FACTORS INFLUENCING THE STRENGTH PROPERTIES OF DOUGLAS FIR PLYWOOD NORMAL TO GLUELINE

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ABSTRACT

The study was designed to evaluate the relative importance of certain factors influencing the strength properties of cold-pressed Douglas fir plywoods normal to glueline. In addition, estimates of strength values were also sought. Rotary-cut veneers were obtained from plywood mills; sawn veneers were prepared from lumber. A 2 x 3 x 3 factorial design was followed using veneer thicknesses of 1/10, 1/7, and 1/5 inch, and gluing pressures of 50, 200, and 350 psi. A cold-setting modified polyvinyl adhesive (Duro-Lok 50) was used in all 18 plywood blocks fabricated. From each of these, 8 tension, 4 compression and 3 glue shear specimens were prepared. Their dimensions were $\frac{1}{2}$ x 1 x $4\frac{1}{2}$ inches, 1 x 1 x $4\frac{1}{2}$ inches and 1 x $3\frac{1}{4}$ x 3/5 inch, respectively.

Plywoods of sawn veneers were only half as strong as solid wood in both compression and tension. Solid wood exceeded the compressive strength of rotary-cut veneer blocks by two, and tensile values by seven times. Stiffness of sawn veneers was twice that of rotary cut ones. The ratio of moduli of elasticity in compression to those in tension was found to approximate seven and six for the two veneer types, respectively. The difference between solid wood and sawn-veneer block strength might be attributed mainly to the influence of a suspected acid hydrolysis at the gluelines or possibly to specimen geometry. The much lower strength values of rotary-cut veneers must have resulted from the presence of lathe checks, and the lower quality of veneer surfaces.

The functional dependence of all strength properties upon some independent factors, and the ranking of the latter, was established and evaluated by multiple regression analyses. The combination of the 16, 17 or 18 most important veneer and plywood variables accounted for practically all the variation, especially for rotary-cut veneers. In addition, the complete dependence of some plywood variables on independent veneer characteristics and gluing techniques were shown by regression equations. It should be noted that the three experimentally controlled factors, veneer type, veneer thickness and gluing pressure, were not always all included in the six most significant ones. The rank of variables was found to differ for each of the various strength properties observed.

Analyses of variance were performed for both observed and adjusted values within each veneer type, both providing almost identical results. The high significance of veneer thickness has been shown for all strength properties, barring shear. This was explained by its strong correlation with a number of independent variables, such as glue content and specific gravity. Gluing pressure exerted a highly significant influence on all strength properties of rotary-cut veneer blocks, and in compressive stress and strain of sawn-veneer plywood construction. Its influence was attributed to the strong correlations indicated between it and other variables, for example, full compression and plastic deformation. Finally, the exploratory nature of the experiment was emphasized.

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INTRODUCTION

Douglas fir (Pseudotsuga taxifolia Britt.) constitutes the major source of peeler bolts for the softwood plywood industry. Since it is indigenous to the western part of this continent, North American conditions, methods and references will be emphasized.

1. Uses of plywood

The structural potentialities of plywood have long been recognized. The Douglas Fir Plywood Association (since 1938) was among the first proponents of plywood construction. Beginning in 1941, the Army-Navy-Civil (A.N.C.) Committee of the Ammunitions Board of the United States of America, in cooperation with the Forest Products Laboratory at Madison, Wisconsin, have published plywood strength values and design recommendations. These were summarized in the A.N.C. Bulletin No. 18 (1951) andthe Wood Handbook (1955). The British Columbia Plywood Manufacturers Association has published technical data on Douglas fir plywood since 1950. Markwardt and Freas (revised 1956) published approximate design methods. On the basis of Russian, German and Hungarian literature, Hilvert (1956) summarized design methods and problems. In the United States, the Timber Design and Construction Handbook (1959) described design specification and practice. The Timber Construction Manual (1961) did the same for Canada.

Establishment of the Plywood Fabricator Service, an affiliate of the Douglas Fir Plywood Association, now known as the American Plywood Association, marked the beginning of a new age of plywood structural usage, according to

Schniewind (1962a). North American and European attitudes and approaches to plywood production and uses are reflected in the comprehensive books written by Perkins (1962) and Kollmann (1963).

The world-wide significance of plywood and other wood-based panels has been illustrated by the recent International Conference held under the auspices of the Food and Agriculture Organization of the United Nations (Fleischer, 1963). In the American Marietta Economic Survey (1960) it was predicted that Douglas fir plywood production will rise to 13.4 billion square feet in the United States, on a 3/8-inch basis, by 1970. Blomquist (1962) reported a total Douglas fir plywood production of 8.5 billion square feet, on the above basis, for 1962 . Plywood manufactured in British Columbia in 1961 was worth almost 83 million dollars (Dominion Bureau of Statistics, 1962), approximately 61 per cent of the total value of Canadian plywood production.

2. Objective and scope

Stress analysis of solid wood and plywood has been hindered since, in order to use modern photoelastic methods or electrical strain gauges effectively, the moduli of elasticity must be known in advance for any direction in the material (Walker, 1961). The strength and elastic properties of plywood parallel to glueline have been investigated theoretically by March (1944) and Hearman (1948), and summarized by Hoff in Dietz (1949) and Meredith (1953). Curry (1954) and Liska (revised 1955) measured these properties experimentally. Preston (1950) and Curry (1957) showed the influence of adhesive to be negligible on the strength properties of conventional plywood. Moduli of elasticity in tension and compression are lacking for plywood stressed normal to glueline and have been assumed to be identical. However, wood in both radial and tangential directions (Walker, 1961), and glue (Marian and Stumbo, 1962), exhibit higher resistance to compression than to tension. Subsequently, one would expect plywood to behave similarly normal to glueline.

Stieda (1962) and Yaworsky, Cunningham and Hindley (1955) proposed rolling shear to be a diagonal tension or "tear" failure. Obviously, moduli of elasticity and strength values perpendicular to the glueline influence rolling shear considerably. Thus, if the factors determining these strength properties were known, resistance to rolling shear might be improved by changes in manufacturing techniques.

The standard plywood (glue) shear tests, if performed jointly with moduli of elasticity determinations, would allow a conventional evaluation of bond quality. One could also relate data obtained from this experiment to those of others, using plywood shear test (rolling shear) values for comparison.

The above considerations, coupled with the challenge of exploring an apparently neglected field, prompted the writer to select the present topic. It was hoped that the information obtained would be useful to research workers concerned with stress analysis and/or possible improvements of plywood.

3. Literature survey

Plywood consists of veneers and glue, joined through boundary layers. The weakest of these determines bond strength, when plywood is subjected to stresses normal to glueline (Bikerman, 1960). Specimen history, geometry and testing methods also influence the apparent strength properties of materials (Marin, 1962). Thus, these factors should be reviewed concisely.

(a) Wood and veneer

Zahner (1963) singled out soil moisture content as the most significant single factor influencing growth rate and anatomical features of wood. Larson (1962) proposed wood characteristics to be a product of heredity and environment. Lee (1961) correlated strength in tension parallel to the grain with the crystallinity of cellulose, as did Ifju (1963), while resistance to compression was believed to depend on the lignin content of cell walls. Schniewind (1959) showed the transverse anisotropy of wood to be a function of gross anatomic structure. Kübler (1957) showed how internal growth stresses increase the resistance of trees to external stresses. He concurred with Haraszty (1956), who emphasized that the bole structure resulted from adaptation to environmental stresses and metabolistic functions.

Rheologically, wood might be classified as a linear visco-elastic solid (Pentoney and Davidson, 1962). As a high polymer, it did not exhibit proportional stress-strain relations. Walker (1961), however, showed that it may be considered as an elastic material, within certain limits. The strength properties of, and factors relating to, variation in specific gravity of young rapid-growth Douglas fir were studied by Littleford (1961) and McKimmy (1959), respectively. The Forest Products Laboratories of Canada (1956) and of the United States (1955) published average strength values for small clear specimens of coast-type Douglas fir in the air-dry condition as listed in Table I. Allowable stresses for various grades of plywoods, parallel to glueline, were summarized in the various design handbooks mentioned above.

Schniewind (1962b), discussing solid wood, reported that moduli of elasticity were greater in the radial than in the tangential direction for every species investigated; further, the differences between the above moduli were not significant for tensile and compressive tests. Walker (1961), however, reported that modulus of elasticity calculated from bending (tension) was significantly different from that obtained by compression tests, unlike values shown in Table I. Moduli of elasticity transverse to grain and the frictional properties of wood were found to be highly important in rotary veneer cutting (McKenzie, 1962). This conforms with McMillin (1958), who showed compression and tension perpendicular to grain, and rolling shear, to be the most important mechanical properties of wood that influence veneer quality.

Feihl, Colbeck and Godin (1963), after studying a large number of factors, concluded that poor quality veneer resulted from badly adjusted lathes, in most cases. Mote (1963) found that, in veneer lathes, the stress distribution in the chips was independent of depth of cut, cutting direction or chip type. On the other hand, Hoadley (1962) reported that wood density, wood temperature at time of cutting, nominal veneer thickness, and degree of nosebar compression, determine the development and final pattern of the dynamic force distribution in the wood. The causes and control of common peeling defects in veneer were summarized by Feihl and Godin (1962).

Collins (1960) suggested lathe checks to be a result of a "snap action" at the cutting edge. Leney (1960) showed the presence of tension, compression and shear "checking" as a corollary of the basic severance action at the knife edge. The cutting force was estimated to range from 5 to 7 pounds per inch of cutting edge. Wangaard and Saraos (1959), examining cutting variables, found a 30 per cent reduction in tensile strength (of lauan) veneers, due to cold cutting. Nosebar pressures were evaluated in terms of the mechanical properties of wood by McMillin (1958). Fleischer (1949) gave the first comprehensive experimental evaluation of rotary cutting in terms of veneer quality. On the basis of the above studies, one might reconstruct the actual variables that resulted in a given quality of green veneer.

The effect of drying, as evaluated by bond quality, remains controversial. This might be attributed to the complexity of factors that determine bond quality. Milligan and Davies (1963) showed that jet-air dryers, working at high temperatures, can be used without reducing veneer quality. They dried 1/8-inch thick Douglas fir heartwood veneers in 0.95 minute at 550°F. They noted, however, that veneer temperatures did not exceed 280°F. at 5 per cent moisture content. Northcott, Hancock and Colbeck (1962) found that heat treatment of wood tended to reduce wettability, but the caustic of the glue, when applied, acted to restore it. The importance of this can be appreciated in the light of Gray's (1962) calculations, which predicted that adequate wetting of wood surfaces is more important than adequate adhesion. Barlai (1961), after discussing the chemical changes that would take place in veneer or lumber, proposed that, by controlling the intensity and duration of heat treatment, wood properties could be altered to a desired degree. The theory of plywood casehardening or surface inactivation was examined by Northcott, Colbeck, Hancock and Shen

(1959), who also proposed sanding as an effective remedy. Northcott and Colbeck (1959) showed that veneer strength is reduced by over-drying veneer at or above 450°F. This confirmed similar conclusions reached by Northcott (1957), Bryant and Stensrud (1954), and others.

(b) Adhesives and gluing

The general principles of wood gluing have been summarised by various authors, such as Perry (1942), De Bruyne and Houwink (1951), Brown, Panshin and Forsaith (1952), Bakai and Salamon (1953) and others. Dietz (1949), Knight (1952), the Wood Handbook (1955), the Manufacturing Chemist's Association (1957), Bergin (1959), and others, have provided basic information on the properties and uses of wood glues. Up-to-date information may be obtained from annual reviews by Blomquist (1962 and 1960) and Hemming (1963). The latter heralded the appearance of modified polyvinyl glues as the greatest glue news of the year.

The room-temperature-setting polyvinyl adhesives became popular following World War II, although their creep property remained a serious drawback. McCormack (1954) listed high setting speed and relative immunity to influences of gluing temperature, pressure and humidity, as the most important characteristics of polyvinyl emulsions.

Duro-Lok 50, the modified polyvinyl emulsion used in this experiment, was reported to be water resistant and thermo-setting (National Starch and Chemicals Co. (Canada) Ltd., 1963). The adhesive film forms partly by water being absorbed into the wood and partly by evaporation. A catalysed chemical reaction, with its temperature dependent rate, develops the heat- and water-resistant bond. The following physical and chemical properties have been published by the manufacturer:

Type	Thermo-setting emulsion	
Properties	Weight	11.0 lb Imp. gal.
	Solids content ..	48.0%
	Viscosity	3000 cp
	Thinner	H_2O, less than 5%
	Freeze-thaw stability	Fair
	pH	5.0
	Storage conditions .	45-65° (Optimum)
	Storage stability ..	3 months (at 70°F)
Catalyst	42-2300 (acid), use 5% by weight (green glueline)	
	42-2301, use 10% by weight (colourless glueline)	
Working life . ..	24 hr at 72°F, 2½ hr at 100°F.	

According to the Manufacturing Chemist's Association (1957) the polyvinyl formal or butyral resins exhibit the ability to be cross-linked or insolubilized, thereby acquiring thermo-setting properties. Thus, Duro-Lok 50 should belong to this family of adhesives. This would allow estimation of their strength properties from data published by the above association for these polyvinyl resins. Percentage elongation and tensile strength for unplasticized polyvinyl formal and butyral were given as approximately 3 per cent at 11,000 and 4 per cent at 10,000 psi, respectively. Modulus of elasticity in tension was reported to vary from 500,000 to 700,000 psi at room temperature.

The boundary layers of the glued joint determine its quality. Interaction between wood and glue must be conceived spatially and through a water monolayer, according to a proposal by Marian and Stumbo (1962). The influence of various chemical and physical properties on bond quality was summarized by the same authors as well as by Bikerman (1960), who emphasized the role of glue, as did Norris (1958). Marian (1955) and Brown, Panshin and Forsaith (1952) suggested qualitative dependence between the various factors. Northcott, Hancock and Colbeck (1962) examined water relations in phenolic bonds, and Keylwerth (1962) studied swelling of compressed wood. The effect of wood moisture content on gluing was explored by Bergin (1959) and on shear strength by Sanborn (1945) and Lewis, Heebink and Cottingham (1945), who found 8 to 12 per cent to be an optimum level of wood moisture content.

Keylwerth and Höfer (1962) showed that plywood strength normal to glueline increased in short time tests (0.86 minute) as compared to long time tests (25 minutes) for polyvinyl acetate glues. Resorcinol-phenol-formaldehyde showed a reverse trend. Driehuysen and Wellwood (1960) studied the influence of temperature and relative humidity on open assembly time in the manufacture of laminates. Freeman (1959) examined the relationship between the physical and chemical properties of wood and adhesion, while Grantham and Atherton (1959) evaluated the overall effect of pre-heating Douglas fir blocks. Curry (1957) concluded that compression of veneers is confined to thin layers at the glueline. This is in agreement with Preston (1950), who observed greater compression of plywood with increasing number of gluelines. Poletika (1950) found that thickness of laminates does not influence strength, provided veneer thicknesses are not used. Norris, Warren and McKinnon (1948) reported increasing shear-through-thickness strength corresponding to decreasing veneer thicknesses. Cockrell and Bruce (1946) found that rolling shear strength decreased with increasing glueline thicknesses.

Murphey (1963) reported plastic deformations to be a result of permanent changes in crystallinity of cellulose. Wood deformations were shown by Perkitny and Helinska (1961) to be governed by a temperature-moisture content interaction, with a significant contribution from the release of growth stresses. Currier (1960) saw an opportunity for substantial savings of veneers through controlled reduction of pressure during hot pressing of Douglas fir plywood. Baumann and Marian (1961) studied gluing pressures as a function of the physical properties of wood. Carruthers (1959) investigated heat penetration in hot pressing and found that compression of plywoods increased with increase in pressing time, temperature, and moisture content of veneer. His findings agreed with those of Currier (1960), Sisterhenm (1958), and McDonald (1951), who was the first to propose the use of pressure (compression) control devices. Klein (1959) summarized all the advantages and disadvantages of both cold- and hot-pressing techniques.

(c) Testing methods

The problems of surface texture measurement were discussed by Stumbo (1963). Staining techniques for wood technologists were summarized by Wilson (1963). Currier (1962) gave detailed description of his methods of measuring and/or calculating plywood variables. A survey of methods for assessing veneer quality was undertaken by Newall (1960). The latter described methods used by Wangaard and Saraos (1959) for measuring veneer thickness, smoothness and tightness; Suziko (1958) for estimating roughness; Hahn (1957) in classifying wood surfaces; Higgins (1956) for determining veneer quality; Kivimaa (1956) in veneer quality determination by tension tests; Kaumann, Gottstein and Lantican (1956) in their comparison of numerical and subjective veneer quality evaluation; and the "droop" method of estimating veneer tightness.

Standard methods for determining the strength parallel to glueline and the durability of plywood have been specified by the Canadian Standards Association (1961) and by the American Society for Testing Materials (1961). However, tests concerning plywood strength properties normal to glueline have not been standardized. Marian and Stumbo (1962) proposed a tension test normal to glueline as the most sensitive method of evaluating bond quality. Keylwerth and Höfer (1962) used 3 by 4 by 16 cm. hyperbolically-necked specimens in tension perpendicular to gluelines, to investigate relaxation of adhesives. They found that the ultimate stress was influenced by plastic deformations of the glue joints. Marra (1962) showed the influence of specimen geometry to be striking, on cross-lapped wooden blocks. He also noted that rheological factors controlled a large portion of the total strength. This is in close agreement with Bikerman's (1960) findings that bond strength is determined by specimen geometry and by the mechanical properties of adhesive, adherend or the boundary layer. Northcott (1958) evaluated percentage wood failure as a measure of bond quality.

Rice (1957) showed that glueline shear stress at failure in compression was over twice as great as in tension; further, that percentage wood failure was conspicuously lower in tension than in compression. Yaworsky, Cunningham and Hindley (1955), investigating standard shear specimens, concluded that the test results might be more influenced by stress distribution peculiar to the specimen than by the variables under investigation. Northcott (1954) presented similar arguments. He also emphasized the importance of reproducibility of test results, acceptable unit of measurement, and ease of preparation of specimens. The problems of evaluating glues and glued products were also discussed by Blomquist (1954). Wakefield (1947) studied the tension normal to glueline plywood test and found that ultimate strength was much lower than could be expected from solid wood having a similar density. He proposed wood permeability and grain direction as the most influential factors in these tests.

Osherovich (1955), who examined tension perpendicular to grain, found that with increasing radii of curvature for necked-down specimens the stress increased as a result of reduced stress concentration. This is supported by the earlier observations of Durelli (1942) and Frocht (1942). The former showed the presence of stress concentration in necked-down tension specimens, whereas the latter found a uniform stress distribution in circular shafts. Thus, one could expect uniform stress distribution by not using necked-down specimens.

According to James (1962), moduli of elasticity of wood should not be influenced by the rate of deflection, but the stress to proportional limit should change, especially for plastic materials. This had been borne out experimentally by Liska (1955). It is also supported by the springwood failure theory proposed by Bodig (1963) for radially-loaded small Douglas fir specimens. Rate of loading did not affect tension perpendicular to grain significantly within the range of 30 to 1000 kg/min., Osherovich (1955) reported. However, loading rates of 1 to 10 kg/min. resulted in a 6 per cent strength reduction over higher rates. For compression perpendicular to grain, Stern (1944) found that twice or four times the standard speed did not cause any appreciable difference in the stress values or moduli of elasticity. It should be noted that the importance of uniformity of testing temperature and relative humidity, thus equilibrium moisture content of specimens, were emphasized by the standards adopted within Canada and the United States.

EXPERIMENT

A listing of assumptions concerning the variables precedes an outline of considerations underlying the statistical design and analysis of the experiment. Following this, preparation of the specimens and various testing methods are described. Experimental data are presented and analysed.

1. Technical assumptions

Certain assumptions are proposed to ensure a unified approach to the objectives of the thesis. Their validity is to be evaluated in the light of the experimental evidence that will be obtained. These technical considerations are:

(1) All Douglas fir veneers manufactured in the Vancouver area constitute a single population.

(2) Plywood bond quality will be high and uniform in the experiment.

(3) Strength values obtained from tension and compression tests may be compared with each other.

(4) Magnitude and variation of strength properties (S_i) obtained may be adequately accounted for by veneer (X_j), plywood (Y_k), and testing (Z_1) variables such that: $S_i = f(X_j, Y_k, Z_1)$.

(5) Plywood, a composite material, fails in its weakest layer, i.e. veneer, when subjected to stresses normal to glueline. The following alternatives may be considered:

(a) The basic properties of wood (veneer) are not altered by the manufacturing techniques, so that $S_i = f(X_j)$,

(b) Manufacturing processes change the basic properties of veneer, so that $S_i = f(Y_k)$ and $Y_k = f(X_j)$,

(c) Better approximation of strength properties is obtained from a combination of the most significant veneer and plywood variables, expressed as $S_i = f(X_j, Y_k)$.

(6) The possible random variations introduced by the testing methods cancel each other (on the average), thus their influence may be negligible.

(7) Consequently, the measurement and/or calculation of the following "independent" variables, explained in detail in the text, may prove adequate to account for the variation in plywood strength properties.

