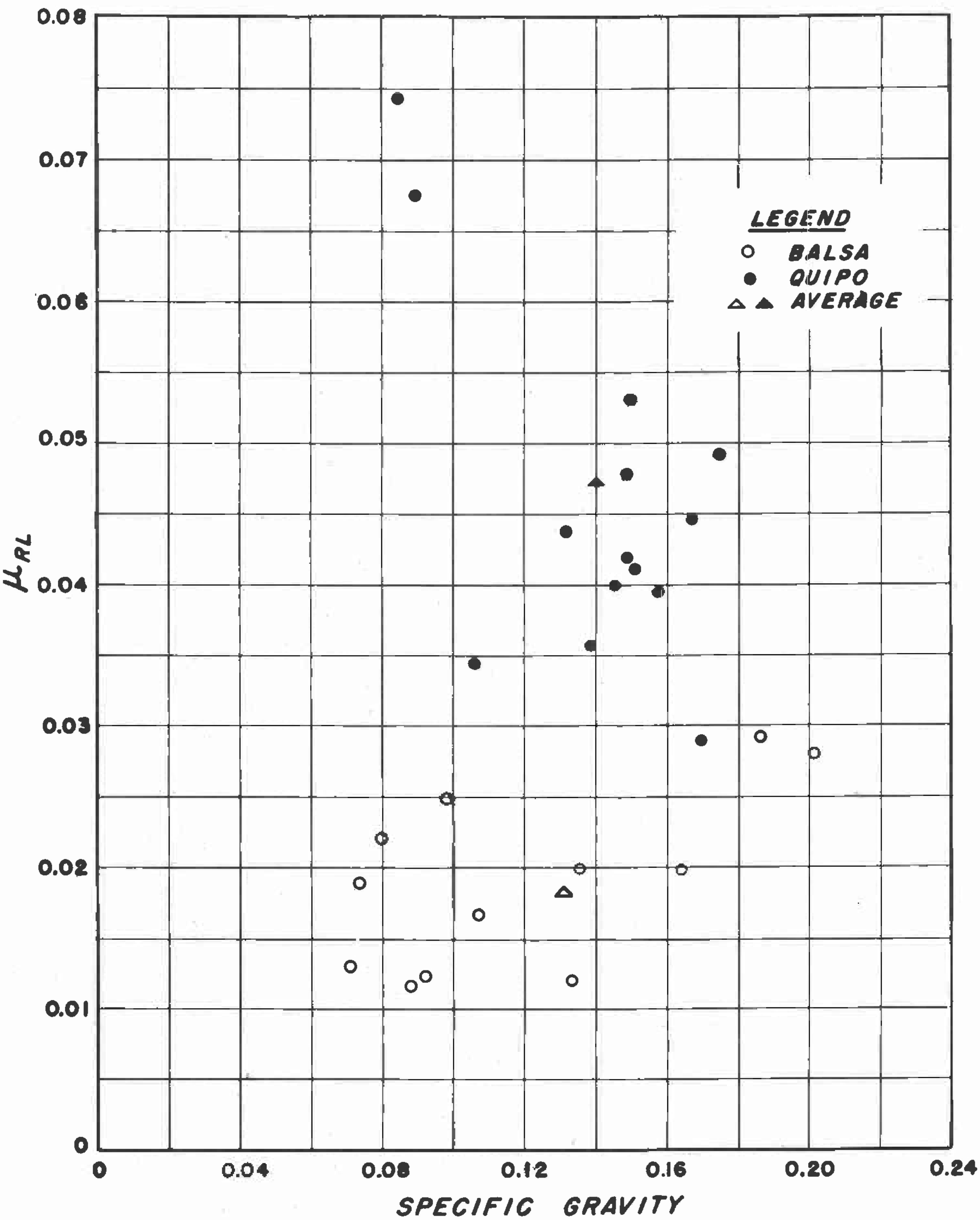

Figure 13.--Poisson's ratio (μ_{RL}) plotted against specific gravity for balsa and quipo.

