CONFINED AND UNCONFINED RADIAL COMPRESSION PERPENDICULAR TO THE GRAIN OF GREEN SAPWOOD FROM PINUS RADIATA AND EUCALYPTUS REGNANS

R. WINGATE-HILL
CSIRO Division of Forest Research, P.O. Box 4008, Canberra,
A.C.T. 2600, Australia

and R. B. CUNNINGHAM
Department of Statistics, Australian National University,
G.P.O. Box 4, Canberra, A.C.T. 2601, Australia

(Received for publication 9 May 1986; revision 10 December 1986)

ABSTRACT

Sapwood specimens from **Pinus radiata** D. Don and **Eucalyptus regnans** F. Muell. were compressed radially to high strains either between flat platens (unconfined compression) or in a jig which prevented expansion at right angles to the direction of compression (confined compression). Stress at proportional limit, stress at 12.5% strain, and work to proportional limit were analysed. Two types of equation often used to express the relationship between wood strength and specific gravity were inappropriate. The two strength properties and work to proportional limit were greater in confined compression than unconfined compression. In both forms of compression **E. regnans** specimens had greater strengths than **P. radiata** specimens.

Keywords: compression; moisture content; stress; strain; strength; **Pinus radiata**; **Eucalyptus regnans**.

INTRODUCTION

Removal of moisture from green wood by compression is a way of increasing the net usable heating value of wood and reducing the mass which may lead to a saving in transport costs (Wingate-Hill 1983a; Wingate-Hill & Cunningham 1984a). The process requires less energy per unit of water removed from green wood than the initial stages of air drying and is much quicker than air drying. Compression drying may, therefore, have a number of industrial applications (Gunzerodt *et al.* 1984; Haygreen 1981; Wingate-Hill 1983b), but more research and development are required before this potential can be realised.

Some physical and mechanical properties of sapwood derived from two compression drying experiments (Wingate-Hill 1985) on two commercially important Australian-grown species, *Pinus radiata* and *Eucalyptus regnans,* are summarised in Table 1. The specific gravities (SG) of the *P. radiata* specimens were generally greater than those of the *E. regnans* specimens but, up to the same level of strain, energy inputs per

TABLE 1—Means and ranges for some of the measured factors for **Pinus radiata** and **Eucalyptus regnans** sapwood blocks in radial compression

Property*	Type of compression	**Pinus radiata**		**Eucalyptus regnans**	
		Range	Mean	Range	Mean
Initial moisture content (%)†	Confined	86–157	115	87–165	127
	Unconfined	77–133	108	96–160	128
Reduction in percentage moisture content‡	Confined	2–69	27	0–71	24
	Unconfined	2–57	27	0–62	21
Initial specific gravity§	Confined	0.45–0.54	0.50	0.42–0.52	0.46
	Unconfined	0.50–0.57	0.52	0.43–0.49	0.46
Energy input per unit initial mass (J/g)‖	Confined	0.1–2.1	0.8	0.2–2.7	1.3
	Unconfined	0.1–2.1	0.8	0.2–2.8	1.2

* Initial = immediately before compression.

† Oven-dry basis.

‡ (Initial moisture content (%) – Final moisture content (%)).

§ Oven-dry mass/Mass of a volume of water equal to the green volume of the specimen.

‖ Area below load, deformation graph/Initial mass of specimen.

unit initial mass were higher in *E. regnans* than *P. radiata*. Differences between the two species were expected because of such factors as contrasting wood structures and differences in degrees of saturation. However, it has generally been found that mechanical strength properties of wood, which influence energy input during compression, are positively correlated with wood SG and that wood strength can be estimated from SG (but at lower strains than those used in the two compression drying experiments – 5% to 40%). For example, Koch (1972) expressed some wood strength properties in the form:

$$S = X + Y.SG \qquad (1)$$

where S is a wood strength property

X,Y are constants which depend on the strength property being considered

SG is wood specific gravity (oven-dry mass/mass of a volume of water equal to the wood volume at current moisture content)

Forest Products Laboratory (1974) and Panshin *et al.* (1964) expressed the relationship between wood strength properties and SG in the form:

$$S = X(SG)^{Y} \qquad (2)$$

where the symbols have the same meaning as in Equation (1).