(a) Veneer variables:

X1: type
X2: thickness
X3: growth rings per inch
X4: summerwood per cent
X5: specific gravity
X6: moisture content
X7: lathe check depth
X8: lathe checks per inch
X9: lathe check angle
X10: radial angle of growth ring
X11: longitudinal angle of growth ring
X12: roughness
X13: tightness of cut
X14: $(X2)^2$: $(\text{thickness})^2$
X15: $(X4)^2$: $(\text{summerwood per cent})^2$
X16: $(X7)^2$: $(\text{lathe check depth})^2$
X17: $(X5)^2$: $(\text{specific gravity})^2$

(b) Plywood variables:

Y1: gluing pressure
Y2: load recovery
Y3: number of plies
Y4: height of block at E.M.C.
Y5: full compression
Y6: permanent compression
Y7: weight loss in press
Y8: veneer densification
Y9: glue content (solids)
Y10: increase in specific gravity
Y11: specific gravity

Y12: equilibrium moisture content (E.M.C.)
Y13: days to E.M.C.
Y14: $(Y1)^2$: $(\text{gluing pressure})^2$
Y15: $(Y6)^2$: $(\text{permanent compression})^2$
Y16: $(Y8)^2$: $(\text{veneer densification})^2$
Y17: $(Y10)^2$: $(\text{increase in specific gravity})^2$
Y18: $(Y11)^2$: $(\text{specific gravity})^2$

(8) These three independent variables may be the most important:

X1: veneer type
X2: veneer thickness
Y1: gluing pressure

(9) The plywood strength properties, i.e. dependent variables, considered are:

S1: modulus of elasticity in compression
S2: unit stress in compression
S3: unit strain in compression
S4: modulus of elasticity in tension
S5: unit stress in tension
S6: unit strain in tension
S7: wood failure in tension
S8: unit stress in shear
S9: wood failure in shear

This notation of variables shall be adhered to in discussions, tables and equations that follow.

2. Experimental design

It has been assumed that wood and glue characteristics, and manufacturing techniques, determine the strength properties of plywood. An analysis involving many of these factors could account for most of the variation in strength values. The physical control of all variables would be impracticable, if not impossible. Their influence, however, can be brought under statistical control and evaluated.

Only the three factors assumed to be the most significant are controlled experimentally at levels laid down by a factorial design. The appropriate levels have been selected on the basis that three points may adequately define the curvature of response surfaces. The 2 by 3 by 3 factorial design chosen is outlined below:

Factor A	:	type of veneer
a_1	:	sawn
a_2	:	rotary cut
Factor B	:	veneer thicknesses
b_1	:	1/10 in.
b_2	:	1/7 in.
b_3	:	1/5 in.
Factor C	:	gluing pressure
c_1	:	50 psi
c_2	:	200 psi
c_3	:	350 psi

The treatment combinations have been assigned according to the following pattern, where numbers designate the experimental units, i.e., the plywood blocks:

A		a_1			a_2		
B		b_1	b_2	b_3	b_1	b_2	b_3
	C_1	1	4	7	10	13	16
C	C_2	2	5	8	11	14	17
	C_3	3	6	9	12	15	18

To rank the independent variables according to their influence on strength properties, and to allow evaluation of assumptions about them, a multiple regression analysis, with automatic reduction, is proposed. The statistical control consists of the recalculation of plywood strength properties from regression equations that exclude factors A, B and C. This would eliminate the effect of all other variables. However, it may suffice to adjust for the most significant ones only. Then, the influence of factors A, B and C can be realistically evaluated by an analysis of variance of the adjusted strength values. These adjusted values may also be used to construct the response surfaces to determine the optimum and/or worst combinations of the three controlled independent variables. It should be noted that the large number of variables necessitates the use of an electronic computer.

3. Statistical assumptions

To achieve a reliable and meaningful interpretation of the results, a close observance of the basic assumptions of the statistical methods is necessary. These assumptions are outlined below.

The regression equations are based on the assumptions that the independent variables are not influenced by treatments and are measured without error. The dependent variables are supposed to be randomly and normally distributed, with a common variance. For calculating the adjusted means, that is, using a covariance analysis, the independence and normality of residuals and the linearity of regression have to be assumed. It should be emphasized that a regression equation expresses a statistical law, it holds true on the average, but it is not an absolute mathematical truth. The multiple linear regression equations conform to the following model, according to Steel and Torrie (1960):

$$Y_i = A + B_j (X_{ij}) + E_i$$

where $i = 1, 2, \ldots, n$ and

$j = 1, 2, \ldots, p$

The calculation of adjusted means assumes the homogeneity of regression coefficients, and is indicated below, as given by Steel and Torrie (1960):

$$A_i = Y_i - B_j (X_{ij} - \bar{X}_{.j})$$

The analyses of variance are based on the assumed additivity of treatment and environmental factors, and the independence, randomness and normal distribution - with a common variance about zero mean - of the dependent variables. The assumption of normality is not required for estimating the components of variance, but randomization is necessary. When the independent variables are fixed, that is, not influenced by treatments, the error variance is the appropriate term for testing hypotheses about any source of variation. For evaluating the adjusted means, the error degrees of freedom must be reduced by the number of independent variables used in the calculation of adjusted values.

4. Preparation of material

Ideally, the plywood blocks prepared in this experiment should differ only in three of their attributes, namely, veneer type, veneer thickness, and gluing pressure. To approach this, one would need identical and defect-free sheets of veneers, processed by the same techniques, apparatus and people. Although the inherent variability of wood, glue, and processing could not be eliminated, an attempt has been made to minimize its influence by both experimental and statistical methods.

(a) Veneers

The rotary-cut veneer sheets were obtained from three different plywood mills in the Vancouver area, since at that time none of them manufactured all three thicknesses. The samples were picked from veneers leaving the dryers. Thus, they should represent the veneer population resulting from standard industrial practices. To secure control specimens, two 1-in. by 6-in. flat-sawn Douglas fir boards were sawn into sheets and planed to the required thicknesses in the University carpenter shop.

The veneer sheets were then cut into 48-in. by 5-in. strips along the grain, using a table saw, and designated by capital letters. These, in turn, were divided into 5-in. by 5-in. sections and identified by numbers from 1 to 9. All sections showing visible defects were excluded from the subsequent phases of the experiment. The 13 veneer variables were then measured on each section and recorded for every plywood block to be assembled.

To render the lathe checks clearly visible, the cross section of each veneer piece had been previously stained by India ink, and sanded. To distinguish springwood from summerwood, a solution consisting of equal parts of methyl blue and malachite green in an alcohol solvent was applied to the sanded cross sections. To ensure accurate measurements, a dissecting microscope - with a calibrated eye-piece - was set up. This allowed readings accurate to 1/10,000 in. at a magnification of 20, without touching (compressing) the specimens, a problem encountered with mechanical gauges.

Three scale ratios of deepest lathe checks to the veneer thickness at the same points, were averaged and recorded as lathe check depth in per cent of thickness. The mean of the above three thickness readings was converted to inches to give the recorded veneer thickness values. Similarly, the average of three scale ratios of summerwood over total growth ring width was calculated as summerwood percentage. Growth ring width was used as a divisor of one inch to obtain the number of annual rings per inch for the veneer sections.

Inclination of lathe checks to the veneer face was measured with a transparent protractor. The recorded values represent the mean of three readings taken to the closest 5°. An inch scale scratched on the straight edge of the protractor facilitated the counting of lathe checks over the central two-inch portion of veneers, from which the average number of lathe checks was calculated. Orientation of growth rings with reference to the veneer face was measured on the cross section (radial angle) and along the grain (longitudinal angle). The latter was intended to serve as a measure of "short grain" - a serious defect in plywoods - which, however, was not entirely eliminated from this experiment. Again, the average of three readings taken to the closest 5° was calculated for every section.

Most weighings were performed on a torsion balance, reading to 0.5 gm (estimated to 0.1 gm). Individual veneer sections were weighed on a semi-micro balance with a sensitivity of 0.01 gm. All nine sections of a strip were weighed before glue spreading and their weights averaged (Ws). One of these was dried at $100 \pm 3^{\circ}C$ for 24 hours to obtain the oven-dry weight (Wo). The average moisture content (M) of the "strip" was determined as:

$$\frac{Ww - Wo}{Wo} \times 100 = M\ (\%).$$

The oven-dried pieces were dipped in paraffin, and the weight of distilled water displaced (Wwo) determined by the standard water immersion method. The average specific gravity of the various veneer strips was calculated from:

$$\frac{Wo}{Wwo} = G$$

Roughness and tightness of rotary cut veneers were also evaluated, after a visual (subjective) inspection under incident light. For purposes of statistical analysis, these classes had been given an arbitrary numerical value, as follows:

Loose side:	(a) rough	-	7
	(b) medium	-	4
	(c) smooth	-	1
Tight side:	(a) tight	-	2
	(b) medium	-	3
	(c) loose	-	4

Measured or calculated veneer variables are presented as block averages in Table II. Sawn veneers should be stronger than rotary-cut samples, due to their larger grain angle, and better (excellent) surface condition, in addition to the lack of lathe checks. A comparison of the other variables indicates a trend in the opposite direction, that would tend to decrease the possible difference in strength properties.

(b) Adhesive

To produce plywood with thicknesses in excess of 4 inches, hot pressing glues and techniques had to be abandoned. Consequently, Duro-Lok 50, with catalyst 42-2300 was selected. This allowed the completion of cold-pressing of all 18 plywood blocks in less than three days. The adhesive was mixed and applied in accordance with the manufacturers' instructions, outlined in Table III.

A small rubber roller glue spreader was used to ensure a uniform glue spread of 50 lb/M ft^2 per double glue line, and to remain within the allowable open assembly time. Dummy veneer sections were used to adjust the spreader to transfer 3.9 gm of adhesive per double glue line. Every second section was spread on both sides. The alternating grain direction was carefully maintained in all blocks. To keep the edges of the plywood blocks properly aligned, at least in two directions, a small L-shaped frame of boards was nailed together. This method facilitated the handling of assemblies as well. The dry weight of adhesive could not be checked at the time of spreading, but was measured later and is listed in Table IV, as per cent of the total weight of the block.

(c) Plywood

The plywood assembly was pressed by a fixed compression head but, in an attempt to ensure a uniform pressure distribution, it was placed on a universal plate. The height of the block, as determined by the movement of the head with reference to a 5-inch high "zero-level", was measured by a dial gauge reading to 0.001 inch. Load readings were taken to the closest 5 pounds.

It was found necessary to adjust the load at 5-minute intervals in the first 20 minutes of pressing time, to maintain (approach) the nominal gluing pressure. The loads were noted before every adjustment. Load recovery was calculated by subtracting the actual load before the first adjustment from that before the second. All values were expressed as a percentage of the nominal load, and are presented in Table IV. It can be seen from the Table that the average gluing pressure asymptotically approached the nominal level during the cycle. Clearly, the water induced different swelling and creep behavior in the two veneer types.

Most likely, lathe checks allowed a release of swelling pressures in the rotary cut veneers. Also, they could have been more plasticized by the water than their sawn counterpart, since moisture movement is facilitated by the lathe checks.

The initial height (thickness) of plywood blocks (Table VI) was determined after applying a 50-pound load to them to flatten the cupped veneers. Following this, dial gauge readings were taken at full pressure, before every adjustment, at the end of the pressing cycle, and after releasing pressure to the initial level of 50 lb. Height measurements were continued daily for seven days after pressing. The blocks were marked at four points and readings were taken by a Starrett height gauge (caliper) to 0.001 inch. The averages of four readings taken at the above points are expressed in per cent of initial height, for ease of comparison, as shown in Table VI. It is also indicated that both full and permanent compressions increased proportionately with gluing pressure in most instances, and that thin veneers were generally compressed more than thick ones.

The average of 200 psi gluing pressure, as indicated in Table IV, resulted in a permanent compression set of 1.99 and 4.29 per cent for the sawn and rotary-cut veneers, respectively. In Table VII it is illustrated that after the pronounced initial swelling (first day) all blocks reached their equilibrium moisture content (EMC) height within 4 to 5 days while being stored in the wood technology laboratory. Veneers were kept in the same room for a month prior to gluing. The same conclusion had been reached by considering changes in weight of blocks, as observed but not shown here.

Specimens were cut from the plywood blocks to determine their moisture content and specific gravity. The method, apparatus and formulae applied were the same as for the veneers. Glue content was calculated as the difference in weight of the assembly prior to gluing and at equilibrium moisture content of blocks, and tabulated as a per cent of the latter weight (Table VIII). The plywood specific gravity was, therefore, expressed in terms of veneer specific gravity to indicate the gross increase in density. By subtracting glue content, converted to percentage of veneer weight, from the gross increase in density, the densification of veneers was obtained. Inspection of Table VIII reveals that plywood blocks of rotary-cut veneers had a higher specific gravity and glue content than those of sawn veneers, and that the latter exhibited a higher degree of densification.

(d) Test specimens

Since the testing of plywood modulus of elasticity perpendicular to glueline has not been standardized, specimen shape and size had to be selected arbitrarily. The main concern was to obtain specimens that ensured a uniform stress distribution, and of a size that allowed the use of the Table Model Instron Testing Instrument available in the wood technology laboratory of the Faculty of Forestry. A constant cross section allowed the first, a small size could fulfil the second restriction. In addition, the plywood had to be of adequate thickness (height) to facilitate accurate strain measurements.

In the preliminary experiment, a 1-in. by 1-in. by 4-in. rectangular specimen had been tentatively selected for both tension and compression. This seemed to be justified by data obtained from twelve 2-in. by 2-in. by 8-in. Douglas fir plywood specimens hot-pressed with phenol-formaldehyde resin (unpublished; Stieda, 1962). However, preliminary specimens prepared by using cold-setting urea resin and cut to the proposed dimensions, did not reach their proportional limit within the capacity of the small testing machine. By reducing the cross section to $\frac{1}{2}$ in. by 1 in., the tension specimens could be tested but not the compression ones. The use of a larger testing machine became necessary to avoid a further decrease in cross section. To reduce the slenderness ratio of the compression specimens, the original 1-in. by 1-in. cross section was retained.

For checking bond quality, three standard plywood shear specimens of three layers were cut out from a section of the plywood block. They were chosen so as to coincide with the failure lines in the tension and/or compression specimens. Another section of the block was assigned for the determination of plywood moisture content and specific gravity.

Results of the preliminary experiment did not indicate a significant difference between the moduli of elasticity in tension and compression. They showed, however, that the variation of strength properties in tension is greater than in compression. It was found that the mean strength value of a plywood block might be kept within the 95 per cent confidence interval by testing 3 compression and 6 tension specimens. This led to the cutting plan depicted in Figure 1. The same pattern was used for all 18 plywood blocks.

5. Testing procedures

The specimens reached and maintained a fairly uniform equilibrium moisture content while stored at the testing machines, as borne out by moisture content determinations at the time of test (Table IV). To minimize testing time, a strain increment of 0.005 in./in./min had been selected for all tests. This resulted in a head movement of 0.025 in./min for compression and 0.01 in./min for tension testing. Since different testing machines were used for the various tests, each set-up requires separate description.

(a) Compression

Compression tests were performed on a hydraulic Baldwin Universal Testing Machine equipped with an automatic X-Y recorder, as shown in Figure 2. Only the lowest range of the machine, that is, 6000 pounds, was utilized. Deformation was measured and transferred to the recorder by a microformer extensometer. Only the central two inches of the specimens were used in measuring deformation, to avoid possible excess compression in the surface layers. The center line of the specimens was marked by pencil and the screws holding the floating rings were positioned on them. A special frame was used in setting up the specimens that ensured a span of two inches between the floating rings. This arrangement is illustrated in Figure 3.

The recorder was adjusted so as to give an easily definable proportional (elastic) limit. The units of the respective axes on the graph represented 0.02 inch of deformation, and 250 pounds of load.

(b) Tension

The screw-gear type Table Model Instron Testing Instrument, complete with a recording unit, was used for tension testing. The machine is shown in Figure 4. For most of the specimens the maximum range, which is 50 kilograms or 110 pounds, was needed. A universal joint - a standard feature on the machine - was thought to ensure a uniform stress distribution. To prevent slippage, serrated tension jaws were used. These were uniformly tightened by means of a torque-wrench set for 65 ft. lb.

The deformation of the specimen over its central two-inch section was automatically recorded by the movement of the cross-bar to which the upper pair of jaws was attached. An advantageous operating characteristic of the machine allowed the jaws to return to the set two-inch span after the completion of each test. Figure 5 depicts a tension specimen in the testing machine. A chart speed of 2 in./min was found to give a load-time curve of sufficient sensitivity.

(c) Shear

A Standard Shear Testing Machine was used to perform the test as set up in the Plywood Section of the Vancouver Laboratory, Forest Products Research Branch. The standard 1-inch by 3-inch shear specimens were tested in the air-dry condition. They were not subjected to any soaking or boiling test because, even without these treatments, the specimens should indicate poor quality bonds, if present. Critical shear area was one square inch; hence ultimate load was recorded directly in psi.

The percentage of wood failure was estimated only after the experimenter "standardized" his judgment by the use of special sets provided by the Forest Products Research Branch for this specific purpose.

6. Results

Methods of calculation are outlined, and results summarized in the following sections.

(a) Computations

Computations were performed on an IBM 1620 electronic computer, utilizing the library programs available for standard statistical techniques. Since the strength properties of plywood blocks made of sawn and of rotary-cut veneers appeared greatly different from one another, they were analysed separately. Thus, regression equations had to be calculated for both veneer types. Also, instead of the 2 by 3 by 3 factorial analysis planned, two separate 3 by 3 analyses of variance were required to be used.

A self-contained Fortran II program was used for obtaining the correlation and regression analysis, with selection and automatic reduction, as programed by Dr. C. Froese in 1962. This program was limited to a maximum of 20 variables at one time. The means, covariances, standard deviations and simple correlation coefficients were printed for each set of data. For each regression analysis, the regression coefficients (B_j), constant term for regression (A), residual variance, and coefficient of determination (R^2) were also printed. The variable contributing the least to the coefficient of determination was omitted, and the analyses repeated until all independent variables had been eliminated. This feature allowed the determination of the most significant factor or factors in an expected 99 per cent of the cases.

Using the results of the above analyses, a simple Fortran II program was written by the experimenter to calculate the adjusted means. The correction was limited to the 11 most important independent variables only, for blocks of both sawn and rotary-cut veneers. To evaluate the role of veneer thickness and gluing pressure on the plywood strength properties, a two-factor analysis of variance with replicates was selected. This self-contained Fortran II program had been written by Dr. A. Kozak in 1962. It was designed to compute the means and summarize sources of variation degrees of freedom, sums of squares, variances, and F-ratios in an analysis of variance table. The analyses were performed for both observed and adjusted plywood strength values.

(b) Multiple regression equations

Firstly, the multiple regression analyses were to establish and evaluate the proposed functional dependence of plywood strength on veneer or plywood variables and their combination. It was found that four to seven significant independent variables could account for most of the variation in plywood strength properties. In some cases, either veneer thickness or gluing pressure and/or both were found unimportant factors. Tables IX and XI list these regression equations for sawn and rotary-cut veneer blocks, respectively. The rank and contribution of the most important variables are summarized in Tables X and XII.

Secondly, the dependence of some plywood variables on independent factors was determined by the use of the multiple regression technique. These factors had also been ranked in accordance with their contribution to the variance of plywood strength properties. The above information is summarized in Tables XIII and XIV.

In addition, regression equations were needed to calculate the adjusted plywood strength values. This time, the three experimentally controlled factors, namely, veneer type, veneer thickness and gluing pressure, were excluded from the independent variables. Their rank and contribution had also been evaluated. Although the means were adjusted for the most important 11 variables, only the first four were summarized in Tables XV and XVI. Lastly, the simple correlation coefficient between veneer thickness or gluing pressure and certain concomitant variables were listed in Tables XVII and XVIII respectively.

(c) Plywood strength values

Block averages were calculated to provide an estimate of plywood strength properties normal to glueline, and to assess the influence of experimentally controlled factors. A summary of observed strength values is given in Table XIX. To obtain a better estimate of the role of these controlled factors, the adjusted strength values were calculated, considerably reducing the effect of concomitant variables. The adjusted means were collected in Table XX. Finally, to facilitate comparisons between observed and adjusted means, sawn and rotary cut blocks, and the different strength properties, various strength ratios were computed and are summarized in Tables XXI, XXII and XXIII. Figures 6 to 9 allow a graphical comparison of strength values, as response surfaces.

(d) Analyses of variance

The analyses of variance were performed on both observed and adjusted values, to test the significance of veneer thickness, gluing pressure and their interaction. Results are summarized in Table XXIV. To focus attention on the highly significant factors only, a separate listing was made in Table XXV.

DISCUSSION

A valid interpretation of results requires a clear understanding of the restrictions associated with the technical and statistical assumptions that constitute the basis of the experiment. The various factors may then be evaluated in compression, tension and shear, with special emphasis on the experimentally controlled variables. Finally, the possibilities of improving future tests should be considered.

1. Validity of assumptions

The technical assumptions have been evaluated by statistical analyses of data. Consequently, the limitations of the statistical methods should be first discussed.

The veneer variables comply to the first assumption of regression analysis, but most of the plywood variables were influenced by the treatments assigned to each block. As a result, regression equations including the latter variables should be less reliable than those based on veneer variables alone. The inclusion of significant interactions in regression equations is a recommended statistical procedure. Some of the plywood variables may be considered as an "interaction" of many independent factors as indicated in Tables XIII and XIV. However, the calculation of adjusted means from regression equations based on plywood variables is bound to remove a part of the treatment effects, thus reducing the sensitivity of subsequent analyses of variance. This applies particularly to adjusted strength values of rotary-cut veneer blocks, where the influence of plywood variables is more pronounced.