Z M 61104 F

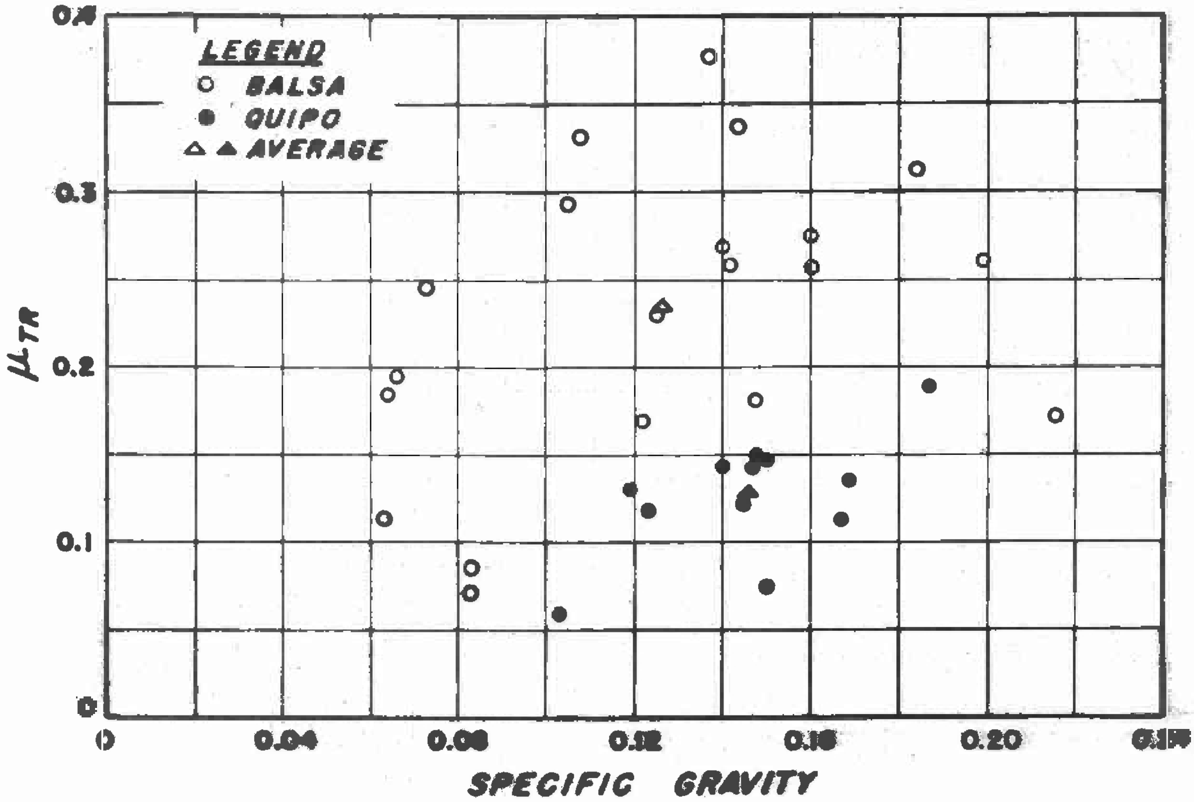

Figure 14.--Poisson's ratio (μ_{TR}) plotted against specific gravity for balsa and quipo.

