STRESS-GRADES FOR PINUS RADIATA PLYWOOD FROM BASIC DENSITY AND KNOT RATIO

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ABSTRACT

From density measurements on **Pinus radiata** D. Don peeler logs, veneer, and plywood, and from bending tests on 5- and 7-ply panels, relationships were derived that predict plywood panel density, bending strength, modulus of elasticity, and compression strength of clear plywood from the basic density of peeler logs. The property-reducing effects of knots were then superimposed on these predictions in an assessment of the log resource that showed current plywood quality may be at least one stress-grade better than the stress values implied by the New Zealand design code. On the other hand, low-density logs yielded plywood with strength properties less than these values. Density of logs and average knot ratios required to achieve desired stress-grades were also identified.

Keywords: plywood; stress-grades; density; log quality; strength; stiffness; knot ratio; **Pinus radiata**.

INTRODUCTION

The usefulness of plywood as a structural panel material depends on its mechanical properties. These depend on the properties of each veneer which in turn depend on the intrinsic wood properties and on the size and position of visual characteristics such as knots.

Wood properties and visual characteristics are integral to the species and the way it is grown. For *Pinus radiata* the clearwood strength properties, the density, and visual characteristics vary according to site and silvicultural treatment (Walford 1985; Cown & McConchie 1983; Bunn 1981).

The allowable stresses in the current New Zealand Standard for plywood design were derived from tests on *P. radiata* plywood produced from the central North Island and Nelson districts in the 1960s (SANZ 1981). These stresses were obtained by:

(a) Testing clear plywood to determine clearwood strength properties;

(b) Limiting the resource to specific districts to control density variation;

(c) Modifying the clear properties for grade by the expected effects of visual characteristics such as knots, splits, and core gaps.

Since these values were derived, other forests have become available. For a national evaluation of the log resource it would be convenient if plywood properties could be predicted direct from log properties. A basis for predicting strength from plywood panel properties already exists. In previous studies (Bier 1983a, 1984a) clear plywood compression strength, bending strength, and stiffness increased with increasing panel density. For in-grade plywood in bending it was found that knots had the greatest effect on strength, though panel density had the greatest effect on stiffness. A model of the bending behaviour of panels containing knots (Bier 1983b) was derived. To evaluate a given log resource for plywood the relationship between panel density and peeler log density must be quantified. Further, if plywood strength properties could be directly predicted from log density variables this intermediate step could be avoided.

The two main objectives in this study were to:

(a) Quantify the dependence of clear plywood strength, stiffness, and density on wood basic density. To achieve this, bending tests were carried out on 5- and 7-ply clear plywood to exclude the knot variables and isolate the effects of density.

(b) Determine what stress-grades of structural plywood (containing knots) result from logs of different quality. This is calculated by superimposing the strength-reducing effects of knots on the clear plywood properties predicted for given densities using the relationships found in (a).

EXPERIMENTAL WORK

Peeler Bolts

Pruned butt logs 5.2 m long were selected to cover a range of diameters as part of a peeling study (Park, in press). Four peelers (41, 50, 61, and 74 cm dbh) were obtained from Cpt 1250 of Kaingaroa State Forest, the age at felling being 27 years. Six larger-diameter logs (59 to 81 cm dbh) were obtained from 42-year-old trees from Cpt 28 of Waiotapu Forest. Each log was cut in half to provide lower (A) bolts and upper (B) bolts.

An increment core directed at the pith was obtained from both ends of each bolt to evaluate the log density profile from bark to pith. Bolts were then peeled to produce veneer of nominal thickness 3.2 mm when dry.

Selection of Veneers

Clear 2.5 × 1.25-m veneers were selected to obtain material of different age and density. From the younger trees the first six sheets were peeled from outer-zone wood from each of three A bolts and three B bolts. From the older trees the first six (from older higher-density outerwood) and last six (younger innerwood) usable clear sheets were obtained. Each veneer was referenced to the peeling study to enable a reconstruction of the bolt to determine the distance of the veneer from the centre of the log. Basic density was determined for each veneer by plotting its position in the log on the density profile obtained from the increment bore.

Veneer Measurements

Each sheet of veneer was dried and then a 50-mm-wide strip was cut across the middle of the sheet. The thickness of the two remaining half sheets of veneer was measured at the middle of each of the four edges to obtain an average thickness. The 50-mm specimen was cut into four pieces, weighed, measured by volume displacement, and oven dried to determine nominal density and moisture content.

Plywood

A panel of 15-mm-thick 5-ply and a panel of 21-mm-thick 7-ply plywood were manufactured from each sample of 12 half sheets of veneer. These were laid up with either high-density (i.e., outermost peeled) or low-density (i.e., innermost peeled) faces and backs.

The glue used in manufacture was phenol formaldehyde resin (ICI P101) with olive stone filler and wheat flour extender to yield a solids content of 50%. Glue spread was 0.2 kg/m^2 per glueline.

Before pressing, aggregate veneer thickness for the panel was determined as the sum of individual dry veneer thicknesses. After pressing, it was measured on the middle of each of the four edges of the panel.

Bending Tests

Specimens 600, 300, 150, and 50 mm wide were cut from each of 18 sheets of 5-ply plywood and 17 sheets of 7-ply plywood. These specimens were tested in third-point bending according to the method described by Bier (1983a). A further 50-mm specimen from each panel was tested according to ASTM D3043 Method A (ASTM 1981) described by Bier (1984a). The influence of testing method and specimen width on strength and stiffness have been reported elsewhere (Bier 1984b). This study uses the results from the 600-mm-wide panels and the ASTM tests. Equations for calculating the apparent modulus of elasticity (E), the true modulus of elasticity (pure bending) (E_t), and modulus of rupture (R) have been given elsewhere (Bier 1984b).