The distribution of dependent variables was found to be normal or near normal, with the exception of wood failure percentages. Consequently, no adjusted means were calculated for wood failures. Observed values, however, were analysed to obtain some information concerning the influence of various veneer and plywood variables on them.

Since regression equations hold true on the average only, their fit to extreme values was expected to be poor. This was borne out by the unrealistically low adjusted values for blocks 13 and especially 16 (see Table XX). Presumably, a better regression equation could have been fitted to the strength properties of rotary-cut veneer blocks by excluding the above two experimental units. This might partly account for the fact that the adjusted values of sawn veneer blocks were much more uniform than the rotary-cut veneer blocks.

The assumptions of the analyses of variance were closely approximated. The dependent variables had a normal frequency distribution and the treatments and measurements were randomized. Thus the qualitative results of analyses of variance should be reliable.

The technical assumptions appeared to be justified, with two notable exceptions. Firstly, as might have been expected, the sawn and rotary-cut veneer blocks formed two distinct populations. This necessitated separate analyses for each. As a result, instead of the planned 18 hidden replicates of the factorial design, the analyses were based on 9 only. Since the factorial experiment was performed only once, the results are strictly exploratory in nature. Secondly, gluing pressure was not found to be an important factor in many cases, e.g., compression modulus of elasticity and tension strain for sawn veneer blocks. Inspection of Tables X and XII supports this statement. Further, blocks 13 and especially 16 had a low bond quality, presumably attributable to the inadequacy of the 50 psi gluing pressure used to flatten the slightly cupped veneers. Their influence on analysis was discussed above.

Finally, the existence of functional dependencies $S_i = f(X_j)$, $S_i = f(Y_k)$, $S_i = f(X_j, Y_k)$ and $Y_k = f(X_j)$ have been adequately demonstrated. These accounted for approximately 65 to 94 per cent of the variation in strength of sawn-veneer blocks, and 75 to 98 per cent in rotary-cut veneer blocks. Tables X and XII list these values as coefficients of determination (R^2). It should be noted, however, that about 50 per cent of the variation is unexplained for tension stress, strain and wood failure, also for shear stress of the sawn-veneer blocks.

2. Influence of controlled factors

Since performance of sawn and rotary-cut veneer blocks was highly significantly different, the influence of various factors must be evaluated separately. A combined multiple regression or analysis of variance would have given unrealistic results, being based on the nonexisting "average" strength of blocks combining both veneer types.

Veneer type alone was responsible for a considerably larger variation in plywood strength properties than all the other controlled and concomitant variables combined. An attempt was made to account for its dominant role. The influence of veneer thickness and gluing pressure was evaluated in light of their association with other variables. Only factors exhibiting a simple correlation coefficient (R) of at least 0.40 were considered.

The response surfaces depicted in Figures 6 to 9 illustrate the dominant role of veneer types. Although there is a considerable difference in magnitude of stiffness in compression and tension, or observed and adjusted values, the pattern of response to the controlled factors remains basically the same for each veneer type in all cases.

(a) Veneer type

An attempt will be made to account for the influence of veneer type by using a simple mechanical model. The reliability of this model is evaluated by comparing the various strength ratios within and between observed and adjusted values, or of sawn and rotary-cut veneer blocks. Finally, the possible role of glue is considered briefly along with the reliability of the magnitude of observed values.

An inspection of the list of independent veneer variables measured, reveals the fact that the only physical differences between sawn and rotary-cut veneers are those related to lathe checks and to the quality of surfaces. Consequently, these factors must be responsible for most of the differences in strength properties. The correlations of these and other independent variables obtained for the $S_i = f(X_j)$ type regression equation in tension, are given below.

Factors:	R values:
(1) Depth of lathe checks.	
Veneer thickness	-0.52
Lathe check angle	0.51
Tightness	0.41

(2) Number of lathe checks per inch.

Veneer thickness	-0.75
Lathe check angle	0.52
Specific gravity	0.46

(3) Lathe check angle

Veneer thickness	-0.75
Lathe checks per inch	0.52
Tightness	0.46
Specific gravity	-0.43

(4) Roughness

Lathe check angle	-0.37

(5) Tightness

Lathe check angle	0.46
Lathe check depth	0.41

These variables appear to be highly correlated with each other, but comparatively independent of other physical properties, except for veneer specific gravity. It may be deducted from this, that veneer quality is determined mainly by the peeling process, barring possible degradation in subsequent drying. The extremely high negative correlation observed between veneer thickness and lathe check variables is the logical result of forces acting on wood chips of various thicknesses in the lathe, and in the subsequent flattening of curved veneers. This alone could account for the dominant role of lathe checks in determining plywood strength properties, since the role of ply thickness alone is proven beyond doubt.

The role of roughness and tightness in determining strength is limited. Loose veneers facilitate the penetration of glue, resulting in better mechanical adhesion, and somewhat improved shear resistance. In tension, however, they might be quite detrimental, since they represent a damaged (weakened) wood surface. The loose or crushed surface fibers cannot offer any substantial resistance to tensile forces. Even in compression, these surfaces tend to increase strain, thus reducing stiffness values.

Most of the reduction in strength must be attributed to lathe checks. They may be considered as slots in the veneer, although some of them might be filled and re-bonded by the resin. The fewer, the steeper, the shallower they are, the less they reduce strength. They might not affect ultimate stress in compression, but by increasing the initial deformation, they decrease modulus of elasticity values. After being compressed tight, veneers may assume the strength of solid wood. In tension, the opening of the checks is bound to reduce both strength and stiffness. Even initially, the load must be carried only by the solid sections of veneers. Their resistance is further reduced by the fact that lathe checks obviously facilitate crack propagation at lower loads than solid wood layers. Thus tensile strength properties must be reduced considerably more than those in compression. Shear strength, on the other hand, may be higher as a result of lathe checks filled with glue. Depending on specimen orientation, lathe checks either tend to close or open in shear. The former would obviously result in higher observed stresses than the latter. In the present experiment, however, no attention has been paid to specimen orientation. This might account for the larger range of shear values for the rotary-cut veneers in comparison with the sawn ones.

The validity of the proposed simple mechanical model ("slotted sheet") in explaining the role of lathe checks and surface quality is demonstrated by the magnitude of observed strength values of sawn and rotary-cut veneer blocks. To facilitate a comparison, the appropriate ratios are summarized in Table XXII. It is shown that both veneer types exhibit the same stress in compression on the average, but rotary-cut veneers deform twice as much as the sawn ones. Their stiffness is, accordingly, reduced by a factor of two. The detrimental influence of weakened surface fibers is more pronounced in tension. Consequently, sawn veneers deform 2.2 times and carry loads 3.6 times as much as their rotary-cut counterparts. The former fail gradually, whereas the latter fail by a sudden snap. Due to the larger deformation induced by higher loads the stiffness of sawn veneers exceeds that of rotary-cut ones by a factor of 1.8 only. The estimated wood failure percentages in both tension and shear are almost identical for the two veneer types.

One would expect the adjusted strain values to be identical for both veneer types. This happens to hold for compression tests only. The extremely large difference in tension might be attributed to the influence of variables not accounted for. These amount to approximately 80 per cent for sawn and 40 per cent for rotary-cut veneers. Consequently, the ratios of adjusted tension values might be in considerable error. The compression strength and stiffness values that are both corrected for about 60 per cent of the observed variance might be more comparable. They indicate a tenfold difference between the two veneer types. In addition to the influence of lathe checks, tentatively, most of this should be assigned to the difference in drying schedules and the associated chemical degradation (pyrolysis) and/or surface inactivation. Rotary-cut veneers are supposedly dried at about 400°F. Lathe checks increase the exposed veneer surface manyfold. The sawn veneers, on the other hand, are strips cut out from 2- by 6-inch lumber, unlikely to have been weakened by normal kiln drying. Consequently, sawn veneer blocks should be considerably stronger than rotary-cut ones, especially in tension, when using adjusted values as a basis of comparison. The ratios of approximately 1 to 90 and 1 to 53 for tension stress and strain, respectively, must be considered erroneous.

Comparison of the appropriate strength ratios of adjusted and observed values is facilitated by Table XXIII. It is interesting to note that, while the average ratio for sawn veneer blocks is quite high, that for rotary-cut veneers approaches unity. Thus it is demonstrated that for the latter group, the influences of various factors tend to cancel each other. Trying to adjust for them does not alter the "status quo" of strength properties.

The various strength ratios calculated separately within each veneer type should be identical, because the mean of the nine blocks in all strength properties should be influenced by the various factors to approximately the same degree. The ratios of adjusted strength values of sawn veneer blocks are expected to be in error, since they had been modified to various degrees of accuracy. The adjusted values of rotary-cut veneer blocks should be comparable since almost all the strength properties are adjusted by about 60 per cent of the variance. The above assumptions are more or less borne out by the ratios of mean values, as listed in Table XXI. The agreement between the ratios of observed values of the two veneer types is quite good. The degree of correspondence among the ratios of observed and adjusted strength values of the rotary-cut veneer blocks is satisfactory. The irregular pattern of adjusted values of sawn-veneer blocks is not surprising.

The compression to tension stress ratio for Douglas fir is 2.05 from Canadian and 2.56 from U.S. data, as given in Table I. The observed ratio for sawn-veneer blocks is 2.54. The good agreement suggests the use of ratios obtained for the sawn-veneer blocks as a control for that of rotary-cut veneers. It should be noted, however, that the veneer strength values observed are only half of that published for solid wood. This calls to attention the possible role of drying techniques, glue, chemistry of adhesion, and specimen geometry. These are to be discussed later.

The compression to tension stress ratio for rotary-cut veneer blocks was 8.59. Almost all of this fourfold increase must be attributed to a corresponding reduction in tensile stress, since the two compression values have a ratio of 1.06. There is, however, no way of estimating from the experimental data how much of the reduction is assignable to loose fibers, lathe checks, chemical degradation or other causes. The strain ratio also exhibits a fourfold increase. This corresponds to only a twofold increase in strain of rotary-cut veneers, since the two compression values have a ratio of 0.52. The moduli of elasticity are fairly close because of the proportional increase in both stress and strain. They are 7.05 and 6.21 for sawn and rotary-cut veneer blocks, respectively. The strength ratios comparing modulus of elasticity, unit stress, and unit strain to shear stress are 913 and 681, 1.74 and 2.45, 0.68 and 0.29, respectively, for the two veneer types. Similar ratios might be used to predict plywood strength properties from any, arbitrarily chosen, single measured strength value.

Although the evaluation of glue is not one of the objectives of the experiment, it cannot be completely ignored. A detailed discussion of it is not warranted either since the bonds were satisfactory, i.e., not directly critical in determining strength. Blocks 13 and 16 were the exceptions to the rule. This may be attributed to the inadequacy of the low gluing pressure used to flatten the thick veneers, to wet the surfaces.

Only factors detrimental to veneer strength should be considered, since wood failure was high even at low tension stresses. Firstly, the solidification of polyvinyl resins is accompanied by loss of water resulting in wood expansion and glue contraction, followed by restricted shrinkage of plies. The resulting stresses may damage the veneers. Rate of solidification, as shown by the importance of weight loss in press in this experiment, also strongly influences strength properties. This, in turn, is partly determined by the relative humidity of air, ambient temperature, and veneer moisture content at the time of pressing and curing. This might be responsible for the important role of veneer moisture content in the experiment.

Finally, strongly alkaline or acidic glues may weaken wood surface by hydrolysis. Thus, the acid catalyst used may be responsible for the relatively high wood failure observed even at low tension stresses. Weakening of surface fibers is also augmented by pyrolysis resulting from high temperature or excessive drying. A corollary of the latter is the formation of chemically inactivated surfaces, covered by a molecular layer of fatty acids. This prevents wetting and results in possible localised, poor bond quality. The influence of the latter two factors is negligible, if any, for the sawn-veneers. Since the "exposed" surface of rotary-cut veneers exceeds that of sawn ones many times, due to the presence of lathe checks, the fourfold decrease in tensile stress might be attributed to the effect of these chemical factors. The tentative nature of this proposal should be emphasized, since there was no attempt made to measure or evaluate experimentally any of the possible chemical factors. As mentioned above, tension tests are much more sensitive to the condition of veneer surfaces than compression or even shear. Indeed, tension stress normal to glueline appears to be the most sensitive single measure of bond quality.

It has been shown that polyvinyl acetate makes stronger bonds with birch wood than does casein. The latter, in turn, is stronger than urea glues. Stronger bonds are made with gaboon using phenolic resins than using animal glues or urea resins. The preliminary blocks prepared by using cold-setting urea exhibited moduli of elasticity ranges of 30,000 to 40,000 psi, in both tension and compression normal to glueline. A small series of bearing tests performed by the writer for the Plywood Manufacturer's Association of British Columbia in 1964, using industrially produced exterior grade (hot-press phenol-formaldehyde resin) Douglas fir plywood, indicated values of 20,000 to 40,000 psi range. These values are based on a limited number of specimens, thus are far from conclusive. The observed experimental values for rotary-cut veneer blocks glued with Duro-Lok 50 range from 11,000 to 27,000 psi and 85,000 to 154,000 psi in tension and compression, respectively. Thus it may be tentatively proposed that this glue produces plywoods slightly inferior in stiffness to urea-bonded panels in tension, and considerably superior to them in compression normal to glueline.

As long as the influence of ply number, size of critical section and specimen geometry are not known, these experimental values may serve only to evaluate the influence of the various factors. Further, the experiment was planned to be a pilot study only in a much neglected field. Thus, the factorial design was not replicated. The conclusions drawn are tentative in nature. The general value of the specific mean strength values observed is open to question and needs further experimental evidence.

(b) Veneer thickness

Inspection of Tables XXIV and XXV reveals that all plywood strength properties normal to glueline of both veneer types were highly significantly affected by the thickness of plies. The interactions of the two controlled factors of veneer thickness and gluing pressure were also highly significant, with the exception of tension strain and wood failure. It should be noted that the analyses of variance performed to evaluate the influence of the above two controlled factors, using both observed and adjusted plywood strength values, provided almost identical results. Under the experimental conditions, blocks of 1/7-inch thick veneers yielded the highest strength values on the average, closely followed by 1/10-inch, and considerably trailed by 1/5-inch thick sheets. This can be easily verified for stiffness by a simple inspection of Figures 6 to 9.

It has already been shown on pages 35 and 36 that ply thickness is highly correlated with lathe check depth, angle, and number per inch. This alone could explain the role of veneer thickness in determining strength properties of rotary-cut veneer blocks. In addition, ply thickness is closely associated with a host of concomitant variables, as shown in Table XVII, which significantly influence the various plywood strength properties. Generally, the same factors were correlated with thickness in both veneer types, although their rank was different. Rotary-cut veneers were associated with more variables.

The high negative correlation coefficients observed support common-sense assumptions that with increasing veneer thickness the proportion of glue and the number of plies to reach a given block height is smaller. Permanent (plastic) deformation is reduced also, since the highly plasticized boundary layers constitute a smaller percentage of the total thickness in blocks of thick veneers. The cores of these plies might retain their air-dry stiffness in the press, resulting in a decreased full compression also. Apparently, the moisture content of thin veneers was higher than that of thick ones, consequently their load recovery in press was lower too.

Radial grain angle was positively correlated with ply thickness and appeared to be of consequence in tension and rolling shear. By chance, higher specific gravities were associated with increasing veneer thicknesses. In summary, veneer thickness might either be considered as an interaction term of all these variables, or as the best single measure of glue content, number of plies, plywood specific gravity and plastic deformation.

(c) Gluing pressure

Both the compressive and tensile strength properties of rotary-cut veneer, and the former only of sawn-veneer blocks, were highly significantly influenced by gluing pressure, as shown in Tables XXIV and XXV. Rolling shear strength appeared to be highly significantly affected by gluing pressure alone. Optimum results were obtained by using 200 psi gluing pressure. The next in rank was 350 psi. For the thick veneers used in this experiment, presumably due to their cupping, 50 psi pressure was found to be inadequate. The analysis of variance, with few exceptions, indicated that gluing pressure contributed less to the variation in strength than did veneer thickness. Again, Figures 6 to 9 illustrate these statements graphically for the moduli of elasticity.

It is shown in Table XVIII that gluing pressure was associated with fewer concomitant variables than veneer thickness. Also, the simple correlation coefficients are lower. Further, the variables differ more markedly in kind and order between test and veneer types than was observed for ply thickness. It might be attributed to the fact that these factors are mostly rheological in nature, thus are dependent on a large number of veneer and/or plywood variables in turn. Another possibility is that these factors cancel each other's influence, making gluing pressure comparatively unimportant.

Larger pressure itself causes an increased full and permanent compression, resulting in a higher degree of veneer densification. It also forces more liquid into the veneers which facilitates plastic deformation farther, thus contributing to a faster decay of pressure (load). Correlation of gluing pressure with summerwood percentage and radial grain angle (for shear) might be considered spurious. The different pattern of weight loss indicated for the two veneer types, must be associated with the higher degree of glue squeeze-out observed on sawn-veneer blocks.

The lathe checks would allow more glue to be retained in the plies and at the same time ameliorate the movement of water, especially under high gluing pressures, which is the by-product of curing polyvinyl resin emulsions. Sawn-veneer blocks, on the other hand, increased their weight loss under lower pressures.In this way, less liquid was forced into the solid plies that hinder moisture movement, compared to the rate of evaporation from the free surfaces of squeezed out (excess) glue. This phenomenon was also responsible for the higher glue content of rotary-cut veneer blocks, in spite of using the same nominal glue spread for both veneer types. In conclusion, gluing pressure might be considered as the best single measure of full compression, plastic deformation, and veneer densification, or as an interaction term of the factors discussed above.

3. Influence of concomitant variables

The use of veneer variables alone accounted for the least, but a quite substantial part of the variation in plywood strength properties. Plywood variables in general explained more. A combination of the most important factors might account for almost all of the variance, particularly for rotary-cut veneer blocks. (See Table XII) The proportion of the variance accounted for by the sawn-veneer blocks was somewhat smaller. (See Table X) Appropriate regression equations, consisting of four to seven terms, were tabulated with their multiple coefficient of determination. (See Tables IX and XI.)

In the following discussion, the above four tables will be referred to exclusively. As an additional restriction, only the $S_i = f\ (X_j, Y_k)$ type regression equations will be considered. The simple correlation coefficients are not summarized in tables, but will be given in the text, when mentioned. The two veneer types have to be discussed separately within each test group, because the variables and/or their rank differs markedly. Modulus of elasticity is defined as the ratio of unit stress to unit strain at or below the proportional limit. Consequently, variables influencing stress and strain will be considered before discussing stiffness in some detail.

(a) In compression

(i) Sawn-veneer blocks

The most important 17 variables selected accounted for 91.43 per cent of the variation in unit stress (Table X). Load recovery, as measured in the press, was responsible for 20.22 per cent of the variance. This implies that the rheological (flow) characteristics of plywood play an important role in determining its strength, even below the proportional limit. The second most important variable, compression at full load, underlines the previous statement. These two factors explained 36.28 per cent of the total variation in strength. They were followed by less important variables, such as growth rate (rings per inch), permeability (number of days necessary to reach an equilibrium moisture content), plastic deformation (permanent compression), and glue content of the plywood. Combined, they were responsible for 85.59 per cent of the variance.

Most of the variation in unit strain, 94.28 per cent, was accounted for by the 17 independent variables used. It is suggested that strain values are much more sensitive than stress to rheological properties, since load recovery alone was responsible for 47.89 per cent of the variance. An additional 29.75 per cent was gained by including veneer moisture content at time of gluing, veneer thickness (squared), weight loss in pressing, and permeability. The preponderance of these chemico-rheological factors on strain implies that the veneers must have been considerably modified (plasticized) during the preparation of plywood blocks.

The 17 most important variables accounted for 94.30 per cent of the variation in the modulus of elasticity values. Of this, 25.44 per cent may be attributed to veneer moisture content. The simplest assumption is that veneer moisture content increased plasticity, whereas a larger number of rings per inch reduced it. More likely, the influence of the former was mainly due to its effect on rate of glue setting, since drier veneers take up water faster than wet ones. Increasing veneer thickness affected stiffness in the same manner as growth rate. Both increased the total amount of stiffer latewood in the plies. The above three factors explained 65.70 per cent of the variance. Adding weight loss to the list raised the percentage by almost 10 per cent. It appears from the experiment that the larger the moisture retentive capacity of the blocks, the stiffer they are. The explanation is proposed that weight loss may be considered as a measure of latewood proportion, since moisture movement is less hindered in earlywood than in latewood of conifers.

The next independent variable in importance, magnitude of full compression, is an obvious measure of plywood stiffness. It adds only 1.75 per cent to the variance, however. Finally, it is indicated that the orientation of latewood zones is also important in determining modulus of elasticity. This raises the proportion of the variance accounted for only slightly, to 77.13 per cent. Curiously, gluing pressure was not among the six most important factors affecting plywood stiffness.

The <u>simple correlation coefficients</u> between stiffness, stress and strain are 0.29, -0.68, and 0.47, respectively. Thus, increase in modulus of elasticity is associated with increasing unit stress in one third, and decreasing unit strain in two-thirds of the cases. In addition, an increasing strain is related to increasing stress in about half of the specimens. These findings emphasize the role of strain in determining plywood strength properties normal to glueline. Deformation appeared to take place in the soft, earlywood zones as expected. Thus, the experiment provided evidence for the critical role of earlywood in connection with the strain failure theory of plywoods (James, 1962).