Data gathered during confined and unconfined compression perpendicular to the grain experiments on sapwood were analysed to assess the unexpected relativities between the two species. Both types of compression were studied because during compression drying of green wood in the form of logs, sawn timber, or chips, some sections of the wood are likely to be subjected to conditions close to confined compression, others to conditions more akin to unconfined compression.

Sapwood strength data at the higher strains and in confined compression are included here because there is little of this information available for planning compression drying experiments and designing compression drying equipment for green wood.

MATERIALS AND METHODS

Breast height sample logs, c. 500 mm long, were cut from 28-year-old *P. radiata* trees selected at random from Pierces Creek plantation, Australian Capital Territory, 35° 21′ S, 148° 57′ E, and from 45-year-old *E. regnans* trees in a regrowth forest near Traralgon, Victoria, 38° 26′ S, 146° 32′ E. Average diameters under bark were 428 mm for the *P. radiata* logs and 269 mm for the *E. regnans* logs. To minimise moisture loss the logs were double-wrapped in polyethylene sheeting immediately after felling and stored in a coolroom. Discs c. 70 mm thick were taken from the logs, at least 70 mm from the ends, and defect-free test specimens were rough-sawn from the periphery of these discs just inside the bark. The test specimens were then finished to 20 × 20 × 60 mm with the grain of the wood parallel to the long axis of each specimen, according to the method of Wingate-Hill & Cunningham (1984b).

Specimens subjected to confined compression were inserted into a steel jig. This consisted of a thick base plate containing an open-ended groove (20 mm wide × 60 mm long) to hold the specimen and a vertical plunger with a rectangular base (20 × 60 mm). Specimens were a close sliding fit in the groove so that almost all lateral expansion was prevented and water loss was confined to the ends of the specimens. The plunger was supported in a guide so that it could be moved up and down in the base-plate slot. During testing the jig was placed between the platens of a small universal testing machine so that when the top platen moved downwards the plunger base was also forced down in the slot and compressed the specimen. Unconfined compression was carried out by compressing specimens between the flat platens of the testing machine. All specimens were compressed on their tangential faces perpendicular to the grain at a deformation rate of 8 mm per minute.

Strains (i.e., reduction in height of specimen/original specimen height) in the radial direction of 5, 10, 15, . . . 40%, i.e., steps of 5%, were imposed on the *P. radiata* specimens. The *E. regnans* specimens were subjected to similar strains except that the upper limit was 30% in confined compression and 35% in unconfined compression because the load capacity of the universal testing machine was limited. Ten unmatched specimens of each species were tested at each level of strain in each type of compression, i.e., for one batch of 10 specimens compression was halted when the strain reached 5%, for the next batch the maximum strain was 10%, and so on.

Deformation and the corresponding force on each specimen were recorded continuously by an X,Y plotter during each test.

Mechanical properties in radial compression derived from the experimental data were stress at proportional limit, stress at 12.5% strain, and work to proportional limit. The stresses at proportional limit and 12.5% strain were calculated in the manner described by Mack (1979). Strains up to about 12.5% are frequently required to achieve "significant" water loss from green wood (Haygreen 1981). The work to proportional limit is the area below the load-deformation curve up to a load corresponding to the proportional limit; it represents the recoverable work (resilience) in the sapwood.

The number of values in the data set for the stress at 12.5% strain was 25% smaller than the others because in some tests compression was halted before the strain reached 12.5% to prevent overloading of the testing machine.