A 200 × 50-mm sample from the ASTM specimens and a 200 × 100-mm sample from across the larger specimens were obtained to determine nominal density and moisture content at test.

RESULTS AND ANALYSIS

Plywood Nominal Density from Basic Density of Peeler Wood

The density of plywood is dependent on the density of the wood veneer, compression due to pressing, thickness of the glueline, and solids content of the glue. These variables were used to derive a theoretical prediction of panel density, which was then compared with regression equations from the data. The results of veneer thickness and density measurements for each panel are presented in Table 1.

The average difference between aggregate veneer thickness before and after pressing divided by the number of gluelines yields a value of 0.2 mm compression per glueline for both 5- and 7-ply panels, or 6% of the initial thickness. This is between two types of compression observed in *Pseudotsuga menziesii* (Mirb.) Franco by Wellons *et al.* (1983) and is consistent with the observations of Curry & Hearmon (1974) who observed that compression was confined to thin layers adjacent to the glueline. They also noted the thickness of these layers was independent of veneer thickness.

TABLE 1—Physical properties of veneer and plywood from each peeler bolt

Tree	Bolt		Number of plies	Aggregate veneer thickness before pressing (mm)	Aggregate veneer thickness after pressing (mm)	Average veneer nominal density (kg/m³)	Average density at veneer position (kg/m³)	Average† nominal density of panel (kg/m³)
Cpt 28 Waiotapu								
32	A*		5	15.82	15.29	520	463	541
			7	22.32	21.25	520	498	554
34	A	outer	5	15.82	14.69	545	524	588
			7	22.22	21.02	548	526	637
		inner	5	15.66	14.99	540	495	586
			7	22.10	21.49	516	494	591
36	A	outer	5	15.86	14.19	605	522	598
			7	21.98	21.11	585	522	637
		inner	5	16.25	15.19	573	463	586
			7	22.71	21.72	567	463	580
38	A	outer	5	15.65	14.79	486	442	544
			7	22.21	20·91	475	440	530
		inner	5	16.27	15.56	441	410	461
			7	22.73	22.09	439	407	476
40	A	outer	5	15.46	14.88	485	464	564
			7	22.08	21.16	492	462	545
		inner	5	16.05	15.38	457	430	517
			7	22.53	21.30	470	430	507
42	A	outer	5	15.73	14.83	453	466	513
			7	22.21	21.11	487	464	540
		inner	5	16.08	15·49	452	432	491
			7	22.56	21.30	458	430	491
Cpt 1250 Kaingaroa								
48	A	outer	5	15.83	14.91	500	462	516
			7	22.27	21.04	490	458	518
50	A	outer	5	15.76	15.01	420	399	468
			7	22.46	21.07	425	399	455
50	B	outer	5	15.88	15.42	421	397	455
			7	22.52	21·08	402	394	457
52	A	outer	5	15.87	15.05	460	456	501
			7	22.53	21.57	475	456	531
52	B	outer	5	15.91	15.33	462	429	508
54	A	outer	5	16.06	15.33	445	389	480
			7	22.62	21.18	448	389	467
54	B	outer	5	15.84	15·12	414	401	483
			7	22.74	21.00	423	401	461

* A composite panel with usable sheets from Tree 32 and spare sheets from Tree 34.

† Mean of densities of all bending test specimens from each plywood sheet, weighted for specimen width.

In the following analysis and discussion the density terms are defined as:

ND_p nominal density of panel (at a specified moisture content of 10% approx.), determined from the specimens cut from each test piece.

D_p basic density of wood from which veneer was cut (average for panel), determined from the position in the log.

D_v basic density of wood from which veneer was cut (for a single veneer), determined from the position in the log.

ND_v nominal density of veneer, determined from veneer strip specimens.

For a panel of n veneers each of a final thickness t, it is possible to develop a theoretical prediction of panel density.

If the thickness of each glueline is a and the observed nett compression is 0.2 mm then:

total thickness before compression

$$= tn + (n - 1)(0.2 + a)$$

and thickness after

$$= tn$$

Therefore the nominal density of the panel is

$$ND_p = \frac{tn + (n-1)(0.2 + a)}{tn} ND_v + \frac{n-1}{n}\,\frac{1000\ Sc}{t} \qquad (1)$$

where S is the glue spread (kg/m^2) and c is the solids content of the glue.

The glueline thickness can be calculated from

$$a = \frac{Sc}{\rho_g}\gamma$$

where ρ_g is the density of glue solids (1.3 g/cc) and γ is the proportion of glue not impregnating into the wood veneer (voids and lathe checks) (assumed 40%). Thus:

$$a = \frac{0.2 \times 0.5}{1.3} \times 0.4$$
$$= 0.03 \text{ mm}$$

Substituting for 5- and 7-ply plywood and 3-mm veneers in (1) we obtain:

5-ply $ND_p = 1.061\ ND_v + 26.7$ (2)

7-ply $ND_p = 1.065\ ND_v + 28.6$ (3)

Dry veneer density is related to the basic density of the log wood and is affected by shrinkage. From the conversion equations given by Collins (1983) an approximate relationship can be determined for veneer at 10% moisture content as

$$ND_v = 1.09\ D_p$$

assuming the mean value from Table 1 as an average value for the basic density (D_p) of veneers in the panel.