The correlation of strength properties and controlled factors as indicated by R values is tabulated below:

	Modulus of elasticity	Unit stress	Unit strain
Veneer thickness	-0.22	0.07	0.33
Gluing pressure	-0.16	0.34	0.32

Possibly, due to their larger influence on strain, an increase in the level of controlled factors tends to lower the modulus of elasticity of sawn-veneer blocks.

(ii) Rotary-cut veneer blocks

The 17 variables selected accounted for 95.43 per cent of the variation in <u>unit stress</u> (Table XII). Of this, 25.50 per cent was attributable to growth rate, illustrating that above all the total amount of latewood in the veneers influenced strength. Plywood specific gravity ranked second in importance. These two variables explained 36.45 per cent of the variance. Moisture content of veneers at the time of gluing ranked behind them, followed by longitudinal grain angle, plywood moisture content at the time of testing, and thickness of plies. A total of 76.24 per cent of the variation in strength may be attributed to the independent factors listed above. The pronounced effect of veneer variables on plywood strength should be noted here.

For <u>unit strain</u>, 93.24 per cent of the variance was explained by the 17 independent variables. Plywood specific gravity (squared) alone was responsible for 77.56 per cent. Apparently, the strain resistance of rotary-cut veneers when incorporated into plywood is almost solely determined by their density. It is of interest that specific gravity assumed its "traditional" importance for rotary-cut veneers, whereas its influence on sawn ones was negligible. Its role might be due to the restrictive influence of latewood on lathe checks, or on compression damage to veneer surface (Collins, 1960). Density and plywood moisture content were responsible for 85.69 per cent of the variance. Thus, strain could be predicted from these two factors. The inclusion of glue content, load recovery, growth rate and permeability added only 3 per cent to the variance.

The 17 most important variables selected were responsible for 94.41 per cent of the total variation in the modulus of elasticity values. Of this, 38.03 per cent may be attributed to the glue content of plywoods. It appears that glue penetration in lathe checks reinforced veneer surfaces, i.e., resulted in a possibly thicker boundary layer. The significance of radial grain orientation was indicated by the fact that it ranked second. Logically, it is followed by the (squared) latewood percentage due to their close association. Plywood stiffness is bound to increase with a larger portion of strong latewood present, especially if the growth rings are oriented nearly perpendicular to the gluelines. Contribution of the above variables amounted to 60.50 per cent of the variance. The significance of longitudinal grain orientation and roughness is also indicated. Their inclusion brings the portion of the variation accounted for to 61.67 per cent. Veneer thickness and gluing pressure seem to influence plywood modulus of elasticity only indirectly.

For the rotary-cut veneer blocks in compression, the simple correlation coefficients between stiffness, stress, and strain were 0.45, -0.59, and 0.38. Thus, increase in stress resulted in higher stiffness values in almost half, and a decrease in strain in more than half of the specimens.

In addition, increasing strains were associated with higher stresses in about one third of the cases. Again, the strain failure theory of wood seems to be in evidence.

The correlation of strength properties and controlled factors is summarized below:

	Modulus of elasticity	Unit stress	Unit strain
Veneer thickness	-0.68	0.03	0.73
Gluing pressure	0.47	0.83	0.13

These coefficients indicate that increase in veneer thickness causes a decrease in modulus of elasticity because it is associated with a large increase in strain and a practically unchanged average stress. On the other hand, a larger gluing pressure increased strength considerably more than deformation. Consequently, the stiffness ratio rises with higher levels of the latter factor. It should also be noted that gluing pressure seems to be a good measure of unit stress, and veneer thickness of unit strain, respectively.

(b) In tension

(i) Sawn-veneer blocks

For wood failure percentage the 16 selected independent variables accounted for 48.93 per cent of the variance (Table X). Gluing pressure (squared) alone explained 25.34 per cent. Its importance must be interpreted through its correlation with other factors. The conclusion may be drawn, however, that rheological phenomena play a dominant role in determining the ultimate strength of plywood. This is underlined by the fact that the next most important variables, namely, weight loss in press, plywood specific gravity (squared), and number of days needed to reach an equilibrium moisture content, are all influenced by the manufacturing process. Together they were responsible for 44.66 per cent of the total variation. The inclusion of both squared and observed values of gluing pressure among the six most important factors, suggested the existence of an optimum pressure level. The low value of the coefficient of determination suggests that the analysis failed to include a number of important factors influencing wood failure. For instance, nothing is known here of the distribution of microscopic failure or slip planes and/or the possible stress concentrations resulting from the small bending moments in the grips, or the role of restricted swelling in press.

Only 40.57 per cent of the total variation in unit stress was explained by the 16 variables chosen. Apparently, the magnitude of permanent (plastic) deformation is the most important single factor, although it is responsible for only 6.61 per cent of the variance. Combined with the related gluing pressure and veneer densification, the three variables account for 28.40 per cent. Plywood moisture content at time of testing and load recovery add another 7 per cent. With the inclusion of summerwood percnetage, 36.01 per cent of the variance can be accounted for. The importance and inadequacy of rheological characteristics in explaining strength properties may be called to attention.

The 16 variables selected were responsible for only 41.73 per cent of the variation in unit strain. Plastic deformation (squared) explained 8.46 per cent of the variance. Combined with gluing pressure (squared), they accounted for 26.44 per cent. Next in rank were permeability and the related weight loss in press (curing rate), plywood moisture content, and summerwood percentage. Their additional contribution amounted to 10.38 per cent. Repeatedly, the role of rheological factors should be noted.

Most of the variation in modulus of elasticity, 76.58 per cent, was accounted for by the 16 independent variables chosen. For the regression analysis in tension, the main factors influencing stiffness were selected. These were not necessarily the most important variables for the other strength properties. This might explain the low coefficients of correlation encountered previously. Specific gravity (squared) alone was responsible for 29.26 per cent of the variation. Surprisingly, stiffness was the only strength property of sawn-veneer blocks dominated by plywood density. Its influence, however, was contrary to the expected pattern. Inspection of data reveals that 1/10-inch thick veneer blocks possessed the lowest density and the highest modulus of elasticity values. The effect of other factors, e.g., glue content, was such that it overrode the relatively small influence of density. This resulted in the multiple regression analysis predicting increasing stiffness for decreasing specific gravity. Obviously, this is a spurious relationship. An increase in the number of experimental units might have eliminated it.

The variable second in rank, weight loss in press, adds 10.86 per cent to the portion of variance accounted for. It may be considered as a measure of the rate of glue solidification. Surprisingly, an increase in curing rate reduces stiffness. By adding load recovery to the regression equation, 60.77 per cent of the variance may be explained. The less a plywood block creeps under pressure the stiffer it is. This factor indicates the importance of rheological properties even under the proportional limit, where their role is assumed to be negligible in short-time tests. Slower growth rate reduces stiffness, as indicated by the regression equation. This accounts for another 5.66 per cent of the variation.

Permanent compression (squared) raises the percentage to 72.68. It seems logical that the amount of plastic deformation is inversely proportional to the stiffness of plywood. Finally, permanent compression brings the variation accounted for to 74.55 per cent. From the presence of the last two factors, the existence of an optimum degree of plastic deformation may be deduced. Modulus of elasticity does not seem to be directly influenced by either veneer thickness or gluing pressure.

For the sawn-veneer blocks in tension, the simple correlation coefficients between modulus of elasticity, unit stress, and unit strain are 0.19, -0.11, and 0.95. Thus, an increase in stiffness is associated with an increase of stress in 19, and a decrease of strain in 11 per cent of the cases. On the other hand, high strain values seem to be an attribute of strong specimens. The correlation of wood failure percentage to the above strength properties, in their previous order, is measured by the following R-values: 0.19, 0.29, and 0.26. Thus, tension wood failure is an inadequate measure of stiffness, stress, or strain.

The correlation of strength properties and controlled factors is summarized below:

	Modulus of elasticity	Unit stress	Unit strain	Wood failure
Veneer thickness	-0.46	0.16	0.29	-0.35
Gluing pressure	-0.13	0.10	0.15	0.18

Inspection of these values clarifies why the analyses of variance indicate veneer thickness as highly significant for all strength properties, compared to the non-significance of gluing pressure. Again, due to their larger influence on strain, the highest level of both factors tends to reduce the stiffness. It may be noted that thickness of plies is apparently a better indicator of plywood stiffness than is wood failure. Also, measurement of thickness is non-destructive, whereas that of wood failure is destructive.

(ii) Rotary-cut veneer blocks

The 16 independent variables selected account for 93.85 per cent of the variation in <u>wood failure percentages</u> (Table XII). The most important single factor, veneer thickness (squared), explained 10.22 per cent of the variance. It appears that increasing veneer thickness results in reducing wood failure percentages. Inclusion of veneer densification in the regression equation raises the portion of variance accounted for to 47.44 per cent. The above variables are followed by roughness, plywood specific gravity (squared), permeability, and summerwood percentage. Their combined contribution to total variation amounts to 80.45 per cent. Wood failure appears to be influenced mainly by veneer variables, as expected.

Most of the variation in <u>unit stress</u>, 95.18 per cent, is accounted for by the 16 variables selected. Apparently, veneer thickness (squared) is the best single measure of plywood strength, since it explains 55.83 per cent of the variance. It clearly indicates that veneer strength must be the limiting factor in determining the magnitude of stress normal to glueline. The combination of veneer thickness with weight loss in press is responsible for 82.35 per cent of the variance. Inclusion of the factors of permeability, gluing pressure, plywood specific gravity (squared), and proportion of latewood, increased the portion of variance accounted for to 90.89 per cent.

Most of the variation in unit strain, 81.12 per cent, may be accounted for by the 16 independent variables. Veneer thickness (squared) alone explained 53.68 per cent of the variance. Coupled with a measure of curing rate, they are responsible for 67.55 per cent. This percentage is increased to 74.77 per cent by the addition of gluing pressure. The inclusion of plywood specific gravity (squared), veneer tightness, and percentage of latewood in the regression equation raised the portion of the variance accounted for to 76.44 per cent.

The 16 independent variables accounted for 98.00 per cent, i.e., almost all, of the variation in modulus of elasticity. Again, veneer thickness appeared to be the most important single factor, being responsible for 55.87 per cent of the variance. This seems to imply that stiffness is mainly determined by veneer variables. Combined with plywood moisture content, they explain 74.05 per cent of the variation. As expected, increasing moisture contents reduce modulus of elasticity by increasing the plasticity of veneers. Plywood from thin veneers, through their higher glue and slightly lower moisture contents, exhibit more stiffness than blocks of thick plies. Inclusion of plywood specific gravity explained only an additional 1.50 per cent of the variation. Its negative effect must be due to the fact that specimens of the lowest density exhibit the highest strength and stiffness. This results from the combined influence of a multitude of factors, whose net effect overrides that of specific gravity alone. The variable next in rank, gluing pressure, contributed 16.41 per cent to the variance. An increase in pressure seemed to result in higher stiffness, as would be expected. Since higher pressures are accompanied by larger full compression, an increase in the latter must result in higher modulus of elasticity also. Lastly, it is indicated by the multiple regression equation that a decrease in summerwood percentage reduced stiffness. The combined effect of the above independent variables accounted for 93.99 per cent of the variance. Repeatedly for tension specimens, both controlled factors are included among the four most significant variables.

For the rotary-cut veneer blocks in tension, the <u>simple correlation coefficients</u> are 0.93, 0.76, and 0.91. These figures suggest that an increase in stiffness is almost always associated with higher strength, and less regularly, with larger deformation. Furthermore, high strain values seem to be an attribute of strong specimens. The association of wood failure percentage with the above strength properties, in their previous order, is estimated by the following correlation coefficients: 0.56, 0.53, and 0.54. This suggests that an increase in strength properties induces a correspondingly higher wood failure in more than half of the specimens. Thus, wood failure percentage might be considered as a rough indicator of plywood strength properties, for the rotary-cut veneer blocks.

The correlation of strength properties and controlled factors are as follows:

	Modulus of elasticity	Unit stress	Unit strain	Wood failure
Veneer thickness	-0.75	-0.74	-0.73	-0.32
Gluing pressure	0.29	0.36	0.41	0.60

These values illustrate the dominant role of veneer thickness. Thickness indicates a trend in three-quarters of the cases observed, thus might be accepted as the simplest and a reasonably consistent plywood strength indicator, for the experimental data at least. The lesser, but still highly significant, association of gluing pressure and strength properties is shown. It is odd that an increase in thickness tends to reduce wood failure, whereas an increase in pressure tends to augment it. This might be a spurious relationship, or the result of stress reversal on veneer behavior, or a phenomenon associated with glue penetration and its effects.

(c) In shear

(i) Sawn-veneer blocks

For wood failure percentage, 68.93 per cent of the variance was explained by the 18 factors chosen (Table X). Summerwood percentage (squared) alone was responsible for 33.95 per cent of the variation. Increasing latewood proportions seemed to reduce wood failure as expected. Coupled with veneer thickness, it accounted for 40.81 per cent. Addition of gluing pressure and full compression raised this to 48.17 per cent. The next two variables, namely, veneer moisture content and load recovery contributed only 0.44 per cent to the variance.

The 18 independent variables accounted for only 56.67 per cent of the total variation in shear stress. Longitudinal grain orientation appeared to be the most important single factor, explaining 11.99 per cent of the variance. A steeper angle increased the number of strong latewood zones to be sheared, resulting in higher stress or failure. A decrease in thickness, perhaps through its relation with glue content and density, increased shear resistance. These two variables are responsible for 23.38 per cent of the variance. Veneer specific gravity, as expected, is important, bringing the portion of variance accounted for to 33.95 per cent. Decreasing plywood moisture content increased resistance to shear stresses, and added another 6.75 per cent to the variance. The role of radial grain angle was similar to that of longitudinal grain orientation, its contribution amounting to 8.13 per cent. Full compression, perhaps through its association with increase in density, influenced shear stress positively. These factors accounted for 49.37 per cent of the variance. Gluing pressure was not among the six most important variables.

The simple correlation coefficient between shear stress and wood failure percentage is 0.54. Thus, an increase in stress is associated with higher wood failure values in slightly more than half of the cases. Therefore, wood failure may be considered only as a very rough estimation of shear stress.

Degree of correlation between strength properties and controlled factors is indicated below:

	Unit stress	Wood failure
Veneer thickness	-0.30	-0.43
Gluing pressure	0.18	0.35

It seems contradictory that increase in veneer thickness reduces wood failure, while increasing the proportion of wood in the block. This may be attributed to the net effect of factors associated with veneer thickness.

(ii) Rotary-cut veneer blocks

Most of the variation in wood failure percentage, 94.01 per cent (Table XII), could be accounted for by the 18 independent variables. Veneer moisture content alone explained 27.90 per cent and, coupled with glue content, they were responsible for 39.66 per cent of the variance. Higher values of both increased the magnitude of the dependent variables. The other variables are veneer densification (squared), permanent compression (squared), lathe check depth and veneer roughness, in order of importance. Together, they accounted for 78.70 per cent of the variance.

The 18 independent variables were responsible for 87.61 per cent of the variation in shear stress. Of this, 45.39 per cent was explained by veneer moisture content alone. As a general rule, increasing moisture content reduces strength. It is known for shear stress, however, that it reaches an optimum when glued in the moisture content range of 8 to 12 per cent, according to Lewis and co-workers (1945). The experimental range was only 7.3 to 9.3 per cent. Thus, an increase in moisture should improve shear strength, to conform with the expected pattern. Larger gluing pressures, probably by facilitating glue penetration, result in higher stress values. Their contribution to the variance is a further 13.18 per cent. Inclusion of the variable next in rank, i.e., glue content, increased the portion of the variable accounted for to 64.19 per cent. Apparently, the more glue a plywood contained, the stronger it was in shear The total contribution of radial grain orientation and roughness of veneers was only 4.07 per cent. From the regression equation it may be deduced that an increase in latewood surfaces bonded and rougher veneers, improve shear strength. Finally, lathe check depth was shown to be a detrimental factor. The above variables accounted for 71.51 per cent of the variance. Veneer thickness was not one of them.

The simple correlation coefficient between shear stress and wood failure is 0.76. In approximately three-quarters of the specimens, higher wood failures coincided with higher strength. This seems to justify the use of percentage wood failure as a simple and fairly consistent measure of glue bond quality, for rotary-cut veneers.

Correlation of strength properties and controlled factors is tabulated below:

	Unit stress	Wood failure
Veneer thickness	-0.36	-0.41
Gluing pressure (squared)	0.67	0.51

The indicated reduction in wood failure, accompanied by increasing veneer thicknesses, is contrary to the expected trend. It may be attributed to the net effect of factors associated with veneer thickness.

CONCLUSIONS

(1) The most important single factor influencing all plywood strength properties normal to glueline, and standard plywood glue shear test, was veneer type. The dominant role of this factor is attributed to the effect of lathe checks and surface quality. Both appear to be determined mainly by the techniques of veneer preparation which alter the mechanical and chemical (surface reactivity) properties of wood. Also, both are highly correlated with veneer thickness.

(2) The analyses of variance performed to evaluate the influence of veneer thickness and gluing pressure, using both observed and adjusted strength values, provided almost identical results.

Apparently, the influence of controlled factors was independently superimposed upon the effect of concomitant variables. Removal of the latter altered (increased) the absolute value of strength properties, but hardly changed the pattern of response.

(3) Veneer thickness affected all plywood strength properties normal to glueline of both veneer types highly significantly.

The importance of veneer thickness may be attributed to its high correlation with a number of independent variables. These include glue content, number of plies, plywood specific gravity, and plastic deformation.

(4) Both the compressive and tensile strength properties of rotary-cut veneer, and the former only of sawn-veneer blocks, were highly significantly influenced by gluing pressure. This factor affected rolling shear strength similarly.

The role of gluing pressure may result from its close association with other independent variables, such as compression at full load, plastic deformation, and veneer densification.

(5) The interaction of veneer thickness and gluing pressure was also highly significant for all plywood strength properties with the exception of tension strain and wood failure.

This may be attributed largely to the peculiar strength pattern observed on blocks of 1/5-inch thick veneers, particularly the rotary-cut ones.

(6) In addition to the three controlled factors, i.e., veneer type, veneer thickness, and gluing pressure, the following independent variables appeared to influence variation in plywood strength properties most.

Sawn-veneer blocks:	Rotary-cut veneer blocks:
Veneer moisture content	Veneer moisture content
Summerwood percentage	Summerwood percentage
Growth rate	Growth rate
Longitudinal grain angle	Radial grain angle
Veneer densification	Tightness of cut
Permeability	Veneer densification
Rate of cure (weight loss)	Permeability
Full compression	Rate of cure (weight loss)
Load recovery in press	Glue content
Plastic deformation	Plywood moisture content
Plywood specific gravity	Plywood specific gravity

The use of veneer variables alone accounted for the least, but a quite substantial part of the variation in plywood strength properties. Plywood variables usually explained more. A combination of the most important factors accounted for almost all of the variance, particularly for rotary-cut veneer blocks.

(7) The average compressive strengths of sawn and rotary-cut veneer blocks were practically the same. They amounted to approximately half that for solid Douglas fir wood.

Apparently, compression strength normal to glueline was hardly influenced by the lathe checks. The difference between plywood and solid wood may then be attributed to different specimen geometries, moisture contents, suspected acid hydrolysis at the gluelines, and/or other causes.

(8) The average tensile strength of sawn-veneer blocks was half that for solid wood, and exceeded that of rotary-cut veneer blocks 3.5 times.

The large differences in tensile strength values of sawn and rotary-cut veneer blocks must result from weakened (mechanically and chemically) surface fibers, since bond quality was acceptable as indicated by the high wood failure percentages. Thus, tension normal to glueline seems to be the best measure of bond quality.

(9) The average rolling shear stress of sawn-veneer exceeded that of rotary-cut veneer blocks by about 1.5.

It is suggested that the reduction in rolling shear resistance attributable to the mechanical effect of lathe checks was comparatively small and/or partly countered by the adhesive penetrating into them. The latter was more pronounced for blocks prepared under high gluing pressure.

It was also found that the standard plywood glue shear test may be accepted as a rough indicator of plywood strength properties (normal to glueline) for rotary-cut, but not for sawn veneers.

(10) The moduli of elasticity of sawn-veneer exceeded those of rotary-cut veneer blocks by approximately two times. Plywoods of rotary-cut veneers deformed half as much in compression and twice as much in tension as those of sawn veneers, before reaching their respective proportional limits.

(11) Under the experimental conditions, 1/7 inch, closely followed by 1/10 inch, and 200 psi appeared to be the optimum levels of veneer thickness and gluing pressure, respectively.

Consequently, the strongest (normal to glueline) Douglas fir plywood panels, glued with the room-temperature setting Duro-Lok 50 would be obtained by using veneer thicknesses of 1/7 or 1/10 inch at 200 psi gluing pressure. Rolling shear strength could be improved by employing higher gluing pressures.

The need for precisely controlled manufacturing processes, that would result in improved plywood strength values, is implied by the dominant role of the techniques of preparation in this experiment, as indicated by their best single measure: veneer type.