RESULTS AND DISCUSSION

Equations with the same forms as (1) and (2) were fitted to the stress at proportional limit and stress at 12.5% strain data. Parameter estimates and standard errors for the parameter Y (the term directly related to specific gravity) are given in Table 2. In unconfined compression there was no significant relationship for either species between specific gravity of the specimens and the two strength properties because none of the parameter Y estimates were significantly different from zero. In confined compression the percentage of variance accounted for by the two models never exceeded 22%, indicating that they are probably of little use for predictive purposes in green sapwood and, for the two data sets used, there is probably no simple relationship between the two strength properties and initial specific gravity of the sapwood blocks.

This suggests that in the compression drying experiments water loss was more strongly related to wood structure than to SG *per se*. Jones (1981), in studies of roll splitting and dewatering of green residue wood from a number of North American species for fuelwood production, came to a similar conclusion. In the present experiments the fairly uniformly distributed tracheids in *P. radiata* with their numerous bordered pits probably formed a more permeable structure for water flow than the diffuse porous hardwood structure of *E. regnans*. Therefore, the effect of wood structure on compressive strength may have been related more to the resistance offered to water flow than to directly resisting the compressive forces – that is, the wood structure served to contain water which then shared in supporting the compressive stress.

Regression methods were used in further analyses of the data, because the levels of compression and initial moisture content of the specimens for each species were unequal in each of the experiments, and thus the two data sets could not be combined directly.

Stress at the proportional limit changed significantly with species (S) ($p < 0.001$), types of compression (C) ($p < 0.001$), and moisture content (MC) before compression ($p < 0.05$). The significant MC effect implied that the stress at proportional limit was not independent of MC above fibre-saturation point, contrary to the generally held view for unconfined compression (Koch 1972; Panshin *et al.* 1964). The trend to greater strength with increasing MC suggested that a larger proportion of the compressive load was supported by higher "free" water pressures as MC increased.

The S × C and S × MC interactions with stress at proportional limit were significant ($p < 0.01$) and the relevant values are given in Table 3. All the unconfined stress values were larger than those reported by Bolza & Kloot (1963) for tests on 50 × 50 × 50-mm heartwood blocks of the two species, tested at a deformation rate of 0.3 mm/min. The stress differences were probably caused by the differences in permeability of heart-

TABLE 2—Models relating measured strength properties of green sapwood from **Pinus radiata** and **Eucalyptus regnans** to its specific gravity

Strength property	Species	Type of compression	Model*	Parameter estimate		Parameter Y		Percentage of variance accounted for
				X	Y	Standard error	Significance	
Stress at proportional limit (MPa)	**P. radiata**	Confined	1	1.53	4.23	1.23	$p < 0.01$	12.1
			2	5.45	0.59	0.17	$p < 0.01$	12.7
		Unconfined	1	2.99	0.48	1.25	ns	0.0
			2	3.46	0.10	0.21	ns	0.0
	E. regnans	Confined	1	4.93	-1.12	1.64	ns	0.0
			2	3.96	-0.14	0.17	ns	0.0
		Unconfined	1	4.74	-2.14	2.98	ns	0.0
			2	3.02	-0.28	0.38	ns	0.0
Stress at 12.5% strain (MPa)	**P. radiata**	Confined	1	-1.22	12.25	3.08	$p < 0.001$	20.0
			2	11.35	1.22	0.29	$p < 0.001$	21.9
		Unconfined	1	2.10	4.25	2.29	ns	4.0
			2	6.03	0.52	0.28	ns	4.0
	E. regnans	Confined	1	3.21	24.24	8.29	$p < 0.05$	16.2
			2	20.73	1.25	0.46	$p < 0.05$	13.9
		Unconfined	1	7.95	-4.28	5.70	ns	0.0
			2	4.63	-0.33	0.44	ns	0.0

* Model 1, Strength property $= X + (Y \times \text{Specific gravity})$,
Model 2, Strength property $= X\,(\text{Specific gravity})^{Y}$

TABLE 3—Values of some mechanical properties of green sapwood from **Pinus radiata** and **Eucalyptus regnans** which show the species, type of compression, initial moisture content interactions