Substituting this in Equations (2) and (3) yields

5-ply $ND_p = 1.15\ D_p + 26.7$ (4)

7-ply $ND_p = 1.16\ D_p + 28.6$ (5)

These relationships may be compared with the regressions for the data from different bending test specimens (Table 2) in Fig. 1.

The theoretical predictions of panel density (Equations (4) and (5)) are consistently higher than the regression predictions by less than 4% or about one standard deviation. The regression equations are similar over the density range. Equation (6) (Table 2)

TABLE 2—Regression equations showing relationship between plywood panel density and basic density of peeler wood

Equation	r^2	Mean dependent variable (kg/m³)	Residual s.d./mean (%)	
5-ply (ASTM-1981)				
ASTM 50 mm wide				
$ND_p = -15.5 + 1.21\ D_p$	0.76	527	5.3	
600 mm wide				
$ND_p = 62.9 + 1.03\ D_p$	0.79	522	4.2	
7-ply (ASTM-1981)				
ASTM 50 mm wide				
$ND_p = -51 + 1.06\ D_p$	0.72	529		
600 mm wide				
$ND_p = -0.9 + 1.17\ D_p$	0.89	524	3.5	Equation (6)
Combined 5- and 7-ply 600-mm-wide panels				
$ND_p = 30 + 1.10\ D_p$	0.84	524	3.8	Equation (7)

for 7-ply 600-mm-wide panels is superimposed in Fig. 2 on individual data points plotted with log number identifiers. The densest panels came from the densest oldest trees. Veneers cut from lower-density innerwood yielded lower-density plywood than high-density veneers cut from the outerwood of the same log. The trend is thus consistent between trees for plywood produced from both young and old stands, and for plywood from different density parts of the same tree. Since the 600-mm-wide panels represent the largest portion of each sheet of plywood, it is reasonable to assume that these provide the best estimate of panel density. The data for both 5- and 7-ply were therefore combined to provide the relationship in Equation (7) (Table 2) which is consistent with a glue content term and about 10% densification due to processing. The equation is slightly conservative relative to the theoretical predictions of Equations (4) and (5). It is concluded that the simple relationship in Equation (7) can be used to predict plywood panel density from peeler wood density.

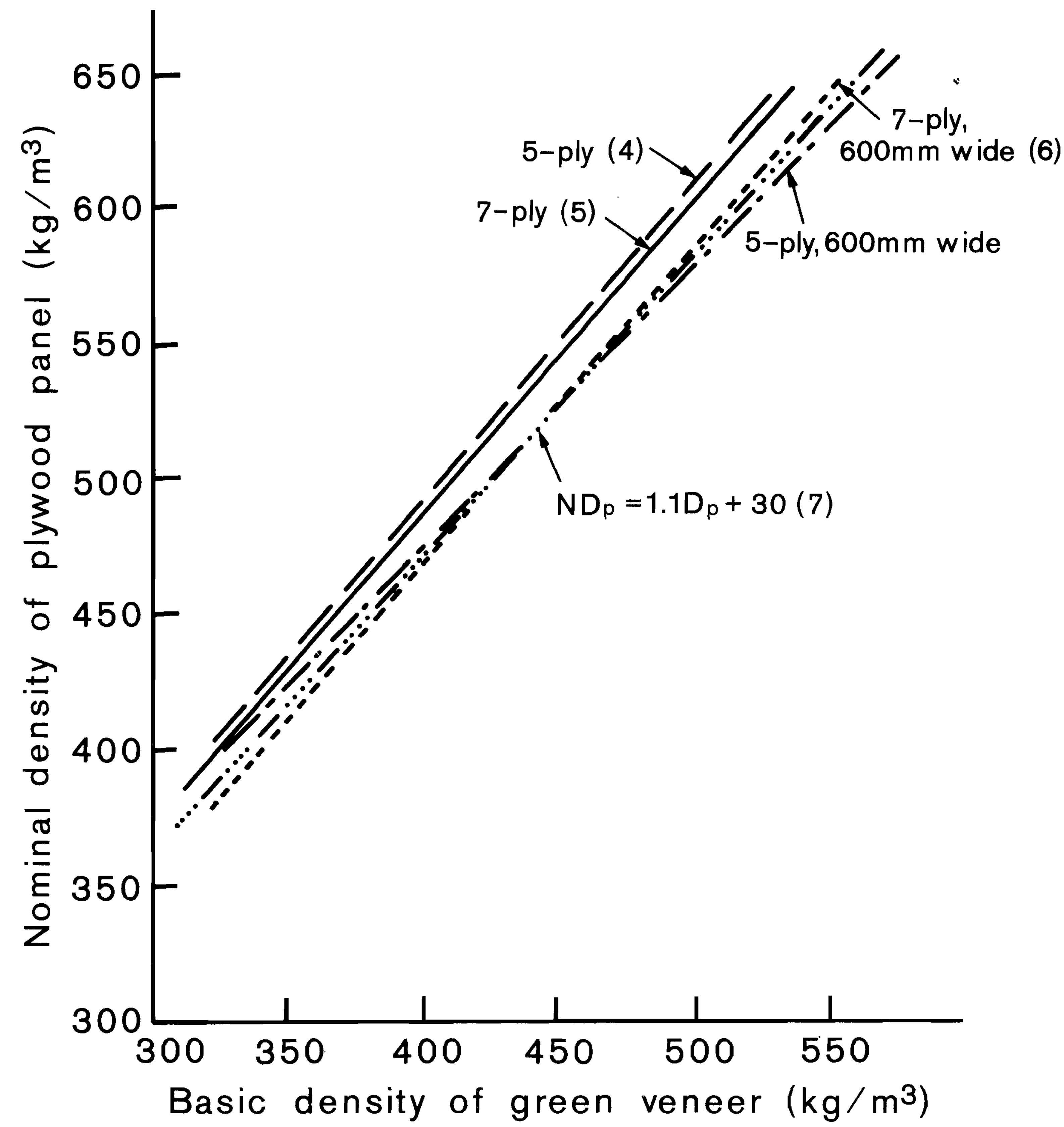

FIG. 1—Comparison of theoretical Equations (4) and (5) with empirical relationships between panel nominal density and wood basic density