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TABLES AND FIGURES

TABLE I. AVERAGE STRENGTH VALUES OF SMALL CLEAR SPECIMENS OF COAST-TYPE DOUGLAS FIRWOOD IN AIR-DRY CONDITION

	Canada	U.S.
Specific gravity (basic):	0.49	0.48
Volumetric shrinkage (%)	5.3	-
Stresses parallel to grain:		
Static bending (tension)		
Stress at proportional limit (psi) ..	7,700	7,800
Modulus of elasticity (1000 psi)	1,980	1,950
Compression		
Stress at proportional limit (psi) ..	4,830	5,850
Modulus of elasticity (1000 psi)	1,950	1,950
Stresses perpendicular to grain:		
Tension: maximum stress		
Radial plane (psi)	420	340
Tangential plane (psi)	470	-
Compression		
Stress at proportional limit (psi) ..	860	870
Cleavage:		
Radial plane (lb/in.)	1,430	
Tangential plane (lb/in.)	1,370	

TABLE II. SUMMARY OF VENEER VARIABLES PER PLYWOOD BLOCKS

Type	Block No.	Thickness (in.) X2	Rings per in. X3	Summer-wood % X4	Specific gravity X5	Moisture content % X6	Lathe check Depth (%) X7	Lathe check No./in. X8	Lathe check Angle (o) X9	Grain orientation Radial (o) X10	Grain orientation Longitud. (o) X11	Rough-ness X12	Tight-ness X13
Sawn veneers	1	.1149	34	32.9	.446	8.4				6.0	.2	1	2
	2	.1011	24	31.6	.441	7.3				11.3	1.3	1	2
	3	.1011	32	29.6	.440	8.4				11.1	1.0	1	2
	4	.1460	17	33.6	.464	8.6				10.0	1.3	1	2
	5	.1465	17	33.5	.455	8.5				12.1	.6	1	2
	6	.1456	18	33.1	.462	8.5				11.8	.4	1	2
	7	.2106	13	37.7	.518	9.3				13.3	1.3	1	2
	8	.2081	30	30.7	.429	8.9				11.9	.7	1	2
	9	.2121	15	35.0	.486	8.0				15.0	1.3	1	2
	Avge.	.1651	22	33.1	.460	8.4				11.4	.9	1	2
Rotary-cut veneers	10	.1051	11	30.1	.450	8.8	90.4	13.2	70.0	7.8	.6	4.3	2.5
	11	.1092	14	37.6	.453	8.2	25.6	14.3	72.2	9.0	1.2	3.9	2.0
	12	.1074	13	39.7	.502	8.9	88.2	11.4	69.4	11.5	1.2	3.3	2.2
	13	.1438	59	37.5	.453	8.6	74.7	10.5	68.5	10.3	.1	3.1	2.0
	14	.1426	24	42.8	.499	8.8	80.3	10.4	72.6	3.8	.0	3.7	3.3
	15	.1437	33	41.8	.477	9.0	85.1	10.3	70.3	8.1	.1	3.6	2.8
	16	.1984	18	42.7	.584	8.6	84.0	8.5	65.4	10.0	1.5	3.8	2.6
	17	.1989	21	44.0	.517	8.8	78.5	8.1	63.3	15.0	.9	3.4	2.0
	18	.1968	21	42.7	.531	8.8	80.3	7.8	60.0	9.3	.2	5.1	2.0
	Avge.	.1495	24	39.9	.496	8.7	83.0	10.5	68.0	9.4	.6	3.8	2.4

TABLE III. MANUFACTURER'S SPECIFICATIONS FOR THE MODIFIED POLYVINYL ADHESIVE, DURO-LOK 50

Application	Brush, roller or glue-spreader; generally any method except spray. One-side application normally acceptable.
Coverage	Smooth surfaces: 25-35 lb M ft.^{2} per single glue line. Screen-backs, foams or absorbent materials: 40-55 lb.
Temperature	Over 65°F at glue lines, 75-85°F preferred.
Open assembly	5 min.
Closed assembly	30 min.
Press time	30 min.
Machining time	1 hr after press cycle.
Strength build-up	Wood to wood: over 400 psi immediately from press, over 500 psi one hour after press.
Clean up	80-90°F water, before glue is fully dry. Hot water will soften film sufficiently to scrape off during next 24 hours.
Cure time	Boiling water resistance is developed very rapidly and meets specifications in 24 hours at 70°F. Cold water resistance is developed approximately to 50% of final strength in 24 hours at 70°F, but is still increasing after 30 days. Complete cure is achieved in approximately 3 minutes at 300°F.

TABLE IV. SUMMARY OF PLYWOOD VARIABLES PER PLYWOOD BLOCKS

Type	Blck. No.	Gluing press. (psi)	Load Recovery (%)	No. of plies	Height at EMC (in.)	Compression full (%)	Compression permt. (%)	Weight loss (%)	EMC (%)	Days to EMC	Densifi-cation (%)	Glue content (%)	Increase in spec. gravity (%)	Specific gravity
		Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11	Y12	Y13
Sawn veneers	1	50	26.6	48	4.748	1.47	1.50	.50	8.5	5	6.1	4.9	11.4	.497
	2	200	10.8	48	4.710	6.72	2.38	.30	8.6	6	6.6	5.3	12.5	.496
	3	350	7.3	48	4.659	6.41	5.38	.20	9.4	5	8.0	5.0	13.6	.500
	4	50	20.0	32	4.655	9.15	.77	.45	8.2	5	4.7	4.2	9.3	.507
	5	200	12.8	32	4.624	2.25	1.91	.30	8.3	4	6.4	3.9	10.8	.504
	6	350	9.2	32	4.592	3.15	2.26	.62	8.8	4	7.4	4.2	12.1	.518
	7	50	19.6	24	5.018	1.13	.95	.46	8.7	4	5.8	2.7	8.7	.563
	8	200	5.0	24	4.983	1.74	1.15	.49	7.9	5	7.9	2.4	10.5	.474
	9	350	7.4	24	4.995	2.01	1.58	.14	8.2	5	8.2	2.1	10.5	.537
	Avge.	200	13.2	34.7	4.776	3.78	1.99	.38	8.5	4.9	6.8	3.9	11.0	.511
Rotary-cut veneers	10	50	8.0	48	4.914	4.68	4.62	.29	8.3	6	.7	6.2	7.3	.483
	11	200	7.4	43	4.334	4.05	5.72	1.08	7.7	4	2.9	6.8	10.4	.500
	12	350	6.4	48	4.822	7.03	6.13	.28	9.3	5	4.2	5.5	10.2	.553
	13	50	13.2	32	4.501	4.96	2.93	.23	8.3	4	.8	5.0	6.2	.500
	14	200	11.0	32	4.382	5.63	5.09	.28	6.8	4	2.8	4.3	7.4	.563
	15	350	7.3	32	4.278	6.84	5.54	2.11	7.5	4	6.3	4.7	11.5	.532
	16	50	6.8	24	4.705	4.89	2.87	.13	8.3	4	3.2	3.4	6.8	.624
	17	200	12.4	24	4.574	4.43	1.15	.17	9.2	4	6.8	3.4	10.4	.571
	18	350	7.8	24	4.553	8.17	4.54	.16	8.0	5	11.1	3.4	15.1	.611
	Avge.	200	8.9	34.1	4.563	5.63	4.29	.53	8.2	4.4	4.3	4.7	9.5	.549

TABLE V. CHANGES IN GLUING PRESSURE WITH TIME

	Block No.	Nominal load (lb)	Actual load (%) at 0 Min.	5 Min.	10 Min.	15 Min.	20 Min.	30 Min.	Load Recov. (%)	Veneer M.C. (%)
Sawn veneers	1	1250	100	70.63	97.22	100.80	104.00	112.00	26.59	8.4
	2	5000	100	83.20	94.00	98.40	98.80	100.80	10.80	7.3
	3	8750	100	80.00	87.31	90.74	91.88	88.91	7.31	8.4
	4	1250	100	73.20	93.20	100.00	104.80	113.20	20.00	8.6
	5	5000	100	82.40	95.20	98.80	100.00	104.80	12.80	8.5
	6	8750	100	83.42	92.57	94.40	95.54	92.80	9.15	8.5
	7	1250	100	65.20	84.80	96.00	100.00	104.00	19.60	9.3
	8	5000	100	88.20	93.20	97.20	98.20	97.20	5.00	8.9
	9	8750	100	88.11	95.54	97.83	98.97	97.37	7.43	8.0
	Avge.			79.37	92.56	97.13	99.13	101.23	13.20	8.4
Rotary-cut veneers	10	1250	100	76.00	84.00	86.00	92.00	82.00	8.00	8.8
	11	5000	100	77.60	85.00	90.80	92.80	88.00	7.40	8.2
	12	8750	100	76.80	83.20	91.20	91.43	85.03	6.40	8.9
	13	1250	100	68.80	82.00	90.00	96.80	94.00	13.20	8.6
	14	5000	100	75.00	86.00	92.00	83.00	88.00	11.00	8.8
	15	8750	100	73.14	80.45	86.86	88.46	81.37	7.31	9.0
	16	1250	100	77.60	84.40	90.00	95.20	86.00	6.80	8.6
	17	5000	100	74.80	87.20	93.20	94.40	89.00	12.40	8.8
	18	8750	100	81.37	89.14	92.80	94.40	90.60	7.77	8.8
	Avge.			75.68	84.60	90.31	93.16	87.11	8.90	8.7

TABLE VI. COMPRESSION RATE OF PLYWOOD BLOCKS

Type	Block No.	Gluing pressure (psi)	Initial height (in.)	Height (%) initial	Height (%) at full pressure	Height (%) after release	Height (%) at 7 days	Compression (%) at full load	Compression (%) permanent	Compression (%) recovery
Sawn veneers	1	50	4.825	100	98.53	98.78	98.50	1.47	1.50	-0.03
	2	200	4.825	100	93.28	97.93	97.62	6.72	2.38	4.34
	3	350	4.929	100	93.59	94.30	94.62	6.41	5.38	1.03
	4	50	4.691	100	90.85	91.09	99.23	9.15	0.77	8.38
	5	200	4.715	100	97.75	98.28	98.09	2.25	1.91	0.34
	6	350	4.698	100	96.85	99.70	97.74	3.15	2.26	0.89
	7	50	5.066	100	98.87	99.07	99.05	1.13	0.95	0.18
	8	200	5.043	100	98.26	98.69	98.85	1.74	1.15	0.59
	9	350	5.075	100	97.99	95.58	98.42	2.01	1.58	0.43
	Average		4.874		96.22	97.38	98.01	3.78	1.99	1.79
Rotary-cut veneers	10	50	5.153	100	95.32	95.71	95.38	4.68	4.62	0.06
	11	200	4.597	100	95.95	96.45	94.28	4.05	5.72	-1.67
	12	350	5.137	100	92.97	93.81	93.87	7.03	6.13	0.90
	13	50	4.637	100	95.04	95.38	97.07	4.96	2.93	2.03
	14	200	4.617	100	94.37	94.78	94.91	5.63	5.09	0.54
	15	350	4.529	100	93.16	94.10	94.46	6.84	5.54	1.30
	16	50	4.844	100	95.11	95.11	97.13	4.89	2.87	2.02
	17	200	4.627	100	95.57	96.39	98.85	4.43	1.15	3.28
	18	350	4.770	100	91.83	95.03	95.45	8.17	4.54	3.63
	Average		4.768		94.37	95.20	95.71	5.63	4.29	1.34

TABLE VII. CHANGES IN HEIGHT OF PLYWOOD BLOCKS DURING AND AFTER PRESSING

Type	Block No.	No. of plies	Height difference in per cent of EMC height, at days: 0	1/48	1	2	3	4	5	6	7	Avge. veneer thickn. (in.)
Sawn veneers	1	48	1.61	.37	.56	.48	.37	.18	.06	.00	.00	.1149
	2	48	2.43	.31	1.16	.84	.40	.12	.00	.00	.00	.1011
	3	48	5.80	-.24	.62	.54	.37	.32	.22	.11	.00	.1011
	4	32	.78	-8.20	.35	.20	.18	.02	.00	.02	.04	.1460
	5	32	1.97	.22	.40	.33	.05	.07	.07	.00	.05	.1465
	6	32	2.31	1.22	.44	.28	.22	.09	.00	.00	.00	.1456
	7	24	.97	.03	.43	.25	.15	.13	.00	.11	.09	.2106
	8	24	1.21	-.11	.37	.15	.13	.11	.00	.05	.09	.2081
	9	24	1.60	.16	.60	.20	.12	.08	.00	.08	.10	.2121
	Avge.		2.08	-.69	.55	.36	.22	.05	.04	.04	.04	.1651
Rotary-cut veneers	10	48	4.86	.37	.39	.33	.26	.08	.02	.02	.00	.1051
	11	43	6.10	2.36	.65	.49	.31	.17	.00	.05	.12	.1092
	12	48	6.54	-.95	.51	.44	.42	.24	.11	.00	.05	.1074
	13	32	3.03	-1.72	.55	.43	.17	.10	.00	.00	.00	.1438
	14	32	5.36	-.14	.86	.18	.13	.09	.00	.07	.09	.1426
	15	32	5.89	-.35	.88	.74	.21	.21	.00	.00	.09	.1437
	16	24	2.95	-2.08	.32	.19	.15	.15	.00	.09	.13	.1984
	17	24	1.16	-3.32	.22	.02	.05	.00	.07	.15	.07	.1989
	18	24	4.77	-.44	.42	.11	.13	.00	.09	.18	.07	.1968
	Avge.		4.45	-.70	.53	.33	.20	.12	.03	.06	.07	.1495

TABLE VIII. COMPARISON OF VENEER AND PLYWOOD SPECIFIC GRAVITIES

Type	Block No.	Plywood specific gravity			Veneer specific gravity		Veneer densification (%)	Glue content (%)	Increase in spec. gravity (%)
		Actual	Ranked	Without glue	Actual	Ranked			
Sawn veneers	1	.497	104.9	.473	.446	104.0	6.1	4.86	11.4
	2	.496	104.7	.470	.441	102.8	6.6	5.28	12.5
	3	.500	105.5	.475	.440	102.6	8.0	5.03	13.6
	4	.507	107.0	.486	.464	108.2	4.7	4.18	9.3
	5	.504	106.3	.484	.455	106.1	6.4	3.94	10.8
	6	.518	109.3	.496	.462	107.7	7.4	4.18	12.1
	7	.563	118.8	.548	.518	120.7	5.8	2.70	8.7
	8	.474	100.0	.463	.429	100.0	7.9	2.40	10.5
	9	.537	102.5	.526	.486	113.3	8.2	2.13	10.5
	Avge.	.511	107.8		.460	107.2	6.8	3.90	11.0
Rotary-cut veneers	10	.483	101.9	.453	.450	104.9	0.7	6.16	7.3
	11	.500	105.5	.466	.453	105.6	2.9	6.76	10.4
	12	.553	116.7	.523	.502	117.7	4.2	5.50	10.2
	13	.500	105.5	.466	.453	105.6	0.8	5.02	6.2
	14	.563	113.1	.513	.499	116.3	2.8	4.32	7.4
	15	.532	112.3	.507	.477	111.2	6.3	4.72	11.5
	16	.624	131.7	.603	.584	136.1	3.2	3.35	6.8
	17	.571	120.5	.552	.517	120.5	6.8	3.36	10.4
	18	.611	128.9	.590	.531	123.8	11.1	3.38	15.1
	Avge.	.549	115.8		.496	115.6	4.3	4.70	9.5

TABLE IX. FUNCTIONAL DEPENDENCE OF PLYWOOD STRENGTH PROPERTIES ON SOME SELECTED INDEPENDENT VARIABLES FOR THE SAWN-VENEER CONSTRUCTIONS

$S_i = f(X_j)$

															R²
Compr.	S1 =	-123764	-1145.5	(X3)	+44981	(X6)	+750.41	(X10)	+1524.7	(X11)	-1399608	(X14)			.6747
	S2 =	518.31	+157.12	(X2)	-1.3884	(X3)	-13.067	(X6)	-0.0501	(X10)	+5.8574	(X11			.1222
	S3 =	463.83	+520.99	(X2)	+0.9842	(X3)	+0.0162	(X4)	+70.084	(X5)	-46.798	(X6)			.5003
Tension	S4 =	35.421	-33.080	(X2)	-0.0570	(X3)	+0.0462	(X4)	-0.0459	(X10)	+0.0421	(X11)			.3210
	S5 =	62.995	+268.06	(X2)	-0.7144	(X3)	+0.9237	(X4)	+6.7007	(X6)	-1.2986	(X11)			.1423
	S6 =	137.53	+1368.4	(X2)	-1.4032	(X3)	+2.1977	(X4)	+21.768	(X6)	-3.3275	(X10)			.1412
Shear	S7 =	35.421	-33.080	(X2)	-0.0570	(X3)	+0.0462	(X4)	-0.0459	(X10)	+0.0421	(X11)			.3210
	S8 =	109.16	-0.4064	(X3)	+307.87	(X5)	+2.3439	(X10)	+3.4417	(X11)	-1673.6	(X14)			.4386
	S9 =	148.34	-2.6113	(X6)	-0.2932	(X10)	+0.9498	(X11)	-219.90	(X14)	-0.0207	(X15)			.4404

$S_i = f(Y_k)$

															R²
Compr.	S1 =	1071382	+5372.7	(Y3)	+9910.2	(Y5)	-91247	(Y7)	+836317	(Y11)	-129902	(Y12)	-77913	(Y13)	.8213
	S2 =	691.96	-10.209	(Y2)	+15.212	(Y5)	-49.711	(Y6)	+4.1824	(Y8)	+40355	(Y9)	-62.366	(Y13)	.8280
	S3 =	142.18	-5.9573	(Y2)	+0.4697	(Y5)	+184.89	(Y7)	+452.87	(Y11)	+24.254	(Y13)	-0.1141	(Y15)	.7409
Tension	S4 =	43.623	+0.3836	(Y2)	+0.3589	(Y5)	+6.8309	(Y6)	-12.794	(Y7)	-2.7330	(Y12)	-0.9699	(Y15)	.7360
	S5 =	327.37	+0.5657	(Y1)	+3.8179	(Y2)	-27.969	(Y6)	-20.142	(Y8)	-202.03	(Y11)	-7.4717	(Y13)	.3541
	S6 =	1718.5	-246.03	(Y4)	-107.46	(Y6)	+64.221	(Y7)	+31.588	(Y12)	-45.839	(Y13)	+0.0023	(Y14)	.3739
Shear	S7 =	43.623	+0.3836	(Y2)	+0.3589	(Y5)	+6.8309	(Y6)	-12.744	(Y7)	-2.7330	(Y12)	-0.9699	(Y15)	.7360
	S8 =	245.09	+0.3644	(Y1)	+2.3584	(Y2)	-32.366	(Y7)	+1.0830	(Y9)	-2.3182	(Y13)	-2.0904	(Y16)	.3421
	S9 =	369.12	+0.0242	(Y1)	-53.637	(Y4)	-0.7694	(Y5)	-23.389	(Y7)	+1.2771	(Y13)	-78.299	(Y18)	.3794

$S_i = f(X_g, Y_k)$

															R²
Compr.	S1 =	214063	-1372.3	(X3)	+40654	(X6)	+630.53	(X11)	+2207.2	(Y5)	-33974	(Y7)	-1583283	(X14)	.7713
	S2 =	703.28	-0.8815	(X3)	-10.674	(Y2)	+12.614	(Y5)	-48.182	(Y6)	+41.059	(Y9)	-52.409	(Y13)	.8559
	S3 =	237.36	-15.444	(X6)	-1.6378	(X11)	-4.2586	(Y2)	+155.99	(Y7)	+14.458	(Y13)	+846.42	(X14)	.7750
Tension	S4 =	49.155	-0.0332	(X3)	+0.2272	(Y2)	+2.1610	(Y6)	-13.389	(Y7)	-67.293	(Y18)	-0.4377	(X15)	.7455
	S5 =	380.97	+0.5630	(X4)	+0.6058	(Y1)	+4.8021	(Y2)	-18.828	(Y6)	-21.426	(Y8)	-28.478	(Y12)	.3601
	S6 =	135205	+5.3047	(X4)	+277.36	(Y7)	+0.00203	(Y14)	-5.4616	(Y15)	-107.41	(Y12)	-55.525	(Y13)	.3682
Shear	S7 =	409.76	+0.6642	(Y1)	+0.0472	(Y7)	+53.518	(Y18)	-470.22	(Y14)	+0.8712	(Y15)	-27.282	(Y13)	.4466
	S8 =	178.61	-545.26	(X2)	+444.39	(X5)	+2.7539	(X10)	+2.9606	(X11)	+1.3140	(Y5)	-22.541	(Y13)	.4937
	S9 =	128.77	-73.768	(X2)	-0.023	(X15)	-1.0528	(X16)	+0.0274	(Y1)	+0.9172	(Y5)	-4.7886	(Y2)	.4861

TABLE X. RANK AND CONTRIBUTION OF SOME SELECTED INDEPENDENT VARIABLES TO THE VARIOUS STRENGTH PROPERTIES OF SAWN-VENEER BLOCKS