Z M 61105 F

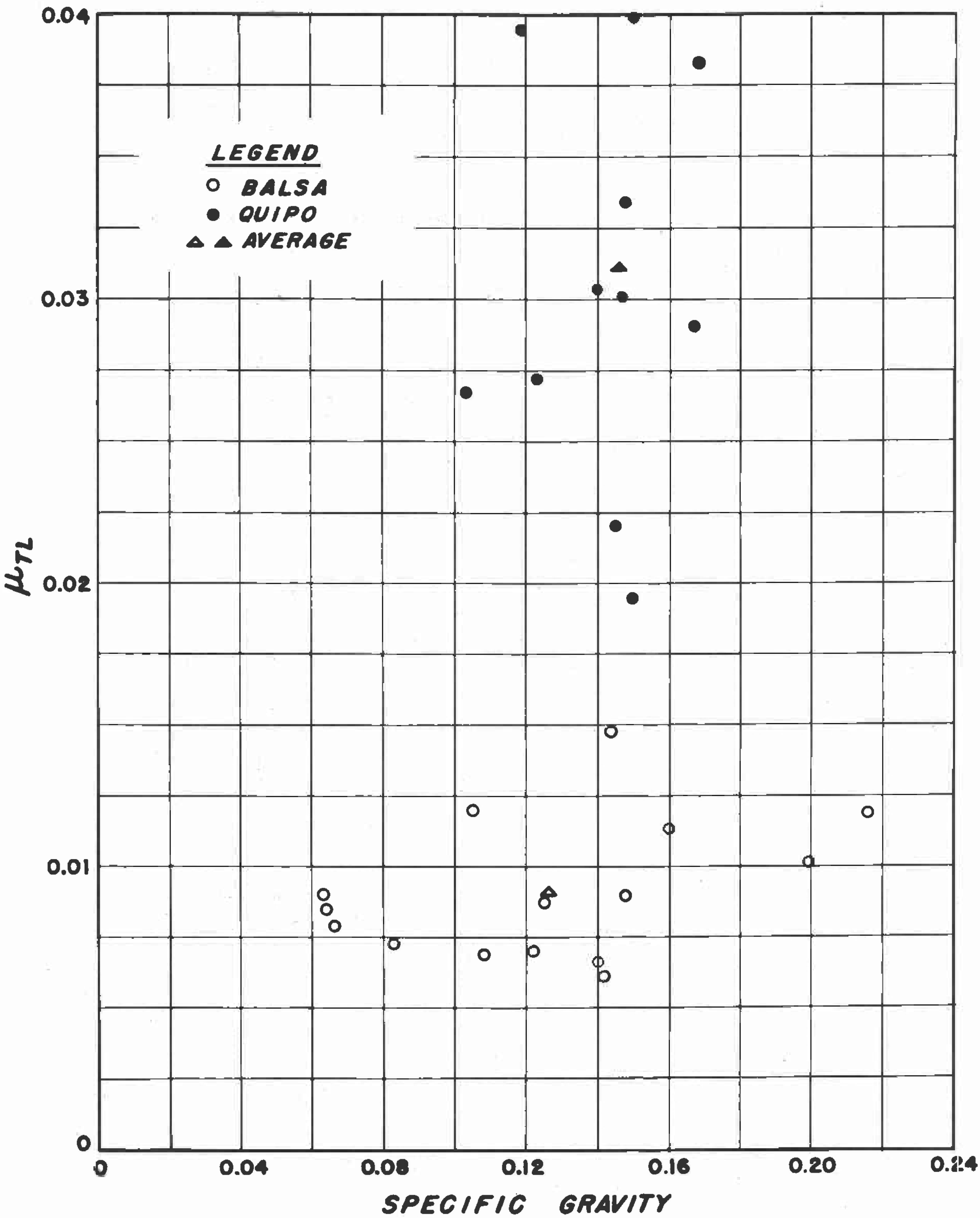

Figure 15.--Poisson's ratio (μ_{TL}) plotted against specific gravity for balsa and quipo.