Predicting Strength and Stiffness from Density of Plywood and Density of Peeler Wood

The properties of 50-mm-wide ASTM specimens and 600-mm-wide specimens are given in Table 3. These are presented because ASTM is a standard method for small clear specimens of plywood, and the others were tested in the same way as the in-grade tests referred to in earlier work (Bier 1983b). Predictions developed in the present study will therefore be applicable to results from either of the two methods. The analyses by Bier (1984b) showed there was no difference between the apparent E values for the two tests, but the R values for the third-point loading were lower than the ASTM test R values, with the difference attributed solely to test method. (There were no differences due to width changes.)

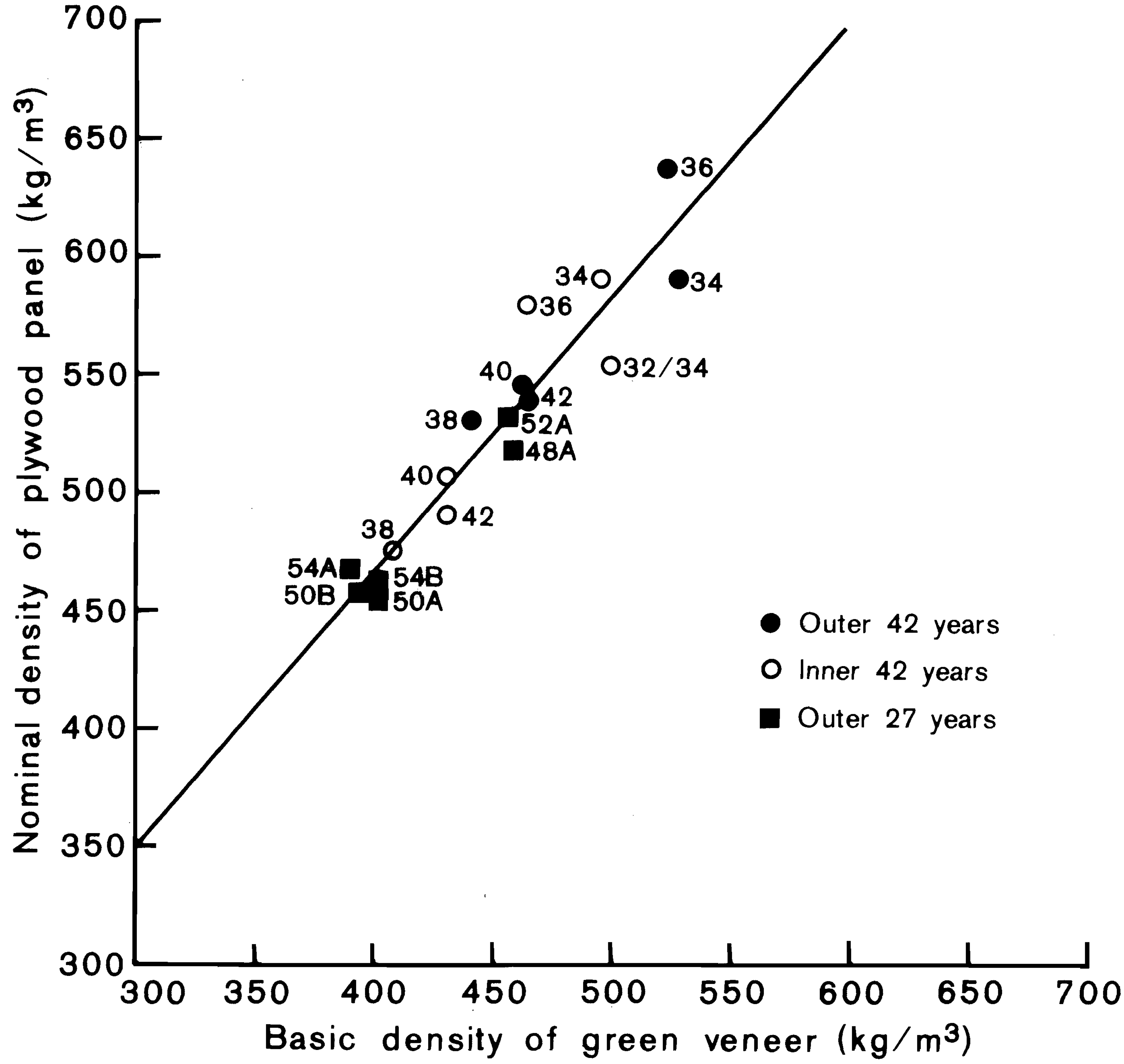

FIG. 2—Effect of basic density on panel density (7-ply, 600-mm).

From the data in Table 3 regression equations in Tables 4 and 5 relate strength (modulus of rupture R (MPa)) and stiffness (as indicated by modulus of elasticity E (GPa)) to the nominal density (kg/m^3) of the clear plywood (ND_p) and the average basic density of the veneers in the panel D_p. Regressions (not tabled) were also carried out on the density of the outer veneers (face and back).