COMPRESSION						TENSION								SHEAR			
S1		S2		S3		S4		S5		S6		S7		S8		S9	
Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2
$S_i = f\ (X_j)$																	
X6	.2544	X3	.0997	X6	.1771	X2	.2088	X3	.0884	X2	.0814	X2	.2088	X11	.1199	X15	.3395
X3	.4206	X11	.1094	X2	.4309	X3	.3103	X4	.0925	X3	.1118	X3	.3103	X14	.2508	X14	.4137
X14	.6570	X2	.1133	X3	.4976	X4	.3171	X2	.1102	X6	.1272	X4	.3171	X3	.3636	X6	.4238
X11	.6669	X6	.1222	X4	.4989	X10	.3206	X11	.1385	X4	.1312	X10	.3205	X5	.3761	X11	.4353
X10	.6747	X10	.1222	X5	.5003	X11	.3210	X6	.1423	X10	.1412	X11	.3210	X10	.4386	X10	.4404
All	.8228		.5841		.6045		.5308		.2581		.2582		.5308		.5136		.8089
$S_i = f\ (Y_k)$																	
Y5	.0581	Y2	.2021	Y2	.4789	Y7	.1597	Y6	.0661	Y6	.0708	Y7	.1597	Y1	.0307	Y4	.2546
Y13	.2131	Y5	.3626	Y7	.6594	Y2	.4463	Y1	.1764	Y14	.2829	Y2	.4463	Y16	.2829	Y1	.3331
Y12	.3240	Y13	.5073	Y13	.6987	Y5	.4732	Y8	.2840	Y13	.3285	Y5	.4732	Y2	.3318	Y18	.3448
Y11	.3311	Y6	.7027	Y5	.6988	Y15	.5030	Y2	.3499	Y7	.3427	Y15	.5030	Y7	.3414	Y7	.3727
Y3	.7299	Y9	.8277	Y15	.7034	Y6	.7158	Y13	.3517	Y4	.3728	Y6	.7158	Y9	.3416	Y13	.3734
Y7	.8213	Y8	.8280	Y11	.7409	Y12	.7360	Y11	.3541	Y12	.3739	Y12	.7360	Y13	.3421	Y5	.3794
All	.9233		.8713		.9148		.7511		.3680		.3837		.7511		.3430		.4657
$S_i = f\ (X_j, Y_k)$																	
X6	.2544	Y2	.2022	Y2	.4789	Y18	.2926	Y6	.0661	Y15	.0846	Y14	.2534	X11	.1199	X15	.3395
X3	.4206	Y5	.3628	X6	.4944	Y7	.4012	Y1	.1764	Y14	.2644	Y7	.2727	X2	.2338	X2	.4081
X14	.6570	X3	.4507	X14	.5603	Y2	.6077	Y8	.2840	Y13	.3194	Y18	.3440	X5	.3395	Y1	.4633
Y7	.7532	Y13	.5360	Y7	.7452	X3	.6573	Y12	.2859	Y7	.3317	Y13	.4249	Y13	.4070	Y5	.4817
Y5	.7707	Y6	.7232	Y13	.7714	Y15	.7268	Y2	.3571	Y12	.3325	Y15	.4398	X10	.4883	X6	.4847
X11	.7713	Y9	.8559	X11	.7750	Y6	.7455	X4	.3601	X4	.3682	Y1	.4466	Y5	.4937	Y2	.4861
All	.9430		.9143		.9428		.7658		.4057		.4173		.4893		.5667		.6893

Note: Var. = Variable

TABLE XI. FUNCTIONAL DEPENDENCE OF PLYWOOD STRENGTH PROPERTIES ON SOME SELECTED INDEPENDENT VARIABLES FOR THE ROTARY-CUT VENEER CONSTRUCTIONS

$S_i = f\ (X_j)$

															R^2
Compr.	S1 =	75661	-348343	(X2)	+13036	(X6)	-1369.2	(X10)	+3797.4	(X11)	-88431	(X15)			.6139
	S2 =	-1123.0	-4.3102	(X3)	+2.6573	(X4)	+1499.6	(X5)	+84.045	(X6)	+18.221	(X11)			.7406
	S3 =	55.709	+1625.2	(X2)	-3.7015	(X3)	-21.889	(X6)	+10.343	(X12)	+1762.1	(X15)			.8947
Tension	S4 =	27.359	+0.2988	(X4)	+0.2955	(X8)	-0.3769	(X10)	-148.19	(X14)	-73.398	(X16)			.8017
	S5 =	37.603	+1.318	(X4)	+2.2884	(X8)	-1.154	(X10)	-628.45	(X14)	-175.59	(X16)			.7604
	S6 =	248.69	-0.9737	(X3)	+3.7155	(X4)	+2.9881	(X8)	-2742.3	(X14)	-372.49	(X16)			.6859
	S7 =	125.57	+1.8541	(X4)	+1.4463	(X8)	-1.5425	(X12)	-24.460	(X13)	-282.54	(X16)			.6011
Shear	S8 =	127.48	-432.17	(X2)	+32.498	(X6)	-1.2860	(X10)	+10.505	(X12)	+0.0215	(X15)			.4707
	S9 =	129.44	-298.19	(X2)	+11.542	(X6)	-1.247	(X7)	+6.8661	(X12)	-119.77	(X16)			.5893

$S_i = f\ (Y_k)$

															R^2
Compr.	S1 =	83527	-4647.9	(Y5)	+3799.9	(Y8)	+12315	(Y9)	-3282.5	(Y12)	-7284.1	(Y13)	+1538.3	(Y15)	.7210
	S2 =	1821.5	+16.845	(Y3)	-897.54	(Y4)	-45.360	(Y9)	+115.88	(Y12)	+124.52	(Y13)	+2617.5	(Y17)	.8927
	S3 =	-648.65	-26.864	(Y2)	+450.91	(Y4)	-23.537	(Y7)	+13.749	(Y8)	-51.617	(Y9)	-132.07	(Y13)	.9023
Tension	S4 =	64.587	+0.0117	(Y1)	+0.9826	(Y5)	-3.3799	(Y12)	-0.6727	(Y13)	+0.0769	(Y15)	-87.619	(Y18)	.9254
	S5 =	40.346	+0.0181	(Y1)	-3.7355	(Y5)	+7.5505	(Y6)	+16.101	(Y7)	-3.6930	(Y12)	+2.2783	(Y13)	.7837
	S6 =	142.16	+0.2392	(Y1)	+13.551	(Y6)	+29.678	(Y7)	-9.8713	(Y8)	+0.9841	(Y12)	+3.4416	(Y13)	.6809
	S7 =	64.587	+0.0117	(Y1)	+0.9826	(Y5)	-3.3799	(Y12)	-0.6727	(Y13)	+0.0769	(Y15)	-87.619	(Y18)	.9254
Shear	S8 =	293.48	-73.832	(Y4)	+29.631	(Y5)	-409.23	(Y11)	+16.113	(Y12)	+21.176	(Y13)	+1.3783	(Y15)	.6739
	S9 =	113.48	+7.8445	(Y2)	+11.969	(Y9)	+4.7985	(Y13)	+0.0002	(Y14)	+1.1946	(Y15)	+0.3259	(Y16)	.7750

$S_i = f\ (X_j,\ Y_k)$

															R^2
Compr.	S1 =	58791	-1703.9	(X10)	+4173.5	(X11)	+18019	(Y9)	-2999.2	(X12)	-5008.5	(Y12)	+17.940	(X15)	.6167
	S2 =	-875.79	-472.49	(X2)	-2.5791	(X3)	+84.075	(X6)	+26.561	(X11)	+1521.1	(Y18)	+20.727	(Y12)	.7624
	S3 =	-131.45	-1.1214	(X3)	-12.389	(Y2)	-32.699	(Y9)	+1405.5	(Y18)	+59.101	(Y12)	-22.721	(Y13)	.8963
Tension	S4 =	59.873	-98.170	(X14)	+0.1217	(X4)	+0.0132	(Y1)	+0.8355	(Y5)	-75.454	(Y18)	-3.6628	(Y12)	.9399
	S5 =	128.41	-951.63	(X14)	+0.3644	(X4)	+0.0459	(Y1)	+9.2430	(Y7)	-62.666	(Y18)	-8.7388	(Y13)	.9089
	S6 =	185.83	-3173.0	(X14)	+1.0706	(X4)	+2.1327	(X8)	+0.1556	(Y1)	+15.429	(Y7)	+12.272	(X13)	.7644
	S7 =	214.67	-1402.3	(X14)	+0.5502	(X4)	+6.0329	(Y8)	-169.73	(Y18)	-17.917	(X13)	-12.773	(Y13)	.8045
Shear	S8 =	72.879	+20.515	(X6)	-1.2359	(X7)	-1.3764	(X10)	+0.0007	(Y14)	+17.226	(Y9)	+11.348	(X12)	.7151
	S9 =	-41.396	+10.494	(X6)	-1.0858	(X7)	+0.4738	(Y15)	+0.3094	(Y16)	+15.259	(Y9)	+7.1466	(X12)	.7870

TABLE XII. RANK AND CONTRIBUTION OF SOME SELECTED INDEPENDENT VARIABLES TO THE VARIOUS STRENGTH PROPERTIES OF ROTARY-CUT VENEER BLOCKS

COMPRESSION						TENSION								SHEAR			
S1		S2		S3		S4		S5		S6		S7		S8		S9	
Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2
$S_i = f(X_j)$																	
X2	.4620	X3	.2550	X15	.6224	X14	.5587	X14	.5538	X14	.5369	X13	.1761	X6	.3613	X6	.2790
X6	.5565	X5	.3887	X2	.7063	X16	.6350	X16	.5721	X8	.5528	X16	.3711	X2	.3903	X2	.3422
X10	.6008	X6	.6767	X3	.8781	X10	.7034	X8	.5769	X16	.5529	X4	.5748	X12	.4371	X7	.4948
X15	.6009	X11	.7225	X6	.8877	X8	.7043	X10	.6215	X4	.6468	X12	.5848	X10	.4416	X16	.5092
X11	.6139	X4	.7406	X12	.8947	X4	.8017	X4	.7604	X3	.6859	X8	.6011	X15	.4707	X12	.5893
All	.8827		.9017		.9288		.9111		.8708		.7583		.8195		.7321		.8283
$S_i = f(X_k)$																	
Y15	.5893	Y17	.1694	Y9	.5194	Y18	.4505	Y6	.5657	Y7	.5281	Y18	.4505	Y5	.4075	Y14	.2569
Y9	.6283	Y3	.3960	Y2	.7643	Y12	.6783	Y7	.7574	Y6	.6124	Y12	.6783	Y15	.5631	Y9	.4826
Y12	.6378	Y12	.3983	Y4	.8023	Y1	.9048	Y12	.7626	Y1	.6125	Y1	.9048	Y11	.6569	Y16	.5330
Y13	.6664	Y9	.3996	Y8	.8030	Y15	.9140	Y13	.7633	Y8	.6796	Y15	.9140	Y13	.6611	Y13	.5369
Y8	.7137	Y13	.4106	Y13	.8987	Y5	.9223	Y1	.7688	Y13	.6809	Y5	.9223	Y4	.6611	Y15	.5398
Y5	.7210	Y4	.8927	Y7	.9023	Y13	.9254	Y5	.7837	Y12	.6809	Y13	.9254	Y12	.6739	Y2	.7750
All	.9316		.9456		.9271		.9781		.9501		.7922		.9781		.7817		.7750
$S_i = f(X_j, Y_k)$																	
Y9	.3803	X3	.2550	Y18	.7756	X14	.5587	X14	.5583	X14	.5368	X14	.1022	X6	.4539	X6	.2790
X10	.4911	Y18	.3645	Y12	.8569	Y12	.7405	Y7	.8235	Y7	.6755	Y8	.4744	Y11	.5851	Y9	.3966
X15	.6050	X6	.6155	Y9	.8618	Y18	.7555	Y13	.8563	Y1	.7477	X13	.5904	Y9	.6419	Y16	.5988
Y12	.6080	X11	.7471	Y2	.8848	Y1	.9196	Y1	.8986	Y18	.7487	Y18	.6206	X10	.6531	Y15	.6054
X11	.6108	Y12	.7583	X3	.8878	Y5	.9266	Y18	.9005	X13	.7552	Y13	.7951	X12	.6826	X7	.7010
X12	.6167	X2	.7624	Y13	.8963	X4	.9399	X4	.9089	X4	.7644	X4	.8045	X7	.7151	X12	.7870
All	.9441		.9543		.9324		.9800		.9518		.8112		.9385		.8761		.9401

Note: Var. = Variables

TABLE XIII. FUNCTIONAL DEPENDENCE OF SOME PLYWOOD VARIABLES ON INDEPENDENT FACTORS FOR SAWN AND ROTARY-CUT VENEER BLOCKS

SAWN VENEER BLOCKS

																	R^2
Y2	=	-18.55	+0.3235	(X3)	+2.864	(X4)	+0.2284	(X6)	-1.936	(X10)	+3.216	(X11)	-0.0095	(Y1)	-10.68	(Y4)	.9941
Y5	=	115.3	-0.8299	(X4)	-0.8794	(X6)	+5.375	(X11)	-0.0426	(Y1)	-15.33	(Y4)	-1.079	(Y9)	+0.00008	(Y14)	.9811
Y6	=	8.706	+0.3600	(X3)	+55.95	(X5)	-0.1181	(X6)	+0.7422	(X10)	+0.4679	(X11)	-10.11	(Y4)	-0.000006	(Y14)	.9944
Y8	=	-4.293	+0.0889	(X3)	-0.2944	(X6)	+0.3297	(X11)	-0.9223	(X11)	+1.690	(Y4)	+0.00001	(Y14)			.9999
Y11	=	-0.1226	+1.083	(X5)	+0.0013	(X6)	-0.0022	(X11)	+0.00006	(X11)	+0.0277	(Y1)	-0.5974	(Y4)	-0.0000004	(Y14)	.9996
Y12	=	-1.014	-0.0048	(X3)	+5.575	(X5)	+0.5584	(X6)	+0.2274	(X11)	+0.0431	(Y3)	+0.0911	(Y9)	+0.0000006	(Y14)	.9514
Y7	=	3.356	-1.657	(X5)	-0.0302	(X10)	-0.1398	(X11)	-1.375	(X11)	+0.7299	(Y4)	+78.63	(Y9)			.9897

ROTARY-CUT VENEER BLOCKS

Y2	=	-0.5947	+0.3752	(X4)	-26.48	(X5)	+0.9566	(X6)	+0.4079	(X10)	-2.835	(X11)	-0.1255	(X12)	-0.00004	(Y14)	.9205
Y5	=	-22.77	+0.0700	(X3)	+9.442	(X5)	+0.0394	(X7)	-0.1332	(X10)	+0.0108	(X12)	+3.344	(Y1)	+0.6913	(Y4)	.9994
Y6	=	17.81	-0.0394	(X4)	-1.303	(X6)	-0.3159	(X10)	+6.976	(X11)	+4.249	(X14)	-53.04	(Y4)	+0.00002	(Y14)	.9977
Y8	=	-9.066	+0.5883	(X6)	+0.2882	(X10)	-0.4779	(X11)	+0.0150	(X12)	-1.653	(X14)	+2.039	(Y1)	+110.5	(Y4)	.9999
Y11	=	0.2308	-0.0004	(X3)	+0.9852	(X5)	+0.0061	(X6)	-0.0020	(X7)	-0.0004	(X9)	+0.00006	(Y1)	-0.0082	(Y4)	.9876
Y12	=	7.017	+25.60	(X2)	-0.0157	(X3)	-0.1686	(X4)	-4.591	(X5)	+0.0045	(X12)	+2.287	(Y1)	-1.225	(Y4)	.8546
Y13	=	9.424	-0.0181	(X3)	+1.410	(X6)	-0.2130	(X9)	-0.0323	(X10)	-0.0028	(X14)	-83.55	(Y1)	+0.0319	(Y14)	.9999

TABLE XIV. RANK AND CONTRIBUTION OF INDEPENDENT FACTORS TO SOME PLYWOOD VARIABLES AS INDICATED BY THEIR COEFFICIENTS OF DETERMINATION

Sawn Veneers

Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2
Load recovery Y2		Full compression Y5		Permanent compression Y6		Veneer densification Y8		Plywood density Y11		Plywood E.M.C. Y12		Weight loss Y7	
X10	.4328	X4	.2993	Y14	.3695	Y14	.6650	X5	.9575	Y9	.3164	X11	.2755
X4	.9575	X11	.7854	X3	.6048	X10	.6683	Y14	.9802	Y14	.5158	X10	.2978
Y1	.9702	X4	.8672	Y4	.6803	X3	.9228	Y1	.9810	X3	.5190	Y4	.3113
Y4	.9742	Y1	.9197	X10	.7464	Y4	.9453	X11	.9811	X5	.8408	Y9	.3730
X3	.9778	Y14	.9559	X11	.8051	X11	.9872	Y4	.9840	X11	.8453	X14	.9518
X6	.9809	X6	.9559	X6	.8402	X6	.9998	X6	.9878	Y3	.8909	X5	.9897
X11	.9941	Z9	.9811	X5	.9944	Y9	1.0000	X14	.9996	X6	.9514	X3	.9900
X14	1.0000	X3	1.0000	X14	1.0000			Y9	1.0000	Y4	1.0000	Y3	1.0000

Rotary-Cut Veneers

Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2
Load recovery Y2		Full compression Y5		Permanent compression Y6		Veneer densification Y8		Plywood density Y11		Plywood E.M.C. Y12		Days to E.M.C. Y13	
X11	.2127	Y1	.5983	X14	.5040	Y1	.5463	X5	.9287	Y4	.4363	X3	.2070
Y14	.5009	X12	.6622	Y14	.7785	X14	.9210	Y1	.9639	X12	.5547	X14	.2906
X10	.7841	X5	.6849	X10	.9056	X12	.9733	X7	.9841	X2	.6258	X9	.7064
X5	.7858	X10	.7054	X4	.9066	X10	.9860	X3	.9889	X3	.6319	X6	.7650
X4	.9151	X7	.7167	X6	.9516	X6	.9860	X9	.9870	X4	.6322	X10	.8285
X12	.9188	X3	.8823	Y4	.9834	Y4	.9981	X6	.9872	Y1	.8497	Y14	.8300
X6	.9205	Y4	.9994	X11	.9977	X11	.9999	Y4	.9876	X5	.8546	Y1	.9999
Y4	1.0000	X6	1.0000	Y9	1.0000	X3	1.0000	X2	1.0000	X6	1.0000	Y4	1.0000

Note: Var. = Variable

TABLE XV. FUNCTIONAL DEPENDENCE OF PLYWOOD STRENGTH ON SOME SELECTED INDEPENDENT VARIABLES, EXCLUDING THE EXPERIMENTALLY CONTROLLED ONES

$$S_i = f(X_j, Y_k)$$

Sawn veneer blocks

											R^2
Compr.	S1 =	-139611	-1008	(X3)	+40985	(X6)	+2977	(X11)	+5296	(Y5)	.5904
	S2 =	519.40	-1.3605	(X3)	-6.4079	(Y2)	+12.657	(Y5)	-24.832	(Y6)	.6227
	S3 =	331.04	+0.4528	(X3)	-10.792	(X6)	-1.2131	(X11)	-3.7808	(Y2)	.5193
Tension	S4 =	76.223	-0.0801	(X3)	-0.0272	(X11)	+0.1323	(Y2)	-88.925	(Y11)	.4846
	S5 =	156.54	-1.0590	(X3)	+7.2822	(X6)	-1.1722	(X10)	-10.725	(Y6)	.1670
	S6 =	391.20	-3.0323	(X3)	-1.4835	(X4)	+37.432	(X6)	-33.305	(Y6)	.1232
Sh.	S8 =	229.38	-0.8121	(X3)	+0.1616	(X10)	+4.2297	(X11)	+6.8146	(Y6)	.2369

Rotary-cut veneer blocks

											R^2
Compr.	S1 =	40695	+16625	(X6)	+4929	(X8)	+10884	(X11)	-16889	(Y12)	.6633
	S2 =	-218.65	-3.7423	(X3)	+6.1799	(X4)	+27.746	(X6)	+33.445	(Y5)	.6675
	S3 =	791.89	-3.0922	(X3)	-56.579	(X6)	-32.166	(X8)	+61.395	(Y12)	.8013
Tension	S4 =	4.861	+0.1408	(X3)	+0.3049	(X7)	+1.2156	(X8)	-3.6208	(Y12)	.6782
	S5 =	-32.745	+1.0879	(X4)	+0.9290	(X7)	+4.867	(X8)	-11.549	(Y12)	.6737
	S6 =	101.50	+1.1492	(X7)	+15.969	(X8)	-9.224	(X11)	+15.775	(Y5)	.5758
Sh.	S8 =	-195.98	+26.206	(X6)	-1.6508	(X10)	+22.913	(X12)	+2.394	(Y5)	.5845