Z M 61106 F

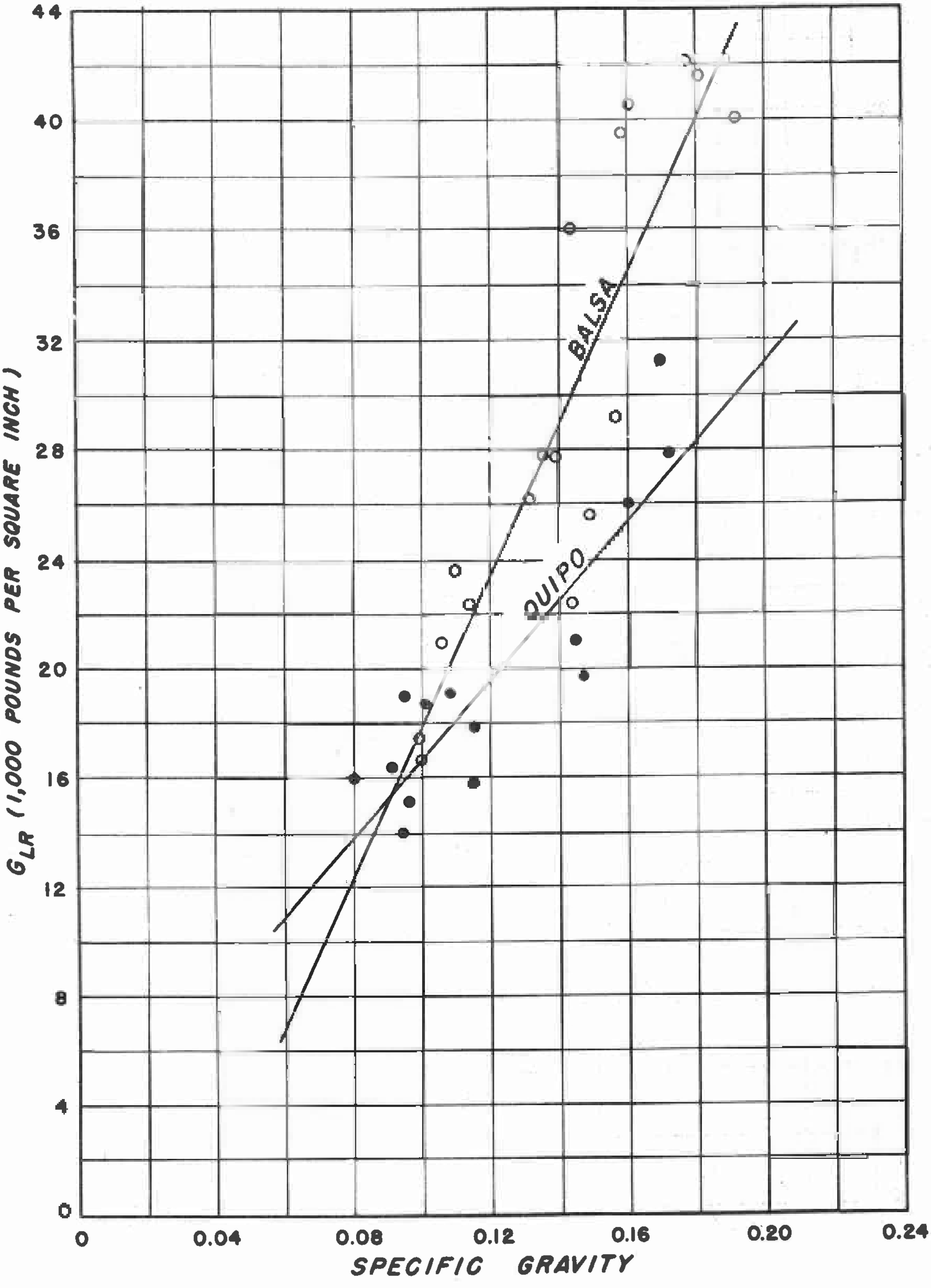

Figure 16.--Relation of modulus of rigidity (G_{LR}) to specific gravity for balsa and quipo.