Property	Species	Type of compression		Initial moisture content interval*				
		Confined	Unconfined	1	2	3	4	5
Stress at proportional limit (MPa)	**P. radiata**	3.65	3.24	3.33	3.50	3.42	3.45	3.55
	E. regnans	4.41	3.75	3.98	3.82	4.17	4.17	4.02
Stress at 12.5% strain (MPa)	**P. radiata**	4.94	4.32	4.61	5.31	5.45	6.39	6.28
	E. regnans	8.00	5.98					
Work to proportional limit (MJ/m^3)	**P. radiata**	0.024	0.019	0.021	0.023	0.021	0.022	0.021
	E. regnans	0.028	0.016					

* The moisture content intervals 1 to 5 were <90%, 90–110%, 111–130%, 131–150%, >150% (oven-dry basis), respectively.

wood and sapwood and by the more rapid rate of loading in the tests described here because stress at proportional limit is known to increase with deformation rate (Bodig 1963; Koch 1972; Markwardt & Liska 1948). *Eucalyptus regnans* specimens had a greater stress at proportional limit than *P. radiata* specimens, which corresponds with Bolza & Kloot's (1963) results. The stress at proportional limit in unconfined compression was lower than that in confined compression.

The values of stress at 12.5% strain showed similar trends to those for stress at proportional limit (Table 3). The main differences were that the S × C interaction for stress at 12.5% strain was very highly significant ($p < 0.001$) whereas the S × MC interaction was not significant. Again, in the S × C interaction for stress at 12.5% strain *E. regnans* specimens were much stronger than *P. radiata* specimens and mean stresses in confined compression were greater than in unconfined compression, especially in *E. regnans.*

The analysis of data on the work to proportional limit showed that there were significant differences between the types of compression (C) ($p < 0.001$) and initial moisture contents ($p < 0.01$). The S × C interaction ($p < 0.001$) was also significant (Table 3). In both species more energy had to be expended to reach the proportional limit in confined compression than in unconfined compression. The work to proportional limit values were greater in *E. regnans* specimens than in *P. radiata* during confined compression but the reverse was true in unconfined compression. No explanation for this behaviour could be found. The differences in work to proportional limit from one moisture content interval to the next, although significant, were small.

For the design of efficient compression drying equipment it would be useful to know the compressive stresses corresponding to given compressive strains during compression drying. Regression equations for the two experiments (Table 4) were fitted to the pairs of values for stress at the instant when compression was halted, and the corresponding strain.

TABLE 4—Regression equations for predicting compressive stress in green sapwood from **Pinus radiata** and **Eucalyptus regnans** at given strains from 5% to 30% during confined and unconfined radial compression* (standard errors in parentheses)

Type of compression	Species	Constants			Percentage of variance accounted for
		a	b	c	
Confined	**P. radiata**	1.38 (0.07)	0.0034 (0.0078)	0.00076 (0.00017)	86.3
	E. regnans	1.58 (0.09)	0.0454 (0.0121)	-0.00021 (0.00036)	79.9
Unconfined	**P. radiata**	1.40 (0.04)	-0.0076 (0.0043)	0.00095 (0.00009)	95.1
	E. regnans	1.46 (0.04)	0.0284 (0.0046)	-0.00015 (0.00011)	88.2

* The general equation is: $\text{Log}_e S = a + b.C + c.C^2$ $5\% < C < 30\%$
where, C is strain (%)
S is stress (MPa) at a given strain

Inclusion of SG as a variable did not help to account for any more of the variance. This supports the earlier conclusion that SG did not have a major effect on the green sapwood strength in radial compression.