All regressions were significant at $p = 0.01$, with two-thirds of them significant at $p = 0.001$.

Little was gained from using the density of the face or back veneers instead of over-all panel densities, with about half the regressions yielding higher r^2 values and half lower. Since outer veneer density would be difficult to measure in plywood manufacture, the panel density regressions are preferred.

Two of the regressions have been plotted with the test data on Fig. 3 and 4. With the exception of the E values for the panel from Log 38 inner veneers, the outer high-density old tree veneers provided the stiffest and strongest plywood, and the inner

TABLE 3—Properties of two constructions of plywood for two test methods and two widths

Log No.	Common densities (kg/m^3)			ASTM (1981) D3043 centre-point flexure 50-mm-wide specimen					Third-point flexure 600-mm-wide specimen					
	D_p	D_v	ND_v	ND_p (kg/m^3)	mc (%)	R (MPa)	E (GPa)	Latewood (%)	ND_p (kg/m^3)	mc (%)	R (MPa)	E_t (GPa)	E (GPa)	Latewood (%)
5-ply														
32Ac*	463	491	527	548	11.9	82.5	11.8	35	541	11.2	75.2	16.6	14.9	32
34A	524	531	523	589	11.4	79.5	14.7	20	588	12.5	72.6	17.5	16.1	29
34Ai	495	493	541	610	10.8	100.7	15.1	0	586	12.1	65.5	14.6	13.5	50
36A	522	522	591	628	10.6	109.2	17.7	90	598	11.7	78.1	17.3	16.7	39
36Ai	463	463	551	615	10.3	89.3	12.4	40	586	11.5	69.5	14.6	13.4	21
38A	442	450	494	543	11.6	90.6	14.1	5	544	10.7	72.5	14.0	13.0	18
38Ai	410	401	429	493	11.6	70.2	7.7	12	461	11.4	41.0	8.1	7.2	8
40A	464	462	485	524	11.1	84.1	13.3	22	564	10.6	61.8	13.2	12.5	25
40Ai	430	430	450	477	10.8	85.0	10.4	20	517	11.8	50.6	10.7	10.3	44
42A	466	480	406	548	10.8	75.2	12.0	47	513	10.2	62.4	12.0	10.9	52
42Ai	432	430	453	470	10.9	64.2	9.4	10	491	11.6	60.4	13.0	10.2	12
48A	462	468	515	517	10.9	84.4	15.0	50	516	11.8	69.6	12.6	13.4	28
50A	399	399	425	479	11.2	69.1	9.4	15	468	11.6	52.2	11.3	10.2	16
50B	397	392	391	464	11.4	68.5	8.9	0	455	12.2	57.3	10.3	10.9	18
52A	456	457	459	513	11.9	79.3	10.4	80	501	11.9	56.6	11.6	10.7	37
52B	429	427	457	487	9.0	76.7	10.7	0	508	12.0	61.1	11.2	10.6	27
54A	389	389	468	462	10.9	79.8	10.6	0	480	11.9	57.9	11.2	10.7	40
54B									483	11.5	57.6	13.7	12.0	20
7-ply														
32Ac	498	501	489	587	12.5	92.4	13.9	50	554	12.8	78.4	15.9	13.1	40
34A	526	531	535	579	11.7	84.1	14.1	40	590	10.6	77.4	18.9	15.2	37
34Ai	494	493	526	575	11.4	86.5	14.5	32	591	11.4	73.3	16.8	13.9	34
36A	522	522	604	621	11.1	112.8	15.9	45	637	11.0	86.3	19.7	15.8	45
36Ai	463	463	552	599	10.7	81.1	12.4	20	580	10.5	74.5	14.8	13.4	23
38A	440	449	488	531	11.0	93.1	13.5	30	530	11.8	73.1	15.1	16.9	28
38Ai	407	401	419	501	10.8	60.1	7.1	5	476	10.3	54.6	8.2	7.5	14
40A	462	462	518	546	11.4	82.4	11.7	50	545	11.9	69.1	13.9	12.7	45
40Ai	430	430	449	571	11.4	79.9	11.0	3	507	10.6	52.8	12.4	9.6	19
42A	464	477	482	536	11.2	73.3	10.4	24	540	10.7	63.5	12.7	10.4	27
42Ai	430	430	465	504	11.6	74.3	9.5	25	490	10.8	58.9	11.6	10.1	16
48A	458	458	497	509	12.0	83.4	13.4	20	518	12.3	73.0	15.1	12.5	27
50A	399	399	432	468	10.8	56.4	8.3	60	455	11.3	65.5	14.2	11.8	27
50B	394	390	401	488	11.8	91.7	12.2	70	457	11.6	59.3	10.7	9.4	16
52A	456	457	486	499	11.5	69.6	11.7	75	531	11.7	63.3	12.8	9.8	30
54A	389	389	444	430	12.8	45.2	10.1	25	467	11.4	51.2	11.6	9.7	17
54B	401	401	424	448	12.9	66.5	10.1	2	461	12.3	52.3	14.4	11.1	25

* Ac composite panel made from veneers from three logs
Ai panels made from inner veneers

TABLE 4—Regression equations showing dependence of strength and stiffness on nominal density for ASTM (1981) tests

Equation	r^2	Mean dependent variable	Residual s.d./mean (%)
5-ply			
$E = -8.19 + 0.0383\ ND_p$	0.63	12.0	14.0
$R = -3.1 + 0.161\ ND_p$	0.60	81.7	9.3
7-ply			
$E = -3.77 + 0.0294\ ND_p$	0.47	11.8	15.0
$R = -40.7 + 0.225\ ND_p$	0.59	78.4	13.5