Z M 61107 F

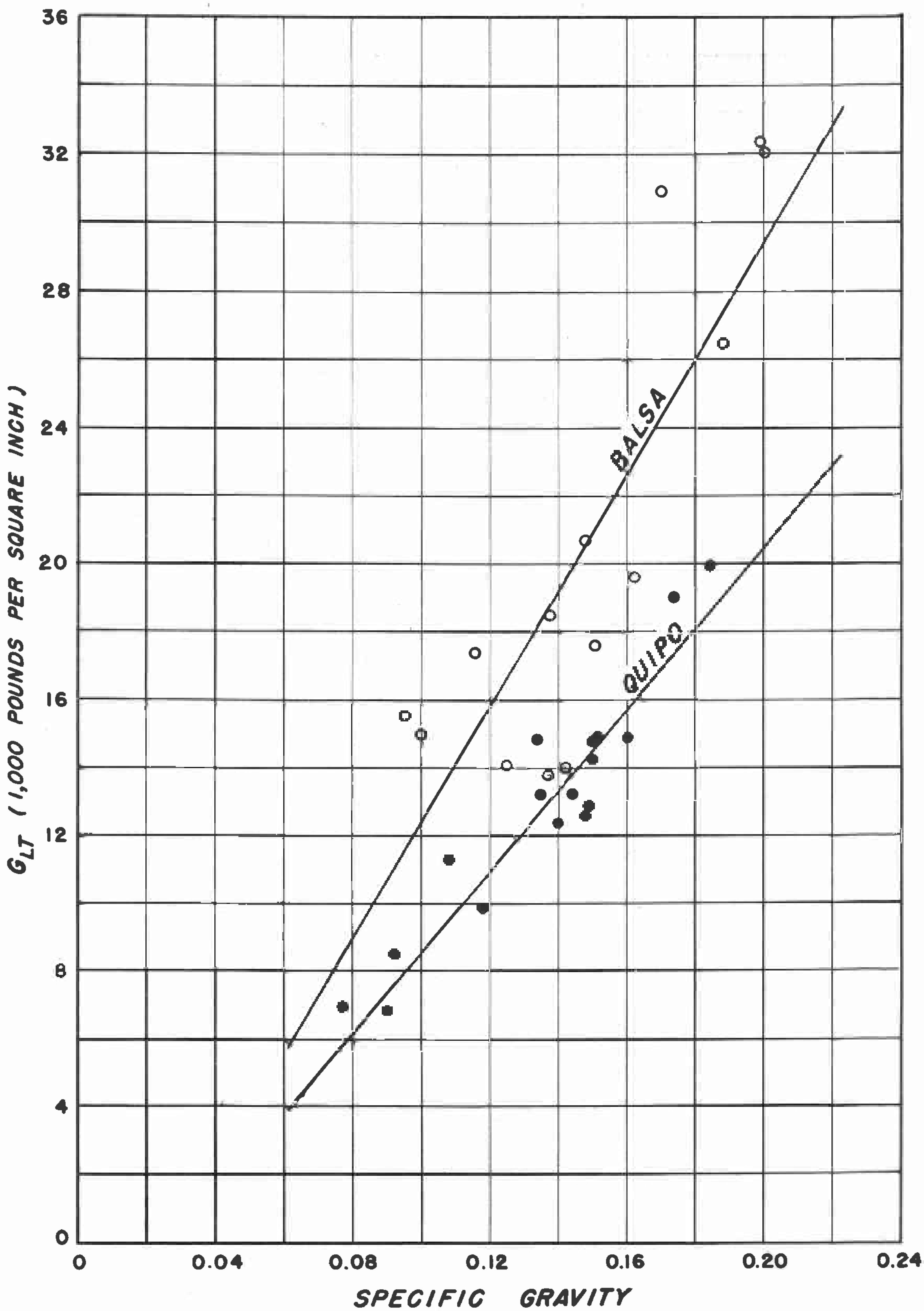

Figure 17.--Relation of modulus of rigidity (G_{LT}) to specific gravity for balsa and quipo.