TABLE XVI. RANK AND CONTRIBUTION OF SOME SIGNIFICANT INDEPENDENT VARIABLES, EXCLUDING THE EXPERIMENTALLY CONTROLLED ONES, TO VARIOUS PLYWOOD STRENGTH PROPERTIES

$$S_i = f\ (X_i,\ Y_k)$$

COMPRESSION						TENSION						SHEAR	
S1		S2		S3		S4		S5		S6		S8	
Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2	Var.	R^2
Sawn veneers													
X6	.2543	Y2	.2022	Y2	.4790	Y11	.2987	X3	.0884	Y6	.0708	X11	.1199
X3	.4206	Y5	.3627	X6	.4944	Y2	.3781	Y6	.1349	X3	.1091	X3	.1869
Y5	.5761	X3	.4507	X3	.5172	X3	.4842	X10	.1625	X6	.1208	Y6	.2364
X11	.5904	Y6	.6227	X11	.5193	X11	.4846	X6	.1670	X4	.1232	X10	.2369
Y2	.6007	X11	.6339	Y12	.5414	Y6	.4931	X4	.1671	Y8	.2357	Y2	.3463
Y12	.6078	Y8	.6960	Y5	.5420	X10	.4964	Y5	.1683	Y2	.2406	Y5	.3578
All	.7420		.8392		.8846		.6030		.3372		.3415		.3807
Rotary-cut Veneers													
X6	.3443	Y5	.3582	X8	.4346	Y12	.2839	X8	.3370	X8	.3850	Y5	.4075
X8	.4630	X3	.5260	X6	.5833	X8	.5114	Y12	.5286	X11	.4453	X6	.5612
Y12	.5233	X4	.6408	Y5	.6899	X7	.5598	X7	.5802	Y5	.5612	X10	.5825
X10	.6633	X6	.6675	X3	.8013	X3	.6782	X4	.6736	X7	.5758	X12	.5845
X3	.6881	Y12	.7233	Y12	.8262	Y5	.7405	Y5	.7161	X4	.6403	X8	.7037
X4	.7368	X10	.7299	X4	.8293	X11	.7461	X11	.7222	Y12	.6541	X7	.7071
All	.8273		.8190		.8912		.8687		.7973		.6954		.7394

Note: Var. = Variable

TABLE XVII. SIMPLE CORRELATION OF VENEER THICKNESS AND SOME CONCOMITANT VARIABLES

Test	Block	Concomitant variables	R
Compression	Sawn	Glue content (solids)	-0.98
		Number of plies	-0.96
		Permanent compression	-0.56
		Plywood moisture content	-0.55
		Full compression in press	-0.50
		Plywood specific gravity	0.45
	Rotary-cut	Number of plies	-0.96
		Glue content (solids)	-0.93
		Plywood specific gravity (squared)	0.80
		Permanent compression (squared)	-0.74
		Plywood specific gravity	0.56
		Veneer moisture content	-0.46
Tension	Sawn	Plywood specific gravity (squared)	0.91
		Full compression in press	0.55
		Plywood moisture content	-0.53
		Load recovery in press	-0.50
		Permanent compression (squared)	-0.48
		Radial grain angle	0.44
	Rotary-cut	Plywood specific gravity (squared)	0.83
		Number of lathe checks per inch	-0.73
		Permanent compression	-0.70
		Full compression in press	-0.69
		Veneer densification	0.58
Shear	Sawn	Glue content (solids)	-0.98
		Height of blocks	0.79
		Plywood specific gravity	0.54
	Rotary-cut	Glue content (solids)	-0.93
		Plywood specific gravity	0.79
		Permanent compression (squared)	-0.72
		Veneer densification (squared)	0.57
		Radial grain angle	0.42

TABLE XVIII. SIMPLE CORRELATION OF GLUING PRESSURE AND SOME CONCOMITANT VARIABLES

Test	Block	Concomitant variables	R
Compression	Sawn	Load recovery in press	-0.84
		Permanent compression	0.62
		Veneer moisture content	-0.42
		Weight loss in press (rate of cure)	-0.41
	Rotary-cut	Veneer densification	0.74
		Permanent compression (squared)	0.59
		Veneer moisture content	0.49
		Growth rate	-0.40
Tension	Sawn	Veneer densification	0.86
		Load recovery in press	-0.84
		Permanent compression	0.62
		Permanent compression (squared)	0.53
		Weight loss in press (rate of cure)	-0.41
	Rotary-cut	Full compression in press	0.74
		Veneer densification	0.73
		Permanent compression (squared)	0.54
		Permanent compression	0.46
		Weight loss in press (rate of cure)	0.42
Shear	Sawn	Weight loss in press (rate of cure)	0.86
		Load recovery in press	-0.84
		Full compression in press	0.41
	Rotary-cut	Full compression in press	0.86
		Veneer densification	0.64
		Permanent compression (squared)	0.59
		Summerwood percentage (squared)	0.46
		Radial grain angle	-0.44
		Weight loss in press (rate of cure)	0.41

TABLE XIX. SUMMARY OF OBSERVED PLYWOOD STRENGTH VALUES FOR SAWN AND ROTARY-CUT VENEER BLOCKS

Factors		Thickness (inch)	1 / 10			1 / 7			1 / 5			
		Pressure (Psi)	50	200	350	50	200	350	50	200	350	
Strength characteristics			Block numbers									
Type		Si / Units	1	2	3	4	5	6	7	8	9	Mean
Sawn veneers	Compr.	S1 1000 psi	223.1	208.9	179.0	261.4	236.6	217.9	178.6	145.4	220.2	210.9
		S2 psi	273	446	363	460	442	488	350	399	399	402
		S3 10 -5	122	230	202	176	169	224	208	275	181	199
	Tension	S4 1000 psi	32.7	32.9	29.2	31.4	32.6	27.3	27.2	24.5	31.8	29.9
		S5 psi	154	126	109	186	177	206	139	124	205	158
		S6 10 -5	470	380	372	590	547	754	504	511	647	531
		S7 %	96	89	88	91	96	99	52	96	78	87
	Shear	S8 psi	227	235	242	243	248	255	215	175	237	231
		S9 %	95	97	98	93	100	100	65	80	97	92
Type		Si / Units	10	11	12	13	14	15	16	17	18	Mean
Rotary-cut veneers	Compr.	S1 1000 psi	97.5	154.1	131.1	89.2	131.6	106.5	46.6	85.0	102.1	104.9
		S2 psi	256	408	553	204	383	364	302	413	519	378
		S3 10 -5	264	265	421	230	296	342	645	487	509	384
	Tension	S4 1000 psi	19.2	21.1	17.5	17.0	22.5	25.3	4.6	10.8	13.9	16.9
		S5 psi	48	62	54	36	60	80	7	21	27	44
		S6 10-5	250	294	306	210	265	319	148	192	197	242
		S7 %	48	93	98	87	82	89	20	84	88	77
	Shear	S8 psi	157	132	250	133	177	185	35	110	210	154
		S9 %	78	93	97	80	83	88	13	67	97	77

Note: The legend of dependent variables (S_i) is given on pages 15 and 16.

TABLE XX. SUMMARY OF ADJUSTED PLYWOOD STRENGTH VALUES FOR SAWN AND ROTARY-CUT VENEER BLOCKS

Factors		Thickness (inch)		1 / 10			1 / 7			1 / 5			
		Pressure (psi)		50	200	350	50	200	350	50	200	350	
Strength characteristics				Block number									
Type		Si	Units	1	2	3	4	5	6	7	8	9	Mean
Sawn veneers	Compr.	S1	1000 psi	1418	1361	1341	1498	1498	1391	1346	1280	1410	1393
		S2	psi	3069	3413	3263	3450	3397	3483	3241	3342	3318	3331
		S3	10^{-5}	112	327	265	217	210	324	272	407	231	263
	Tension	S4	1000 psi	320	318	313	317	319	310	308	304	316	314
		S5	psi	4493	4451	4398	4548	4527	4584	4464	4441	4582	4498
		S6	10^{-5}	12582	12486	12368	12776	12706	13089	12666	12670	12918	12696
		S7	%										
	Shear	S8	psi	789	810	829	824	823	829	779	702	807	799
		S9	%										
Type		Si	Units	10	11	12	13	14	15	16	17	18	Mean
Rotary-cut veneers	Compr.	S1	1000 psi	122	210	175	93	180	134	13	84	115	125
		S2	psi	140	343	685	-7	350	352	196	403	588	339
		S3	10^{-5}	40	29	357	-25	96	227	789	482	501	277
	Tension	S4	1000 psi	24	28	22	20	32	35	-15	8	15	19
		S5	psi	63	92	72	38	89	117	-55	7	28	50
		S6	10^{-5}	267	354	360	177	291	379	-15	150	179	238
		S7	%										
	Shear	S8	psi	154	84	292	111	169	210	-76	49	263	140
		S9	%										

TABLE XXI. RATIOS COMPARING VARIOUS PLYWOOD STRENGTH PROPERTIES WITHIN EACH VENEER TYPE

Thickness (inch)			1 / 10			1 / 7			1 / 5			
Pressure (psi)			50	200	350	50	200	350	50	200	350	
	Ratio	Block	1	2	3	4	5	6	7	8	9	Mean
Observed values	S1 / S4	Sawn veneers	7.09	6.35	6.13	8.32	8.08	7.98	6.57	5.93	6.92	7.05
	S2 / S5		1.77	3.54	3.33	2.47	2.50	2.37	2.52	3.22	1.94	2.54
	S3 / S6		.26	.61	.54	.30	.31	.30	.41	.54	.28	.37
	S1 / S8		983	889	740	1076	1063	855	831	831	929	913
	S2 / S8		1.20	1.90	1.50	1.89	1.78	1.91	1.63	2.28	1.68	1.74
	S5 / S8		.68	.53	.45	.76	.71	.81	.65	.71	.87	.68
	S7 / S9		1.01	.92	.90	.98	.96	.99	.80	1.20	.80	.95
	Ratio	Block	10	11	12	13	14	15	16	17	18	Mean
	S1 / S4	Rotary-cut veneers	5.08	7.30	7.50	5.25	5.85	4.21	10.13	7.87	7.35	6.21
	S2 / S5		5.33	6.58	10.24	5.67	6.38	4.55	43.14	19.67	19.22	8.59
	S3 / S6		1.06	.90	1.38	1.10	1.12	1.07	4.36	2.54	2.58	1.59
	S1 / S8		621	1167	525	671	744	576	2330	773	486	681
	S2 / S8		1.63	3.09	2.21	1.53	2.16	1.97	8.63	3.75	2.47	2.45
	S5 / S8		.30	.47	.22	.27	.34	.43	.20	.19	.13	.29
	S7 / S9		.62	1.00	1.01	1.09	.99	1.01	1.54	1.25	.91	1.00
	Ratio	Block	1	2	3	4	5	6	7	8	9	Mean
Adjusted values	S1 / S4	Sawn veneers	4.43	4.28	4.28	4.72	4.67	4.49	4.37	4.21	4.46	4.44
	S2 / S5		.68	.77	.74	.76	.75	.76	.73	.75	.72	.74
	S3 / S6		.009	.026	.021	.017	.017	.024	.024	.032	.018	.021
	S1 / S8		1797	1680	1618	1818	1809	1678	1728	1823	1747	1743
	S2 / S8		3.89	4.21	3.94	4.19	4.13	4.20	4.16	4.76	4.11	4.17
	S5 / S8		5.69	5.50	5.31	5.52	5.50	5.53	5.73	6.33	5.68	5.63
	Ratio	Block	10	11	12	13	14	15	16	17	18	Mean
	S1 / S4	Rotary-cut veneers	5.08	7.50	7.95	4.65	5.62	3.83	-	10.50	7.67	6.58
	S2 / S5		2.22	3.73	9.52	-	3.93	3.01	-	-	-	6.78
	S3 / S6		.15	.08	.99	-	.33	.60	-	3.21	2.80	1.16
	S1 / S8		792	2500	599	838	1065	638	-	1714	437	893
	S2 / S8		.91	4.08	2.35	-	2.07	1.68	-	8.22	2.24	2.42
	S5 / S8		.41	1.10	.25	.34	.53	.56	.72	.15	.11	.36

TABLE XXII. RATIOS COMPARING VARIOUS PLYWOOD STRENGTH PROPERTIES OF SAWN AND ROTARY-CUT VENEER BLOCKS

Thickness (inch)		1 / 10			1 / 7			1 / 5			
Pressure (psi)		50	200	350	50	200	350	50	200	350	
Ratio	Block	1/10	2/11	3/12	4/13	5/14	6/15	7/16	8/17	9/18	Mean
S1 / S1	Observed values	2.29	1.36	1.37	2.93	1.80	2.05	3.83	1.71	2.16	2.01
S2 / S2		1.07	1.09	.66	2.25	1.15	1.34	1.16	.97	.77	1.06
S3 / S3		.46	.87	.48	.76	.57	.62	.32	.56	.36	.52
S4 / S4		1.70	1.56	1.67	1.85	1.45	1.08	-	2.27	2.29	1.77
S5 / S5		3.21	2.03	2.02	5.17	2.95	2.58	-	5.90	7.59	3.59
S6 / S6		1.88	1.29	1.22	2.81	2.06	2.36	-	2.66	3.28	2.19
S7 / S7		2.00	.96	.90	1.04	1.17	1.11	2.60	1.14	.89	1.13
S8 / S8		1.45	1.78	.97	1.83	1.40	1.38	-	1.59	1.13	1.50
S9 / S9		1.22	1.04	1.01	1.16	1.20	1.14	5.00	1.19	1.00	1.19
Ratio	Block	1/10	2/11	3/12	4/13	5/14	6/15	7/16	8/17	9/18	Mean
S1 / S1	Adjusted values	11.62	6.48	7.66	-	8.27	10.38	-	15.24	12.26	11.14
S2 / S2		21.92	9.95	4.76	-	9.71	9.89	-	8.29	5.64	9.82
S3 / S3		2.80	11.28	.74	-	2.19	1.43	-	.84	.46	.95
S4 / S4		13.33	11.36	14.23	15.85	9.67	8.86	-	-	11.28	16.52
S5 / S5		71.32	43.38	61.08	119.68	50.86	39.18	-	-	163.64	89.96
S6 / S6		47.12	35.27	34.36	72.18	43.66	34.54	-	84.46	72.17	53.34
S8 / S8		5.12	9.64	2.84	7.42	4.87	3.95	-	14.33	3.06	5.71

TABLE XXIII. RATIOS OF PLYWOOD STRENGTH PROPERTIES COMPARING ADJUSTED AND OBSERVED VALUES

Thickness (inch)		1 / 10			1 / 7			1 / 5			
Pressure (psi)		50	200	350	50	200	350	50	200	350	
Ratio	Block	1/1	2/2	3/3	4/4	5/5	6/6	7/7	8/8	9/9	Mean
S1 / S1	Sawn veneers	6.35	6.51	7.49	5.73	5.65	6.38	7.54	8.80	6.40	6.60
S2 / S2		11.24	7.65	8.99	7.50	7.68	7.14	9.26	8.38	8.32	8.29
S3 / S3		.92	1.42	1.31	1.23	1.24	1.45	1.31	1.48	1.28	1.32
S4 / S4		9.78	9.66	10.72	10.10	9.78	11.36	11.32	12.41	9.94	10.50
S5 / S5		29.18	35.32	40.35	24.45	25.58	22.25	32.12	35.81	22.35	28.47
S6 / S6		26.77	32.86	33.24	21.65	23.22	17.36	25.13	24.79	19.96	23.91
S8 / S8		3.48	3.48	3.43	3.39	3.32	3.25	3.62	4.01	3.41	3.46
Ratio	Block	10/10	11/11	12/12	13/13	14/14	15/15	16/16	17/17	18/18	Mean
S1 / S1	Rotary-cut veneers	1.25	1.36	1.33	1.04	1.37	1.26	-	.99	1.13	1.19
S2 / S2		.56	.84	1.24	-	.91	.97	.65	.975	1.13	.90
S3 / S3		.15	.11	.85	-	.32	.67	1.22	.99	.98	.72
S4 / S4		1.25	1.33	1.26	1.18	1.42	1.37	-	.74	1.08	1.12
S5 / S5		1.31	1.48	1.33	1.06	1.48	1.46	-	.33	1.04	1.14
S6 / S6		1.07	1.20	1.18	.84	1.10	1.19	-	.78	.91	.98
S8 / S8		.98	.64	1.17	.83	.95	1.14	-	.44	1.25	.91

TABLE XXIV. SUMMARY OF ANALYSES OF VARIANCE FOR OBSERVED AND ADJUSTED PLYWOOD STRENGTH VALUES

Test		Strength property	Factors	Observed				Adjusted			
				Sawn		Rotary		Sawn		Rotary	
				F value	Com.	F value	Com.	F value	Com.	F value	Com.
Compression	S1	Modulus	Thickness	43.21	**	87.11	**	54.95	**	76.44	**
			Pressure	2.94	N.S.	79.80	**	9.30	**	57.36	**
			Interaction	14.89	**	7.83	**	19.51	**	4.82	**
	S2	Stress	Thickness	45.39	**	37.74	**	40.21	**	27.54	**
			Pressure	20.49	**	175.84	**	18.56	**	150.07	**
			Interaction	12.77	**	9.90	**	13.38	**	8.19	**
	S3	Strain	Thickness	22.54	**	130.99	**	21.23	**	187.43	**
			Pressure	45.75	**	9.21	**	55.10	**	16.23	**
			Interaction	38.33	**	15.79	**	40.40	**	25.75	**
Tension	S4	Modulus	Thickness	20.85	**	734.45	**	43.16	**	56.00	**
			Pressure	1.52	N.S.	154.45	**	3.39	*	16.73	**
			Interaction	23.02	**	58.38	**	32.41	**	6.28	**
	S5	Stress	Thickness	6.64	**	286.46	**	11.52	**	61.71	**
			Pressure	1.78	N.S.	87.09	**	2.46	N.S.	24.01	**
			Interaction	2.34	N.S.	20.69	**	5.04	**	3.83	**
	S6	Strain	Thickness	8.98	**	56.21	**	15.17	**	65.50	**
			Pressure	2.23	N.S.	24.02	**	3.02	N.S.	34.17	**
			Interaction	1.38	N.S.	1.86	N.S.	3.38	*	1.84	N.S.
	S7	Wood failure	Thickness	7.00	**	39.27	**				
			Pressure	3.25	*	146.70	**	-		-	
			Interaction	3.92	**	40.79	**				
Shear	S8	Stress	Thickness	2.43	N.S.	6.88	**	2.19	N.S.	5.72	*
			Pressure	0.95	N.S.	20.30	**	0.98	N.S.	21.13	**
			Interaction	0.58	N.S.	3.76	*	0.68	N.S.	4.09	*
	S9	Wood failure	Thickness	3.99	**	9.16	**				
			Pressure	2.08	N.S.	11.98	**	-		-	
			Interaction	0.88	N.S.	4.93					

Note: N.S. = not significant; * = significant (5%); ** = highly significant (1%).

TABLE XXV. RANK OF HIGHLY SIGNIFICANT CONTROLLED FACTORS ON THE VARIOUS PLYWOOD STRENGTH PROPERTIES

Test		Strength property	Rank of controlled factors on: Observed values		Adjusted values	
			Sawn veneers	Rotary veneers	Sawn veneers	Rotary veneers
Compression	S1	Modulus	Thickness -	Thickness Pressure	Thickness Pressure	Thickness Pressure
	S2	Stress	Thickness Pressure	Pressure Thickness	Thickness Pressure	Pressure Thickness
	S3	Strain	Pressure Thickness	Thickness Pressure	Pressure Thickness	Thickness Pressure
Tension	S4	Modulus	Thickness -	Thickness Pressure	Thickness -	Thickness Pressure
	S5	Stress	Thickness -	Thickness Pressure	Thickness -	Thickness Pressure
	S6	Strain	Thickness -	Thickness Pressure	Thickness -	Thickness Pressure
	S7	Wood failure	Thickness -	Pressure Thickness		
Shear	S8	Stress	- -	Pressure Thickness	- -	Pressure -
	S9	Wood failure	Thickness -	Pressure Thickness		

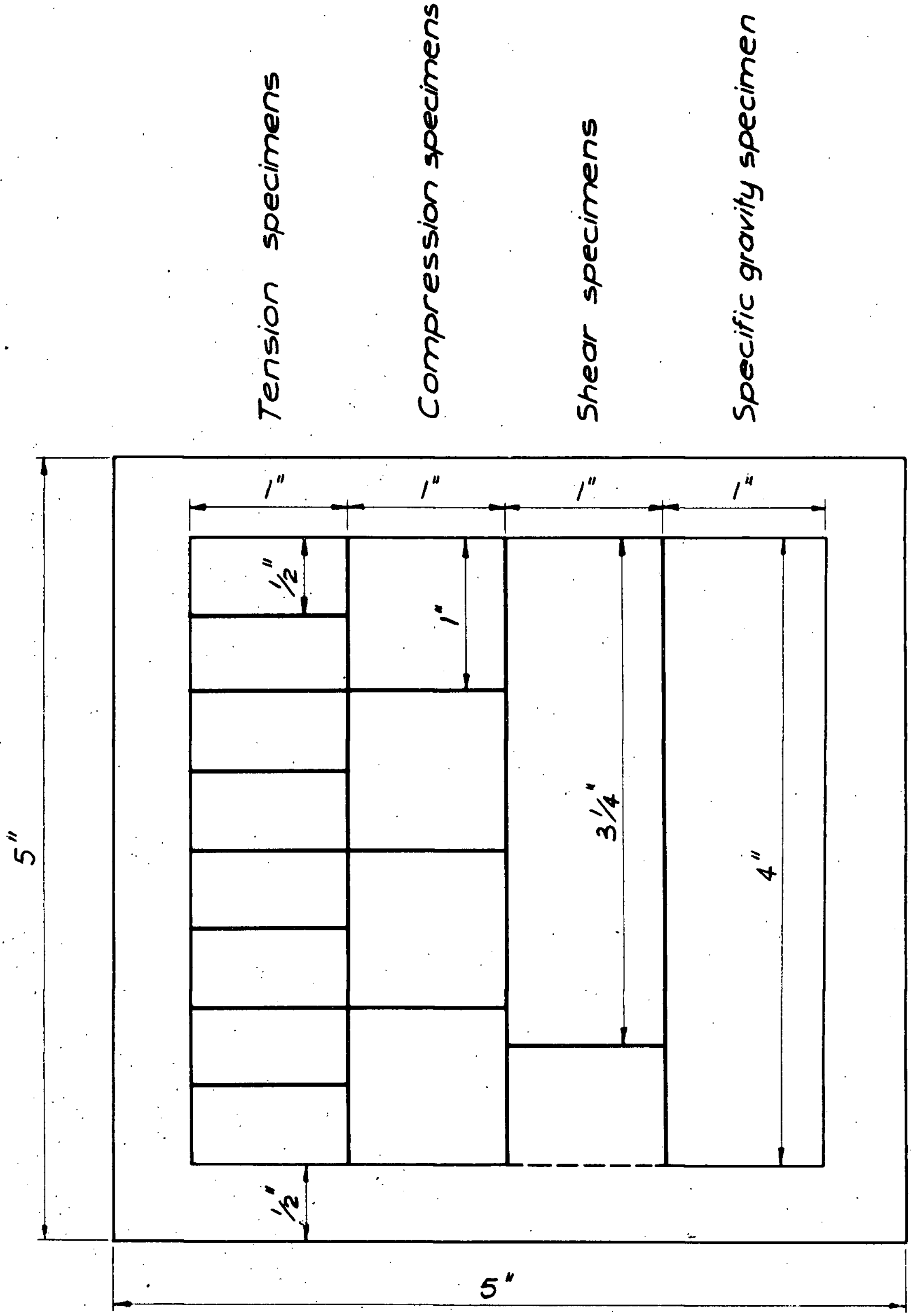

Figure 1. Cutting plan of plywood blocks.