TABLE 5—Regression equations showing dependence of strength and stiffness on basic density

Equation	r^2	Mean dependent variable	Residual s.d./mean (%)
5-ply ASTM (1981), 17 tests			
$E = -13.1 + 0.056\ D_p$	0.70	12.0	12.6
$R = -4.9 + 0.192\ D_p$	0.45	81.7	10.9
7-ply ASTM (1981), 17 tests			
$E = -7.19 + 0.042\ D_p$	0.61	11.8	12.8
$R = -34.0 + 0.250\ D_p$	0.46	78.4	15.4
5-ply 600-mm-wide, third-point loading, 18 tests			
$E = -8.52 + 0.046\ D_p$	0.62	12.1	12.2
$R = -13.0 + 0.169\ D_p$	0.51	62.3	11.0
7-ply 600-mm-wide, third point loading, 17 tests			
$E = -6.07 + 0.040\ D_p$	0.46	11.9	16.5
$R = -25.4 + 0.204\ D_p$	0.72	66.3	8.6

older tree veneers overlapped with the outer veneers of the young trees. Trends within logs (e.g., Logs 36 and 34) were virtually parallel to the regression line. From these observations it may be inferred that the results can be used for the evaluation of both old and young stands.

The panels made from the inner veneers of Log 38 had the lowest E value in all four test results. One contributing factor was that there was an extremely low percentage of latewood in the outer veneer of the panel. This is indicated by the data for the 600-mm-wide 5-ply panel which represents half of one sheet. Regressions on latewood were, however, not significant because of the high variability of the data.

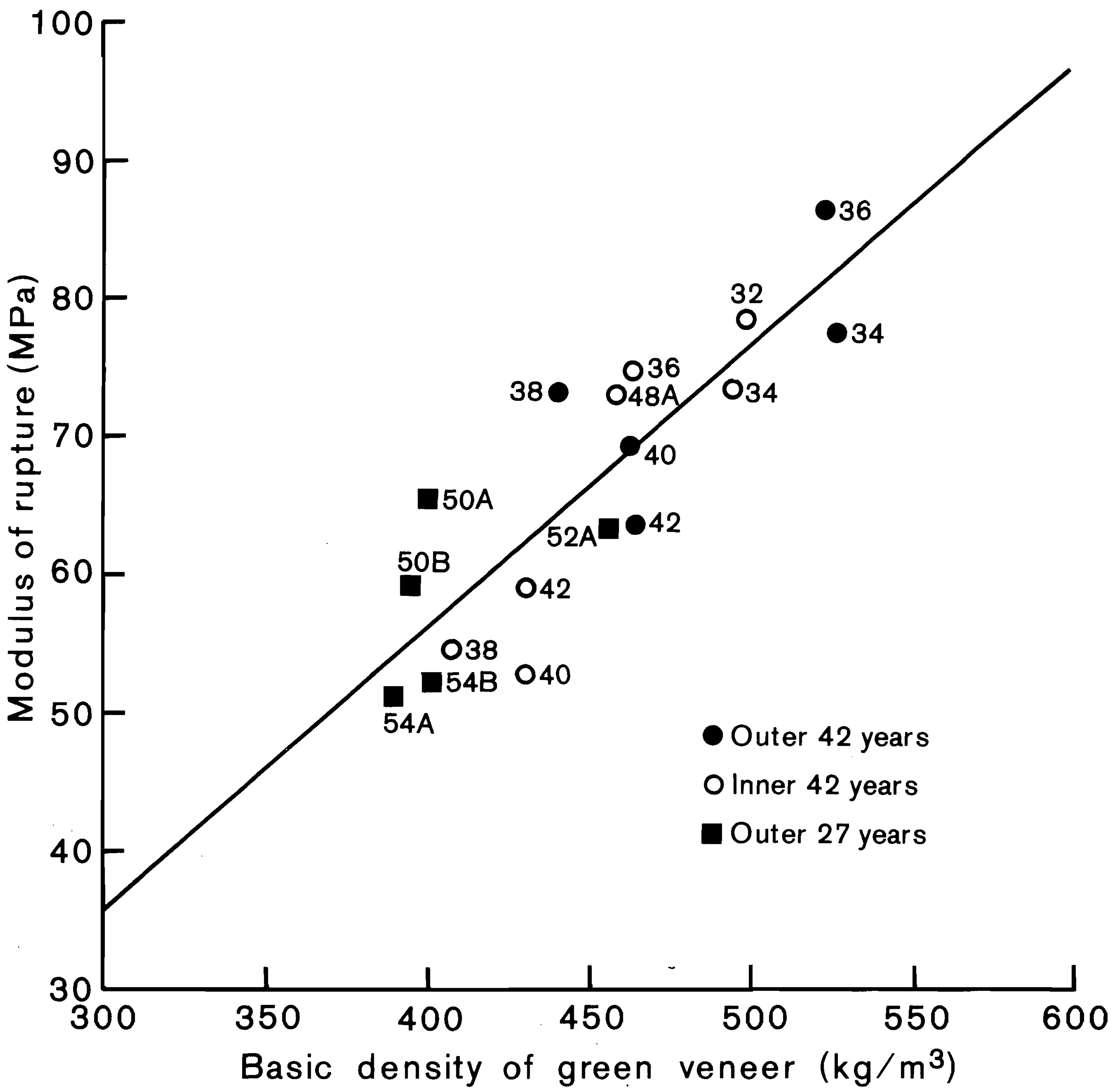

FIG. 3—Effect of basic density on panel strength (7-ply, 600-mm).