Z M 61108 F

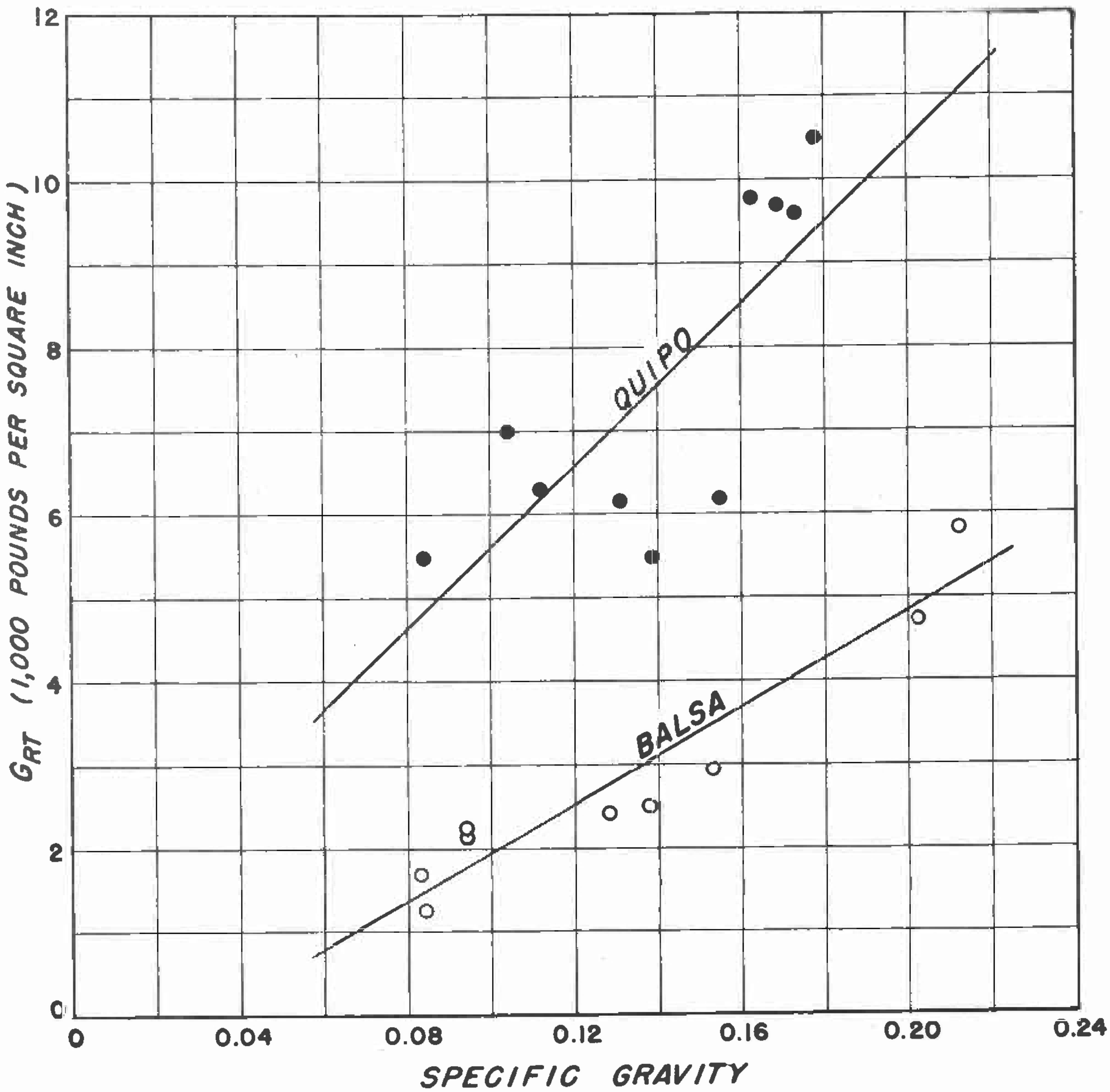

Figure 18.--Relation of modulus of rigidity (G_{RT}) to specific gravity for balsa and quipo.

Z M 61109 F