The equations fit the data well (Table 4, Fig. 1 and 2). While they are directly applicable only to small sapwood blocks of the two species, they do provide an initial

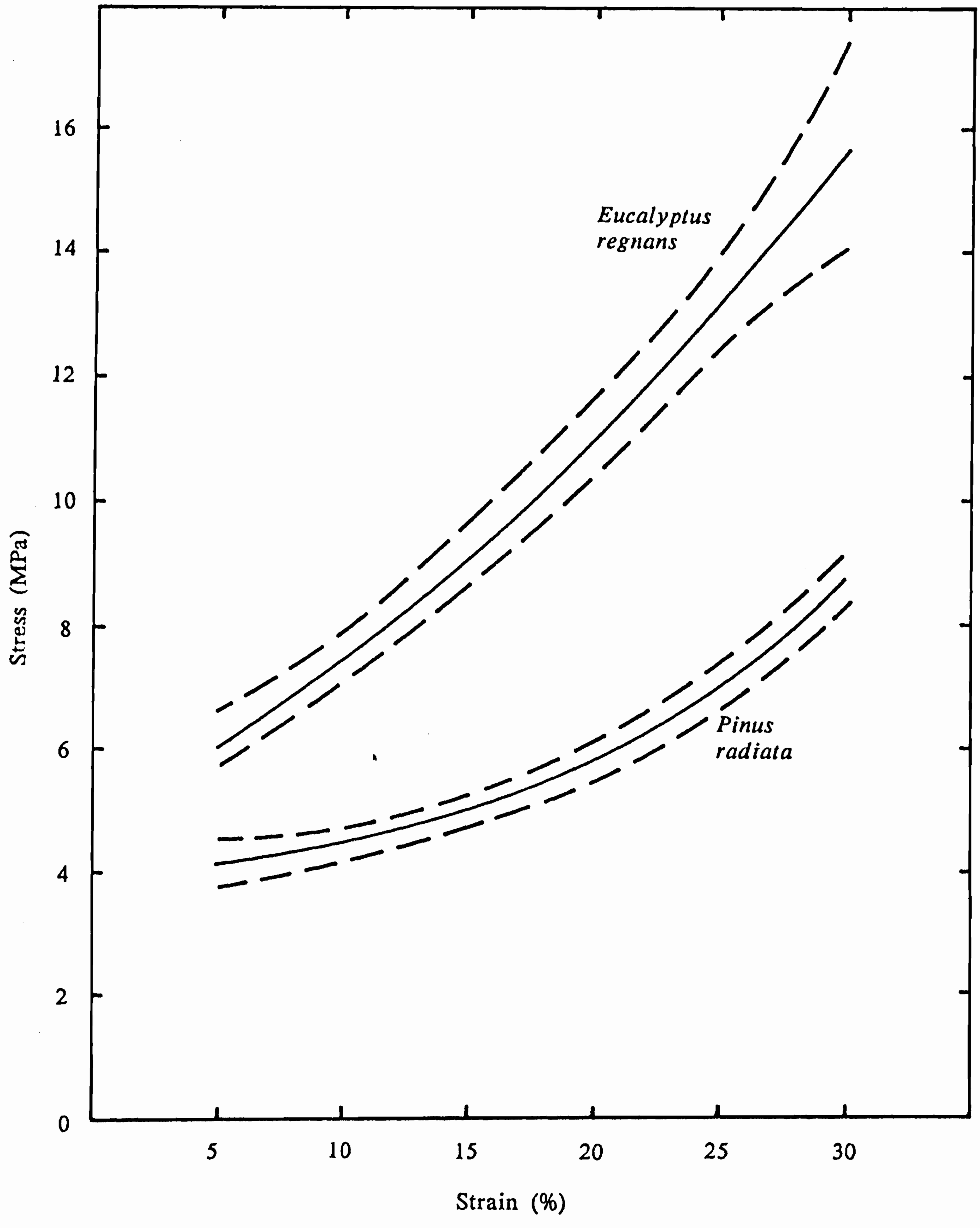

FIG. 1—Stress, high-strain relationships for green sapwood specimens from **Pinus radiata** and **Eucalyptus regnans** during confined compression perpendicular to the grain. The curves are based on the regression equations in Table 4 (— — — 95% confidence limits).