EVALUATION OF LOG RESOURCE FOR PLYWOOD

Nominal Density of Plywood from Log Density

To assess the potential of a log resource for plywood, allowance must be made for the density of wood lost in round-up and for the wood extracted in the peeler core. The density of wood available for peeling will depend on the silvicultural history of a given stand since extremely fast-grown trees will have different density profiles from trees that have been suppressed. Cown & McConchie (1983) have presented values of basic density for butt logs and outerwood densities of trees of given age-classes. These were based on assumed stocking and tending regimes with average contemporary silviculture that excludes extreme effects.

There is evidence that, for such average silviculture, corewood size is similar for trees of different ages (R. N. James pers. comm.). Core density effectively reduces the average density of the tree because it is substantially lower than wood in the outer zone, and the bulk of the wood in the outer zone has a much flatter density gradient than

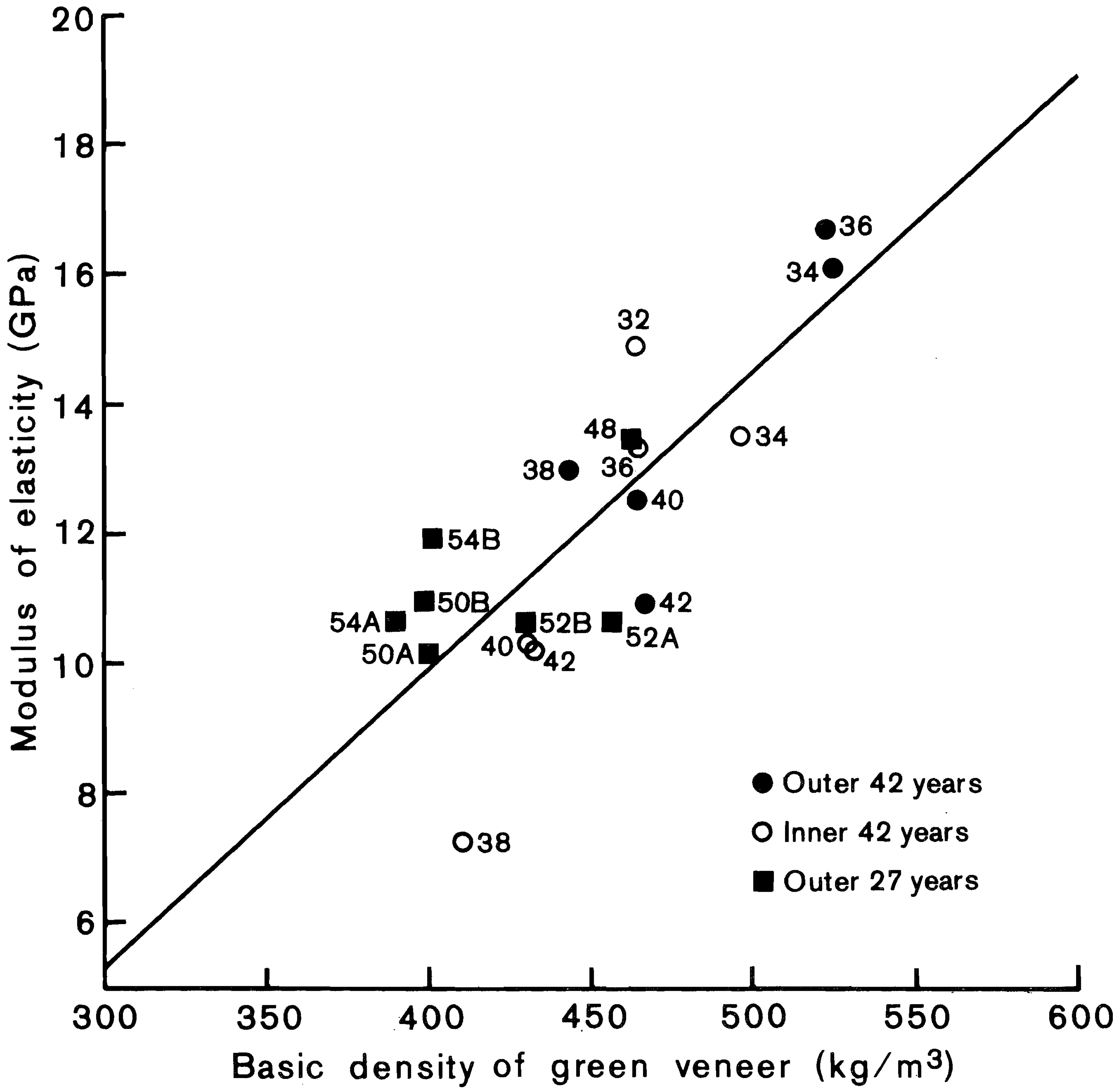

FIG. 4—Effect of basic density on panel stiffness (5-ply, 600-mm).

the corewood. If the low-density wood is removed in the peeler core, then wood available for peeling will be closer in density to that of the outer five rings. For a general assessment, the basic density of wood available for peeling was derived using a value less than the outerwood density by about one-third of the difference between the outerwood and butt log densities given by Cown & McConchie (1983).

This yielded the panel densities in Table 6 from Equation (7) for different ages and site density classes, and assumes only butt logs are peeled. A more accurate assessment could be obtained for a given stand if the density profiles of the peeler logs were known.