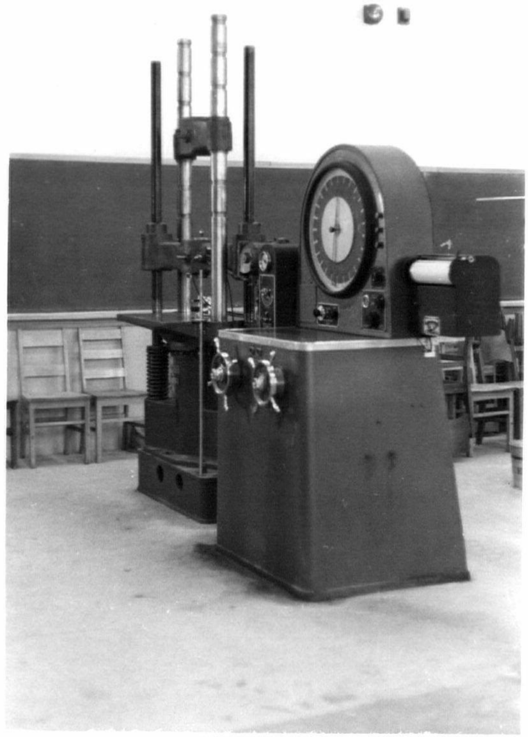

Figure 2. Baldwin Universal Testing Machine in the materials testing laboratory of the Faculty of Applied Science.

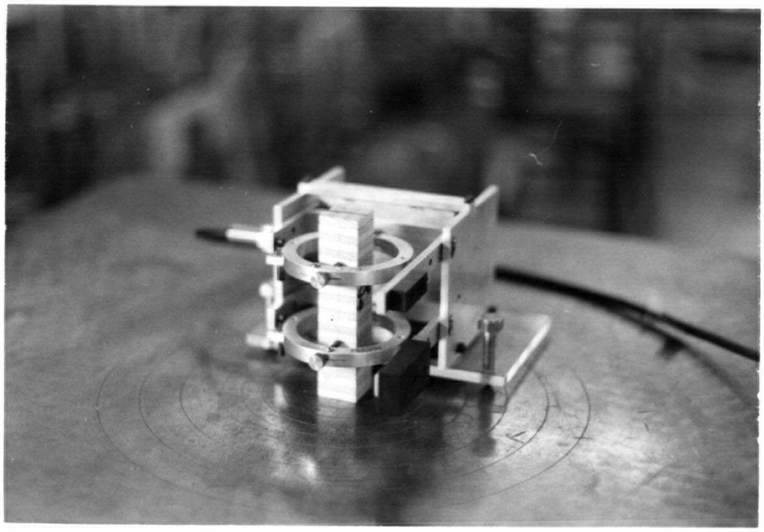

Figure 3. Compression specimen in the microformer extensometer.

Figure 4. Table Model Instron Testing Instrument in the wood technology laboratory of the Faculty of Forestry.

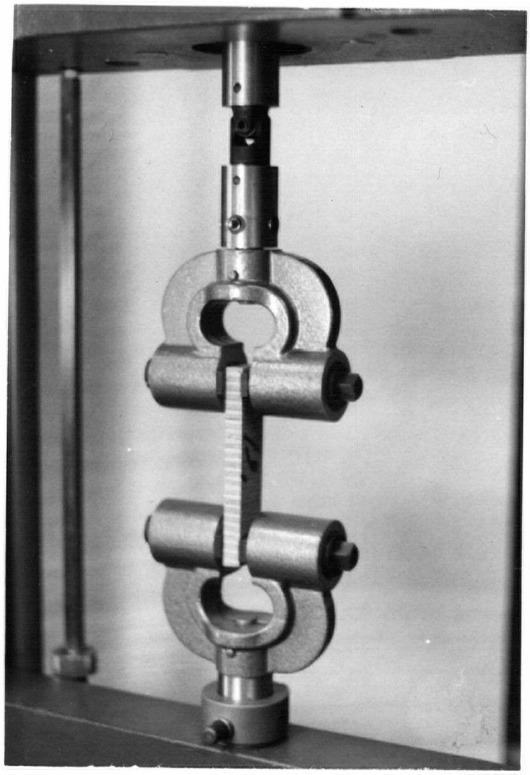

Figure 5. Tension specimen in the grips of the table model Instron testing instrument.

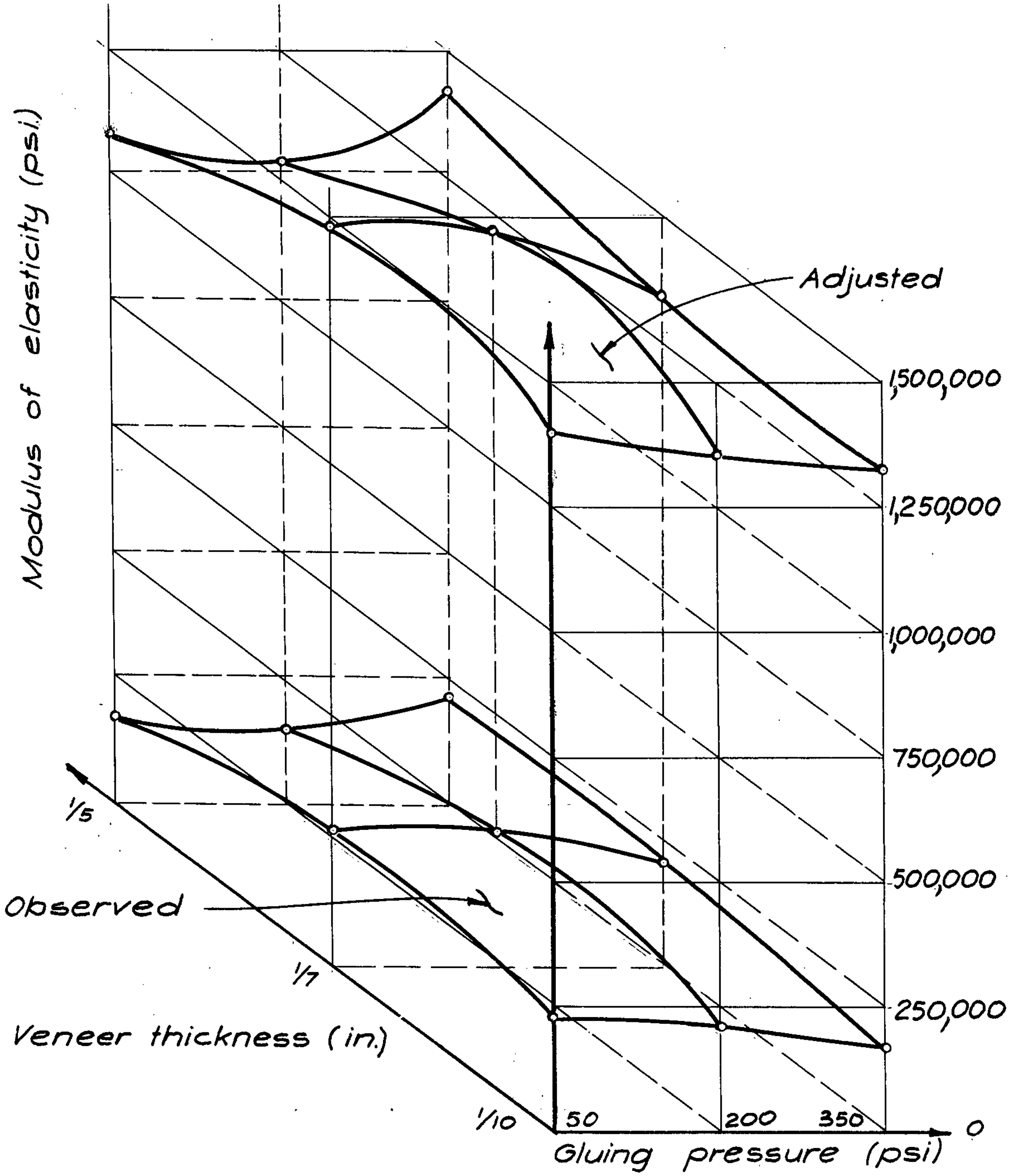

Figure 6. Influence of controlled factors on modulus of elasticity of sawn-veneer blocks in compression.

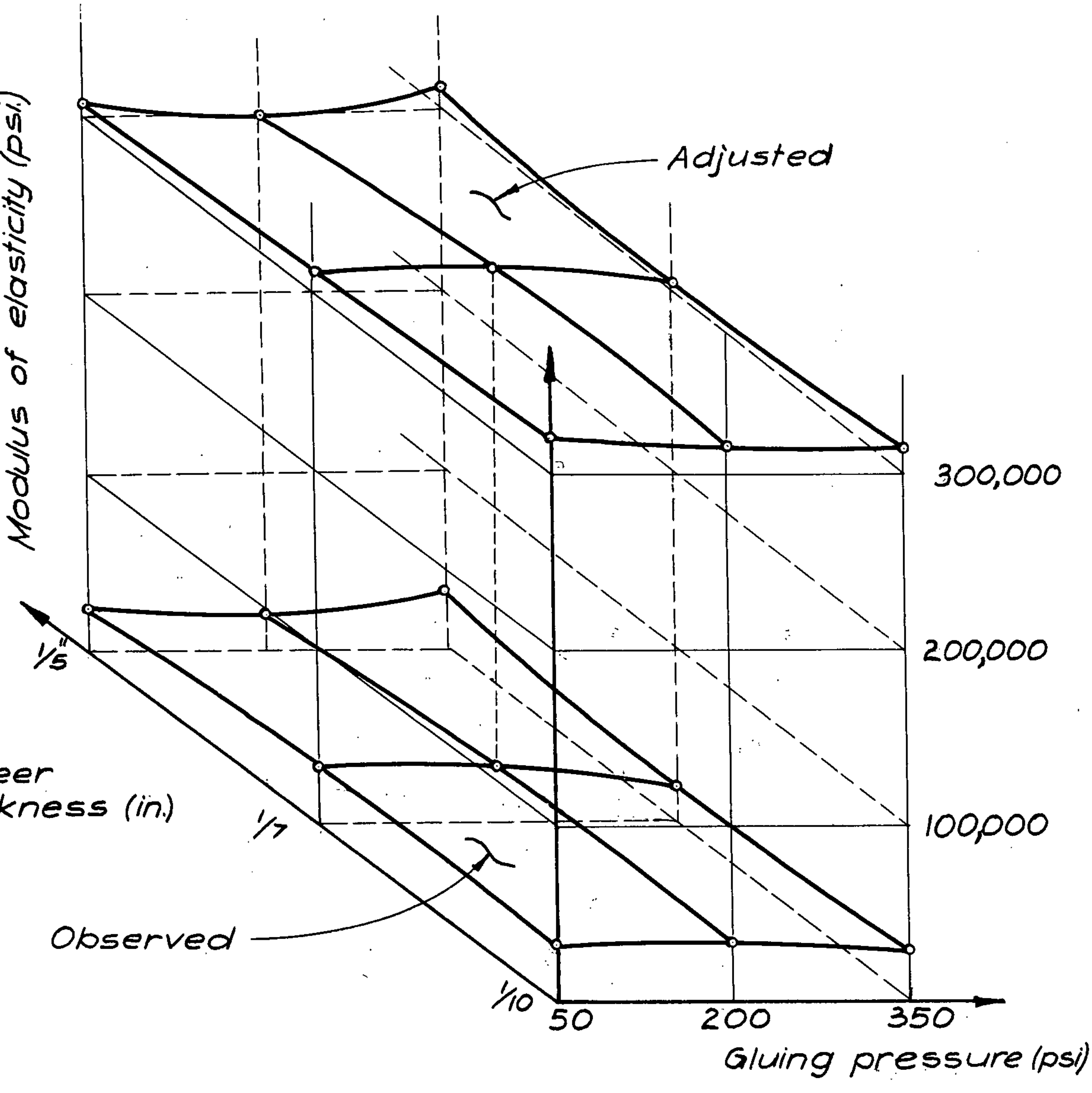

Figure 7. Influence of controlled factors on modulus of elasticity of sawn-veneer blocks in tension.

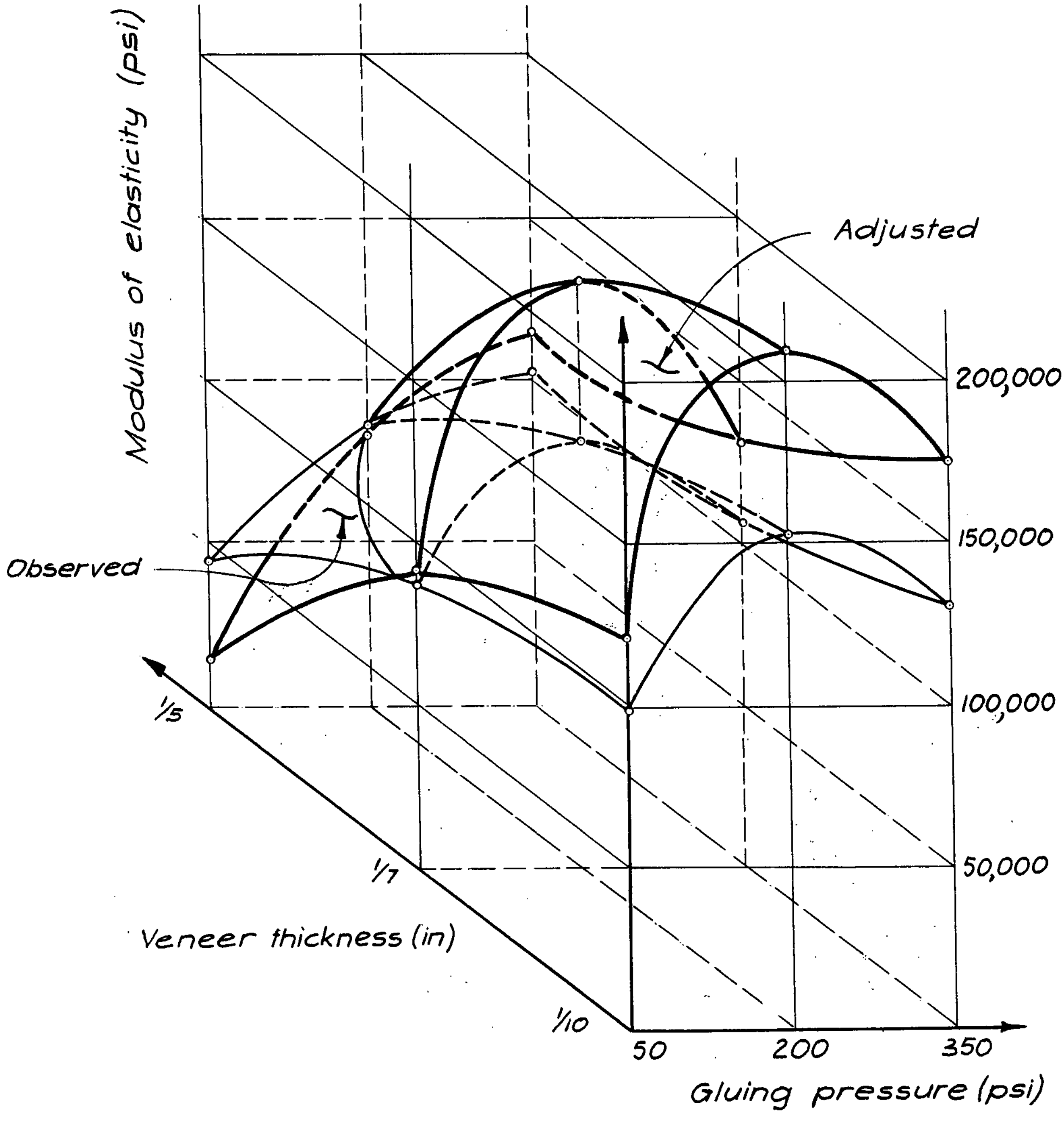

Figure 8. Influence of controlled factors on modulus of elasticity of rotary-cut veneer blocks in compression.

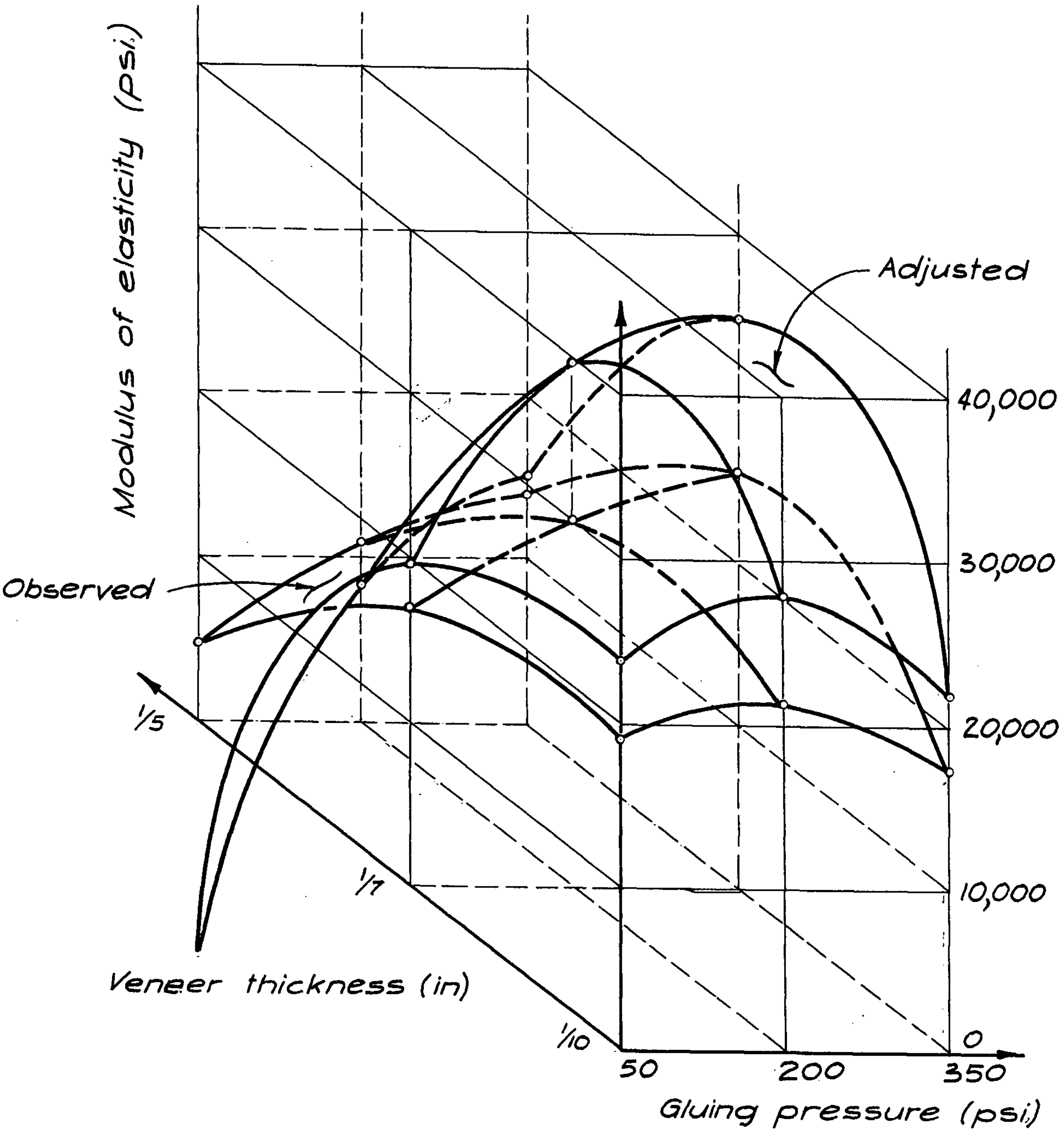

Figure 9. Influence of controlled factors on modulus of elasticity of rotary-cut veneer blocks in tension.