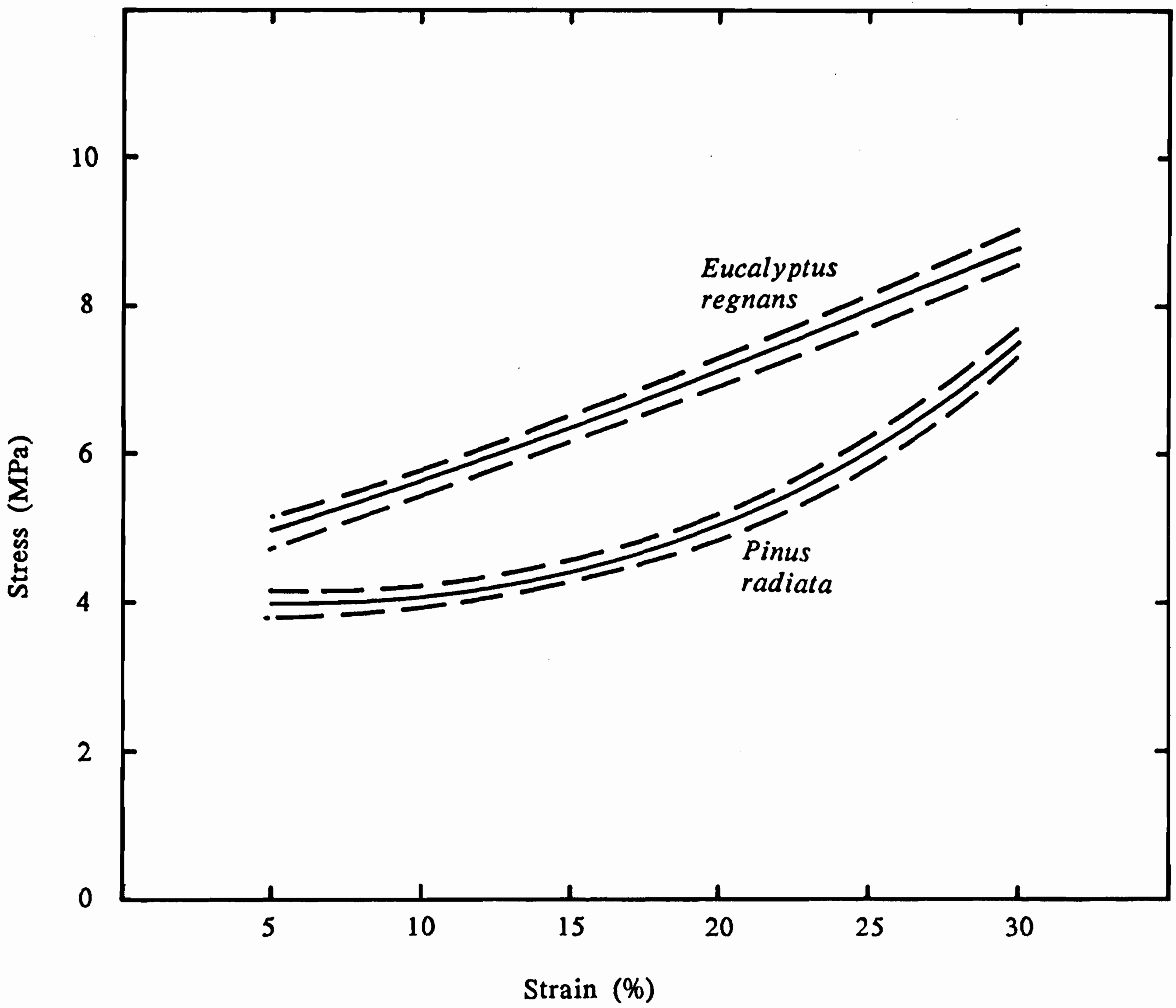

FIG. 2—Stress, high-strain relationships for green sapwood specimens from **Pinus radiata** and **Eucalyptus regnans** during unconfined compression perpendicular to the grain. The curves are based on the regression equations in Table 4 (— — — 95% confidence limits).

basis for determining loads that may have to be applied to small pieces of sapwood for compression drying.