Plywood Properties for a Given Log Resource

To derive E and R values for (say) 5-ply plywood, basic peeler wood densities from Table 6 were substituted in the regressions in Table 5. Values for compression parallel to grain (C) were derived from the nominal panel density in Table 6, and the following regression (Equation (13) Bier 1984a).

$$C = 0.121 \ ND_p - 11.6$$

TABLE 6—Plywood panel density by site density class and age of butt log

Site density class*	Age (yr)	Basic density of peeler wood in butt log† (kg/m³)	Nominal panel density at 10% mc‡ (kg/m³)	Density at 10% mc§ (kg/m³)
High density				
Northland; Auckland;	15	440	514	565
Waikato;	25	490	569	625
coastal Rotorua;	35	505	585	645
coastal Nelson;	45	510	591	650
coastal Marlborough;				
Medium density				
inland Rotorua;	15	390	459	505
Hawke's Bay;	25	450	525	580
inland Nelson;	35	460	536	590
inland Marlborough;	45	470	547	600
coastal Wellington;				
coastal Taranaki				
Low density				
inland Wellington;	15	370	437	480
inland Taranaki;	25	420	492	540
Westland; Canterbury;	35	435	508	560
Otago; Southland	45	445	520	570

* See Cown & McConchie (1983) Fig. 5
† o.d. weight/green volume
‡ o.d. weight/volume at test
§ test weight/volume at test

This yielded the values in Table 7 for clear plywood.

The E values may be assessed in terms of standard plywood stress-grades (SAA 1975). Dry F8, F11, F14, and F17 plywood should have moduli of elasticity of 9.1, 10.5, 12.5, and 14 GPa. (There is a smaller than 2% adjustment of E required for the difference between moisture content for the plywood in this study (about 11%) and the moisture content in the standard (12%), so this has been ignored.) The resulting stress-grades for clear plywood are included in the Table. Structural plywood contains defects, particularly in the inner plies. For 5-ply plywood 98% of bending stiffness is provided by the face and back plies. The relationships derived in this study for clear plywood are therefore directly applicable to structural plywood with clear faces and backs (A-A grade). For lower grades a grade factor is superimposed to allow for the property-reducing effects of defects.

Any visual grade of plywood has a lower limit on the aggregate number or size of defects (knots) in the face veneer. For a given grade, however, there is a range of knot ratios (K) and the average E value of the grade will be determined by the average knot ratio, not the lower limit. The precise distribution of knot ratios (and its mean)

TABLE 7—Plywood strength and stiffness by site density class and age of butt log - dry 5-ply plywood

Site density class*	Age (yr)	E (GPa)	R (MPa)	C (MPa)	Stress-grade for clear plywood
High density	15	11.5	79.6	50.6	F11
	25	14.3	89.2	57.2	F14
	35	15.2	92.0	59.2	F17
	45	15.5	93.0	59.9	F17
Medium density	15	8.7	70.0	43.9	F8
	25	12.1	81.5	51.9	F11
	35	12.7	83.4	53.3	F14
	45	13.2	85.3	54.6	F14
Low density	15	7.6	66.1	41.3	
	25	10.4	75.7	47.9	F8
	35	11.3	78.6	49.9	F11
	45	11.8	80.5	51.3	F11

* See Table 6
E = modulus of elasticity (measure of stiffness)
R = modulus of rupture (measure of strength)
C = compression parallel to grain

will depend on each grade, and may vary according to the branch characteristics of the log resource.

The prediction of average E for structural plywood can be made for an average knot ratio using the equation by Bier (1983b) for 5-ply plywood.

$$E_{\text{in-grade}} = E_{\text{clear}} (1 - 0.783 (1 + 0.13K) K)$$

For knot ratios of 0.1, 0.2, 0.3, and 0.4 this gives grade factors 0.92, 0.84, 0.76, and 0.67. When these grade factors are applied to the E values given in Table 7 and compared with the stress-grade moduli from SAA (1975), the plywood stress-grades in Table 8 are obtained.

TABLE 8—Prediction of stress-grades from mean knot ratio of graded plywood*

Site density class	Age (yr)	Mean knot ratio				
		Clear	0.1	0.2	0.3	0.4
High	15	F11	F11	-		
	25	F14	F14	F11	F11	F8
	35	F17	F17	F14	F11	F8
	45	F17	F17	F14	F11	(F11)
Medium	25	F11	F11	F8	F8	
	35	F14	F11	F11	F8	
	45	F14	F11	F11	F8	
Low	25	F8	F8			
	35	F11	(F11)	F8		
	45	F11	F11	F8		

* Grades in parentheses had E values 0.1 less than requirement for that grade

The knot ratio for the lower limit allowed for Australian stress-grades is 0.4. For the sample of plywood tested by Bier (1983a), the average for the knotty panels with K greater than 0.4 was 0.183. From K = 0.2 in Table 8, F11 stress-graded plywood of this visual quality can be obtained from older age-class trees on high- and medium-density sites but not from medium-density young trees or low-density sites.

If current standards are to be maintained, and if New Zealand *P. radiata* plywood is to retain an F11 stress-grade rating on the Australian market, both visual grade and the age and density of the peeler log source are important.

The predictions in Table 8 indicate the average stress-grades for visual grades of plywood in each density group. In any one stand there will be a range of log densities and log grades, with consequent distributions of plywood density and veneer visual grade. Nevertheless, the indications of average stress-grade in this study should lead to more competitive use of plywood from the current production, and enable a more rational choice of peeler log in the future.

CONCLUSIONS

Relationships have been established that predict plywood panel density, bending strength, and modulus of elasticity from peeler wood density. Evaluations indicate that plywood from currently used log resources, although being sold as F11 grade, is in fact of better quality. The age and density of logs required to produce various plywood stress-grades can be identified.

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