The stress, strain equations for confined compression (Table 4) are shown graphically in Fig. 1. Stress increases at a greater rate than strain as strain increases. The stress values for *E. regnans* are much higher than those for *P. radiata* at the same strain and the differences in stress between confined and unconfined compression are much greater in *E. regnans* than *P. radiata*.

CONCLUSIONS

Equations of the form $S = X + Y.SG$ and $S = X(SG)^Y$, where S is a wood strength property, SG is specific gravity, and X and Y are constants, are inappropriate for representing the stress at the proportional limit and stress at 12.5% strain in green sapwood blocks of *P. radiata* and *E. regnans* because the "Y" parameters do not differ significantly from zero.

Stress at proportional limit and stress at 12.5% strain were significantly larger in the *E. regnans* than the *P. radiata* specimens, and greater in confined compression than in unconfined compression.

The regression equations developed for calculating the stress at a given compressive strain in sapwood specimens from each of the two species in confined and unconfined compression are a good fit to the data.

ACKNOWLEDGMENTS

The authors gratefully acknowledge assistance given by R. McDermott and K. W. Johnson; constructive criticism of the draft manuscript by H. Bier, J. Boyd, P. U. Grossman,, K. W. Groves, and D. M. Stodart; use of a universal testing machine owned by the University of New South Wales, Faculty of Military Studies; and supply of **P. radiata** logs by ACT Forests.

REFERENCES

BODIG, J. 1963: A study of the mechanical behaviour of wood in transverse compression. Ph.D. Thesis, University of Washington, United States.

BOLZA, E.; KLOOT, N. H. 1963: The mechanical properties of 174 Australian timbers. **CSIRO Division of Forest Products Technical Paper No. 25.**

FOREST PRODUCTS LABORATORY 1974: Wood handbook: Wood as an engineering material. **U.S. Department of Agriculture Handbook No. 72.**

GUNZERODT, H.; JOHNSON, G. R.; WHYBREW, K.; WALKER, J. C. F. 1984: Compression rolling of **Nothofagus fusca**. Proceedings of the Pacific Timber Engineering Conference, Institute of Professional Engineers of New Zealand.

HAYGREEN, J. G. 1981: Potential for compression drying of green wood chip fuel. **Forest Products Journal 31(8):** 43–54.

JONES, K. C. 1981: Field tests to develop energy saving wood comminution techniques. **Canadian Forest Service, ENFOR Project P-28, Special Report No. SR-15.**

KOCH, P. 1972: Utilization of the southern pines. I. The raw material. **U.S. Department of Agriculture Handbook No. 420.**

MACK, J. J. 1979: Australian methods for mechanically testing small clear specimens of timber. **CSIRO Division of Building Research Technical Paper (second series) No. 31.**

MARKWARDT, L. J.; LISKA, J. A. 1948: Speed of testing of wood: factors in its control and its effect on strength. **American Society for Testing and Materials, Proceedings 48:** 1139–59.

PANSHIN, A. J.; ZEEUW, De C.; BROWN, H. P. 1964: "Textbook of Wood Technology. Volume I - Structure, Identification, Uses and Properties of the Commercial Woods of the United States." McGraw-Hill, New York.

WINGATE-HILL, R. 1983a: A process for reducing pulpwood transport costs. **CSIRO Division of Forest Research Technical Paper No. 1.**

——— 1983b: A review of processes which involve compressing wood perpendicular to the grain. **Australian Forest Research 13:** 151–64.

——— 1985: Removal of moisture from green wood by compression. Ph.D. Thesis, Australian National University, Canberra.

WINGATE-HILL, R.; CUNNINGHAM, R. B. 1984a: Removal of moisture from green sapwood by compression. **Journal of the Institute of Wood Science 10(2):** 66–75.

——— 1984b: Preparation of wood specimens for compression tests parallel to the grain. **Journal of the Institute of Wood Science 10(2):** 91–3.