VARIATION IN WOOD, KRAFT FIBRE, AND HANDSHEET PROPERTIES AMONG 29 TREES OF *EUCALYPTUS REGNANS*, AND COMPARISON WITH *E. NITENS* AND *E. FASTIGATA*

R. P. KIBBLEWHITE, M. J. C. RIDDELL, and C. J. A. SHELBOURNE

New Zealand Forest Research Institute,
Private Bag 3020, Rotorua, New Zealand

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ABSTRACT

Variation in and relationships between wood, chemical, kraft fibre, and kraft handsheet properties were studied in 29 individual trees of *Eucalyptus regnans* F. Mueller, aged 20–21 years, grown in Kaingaroa Forest, New Zealand. Means and ranges of these characteristics for *E. regnans* were also compared with those for similar 29-tree samples from *E. nitens* (Deane et Maiden) Maiden and *E. fastigata* Deane et Maiden from the same forest, aged 15–16 years.

The trees sampled of *E. regnans* were of lower wood density (in spite of their greater age) and had kraft fibres that were longer, broader, thinner-walled, and had higher levels of collapse than those of either of the other species. *Eucalyptus regnans* individual-tree pulps showed the widest range of apparent sheet density compared with the other two species but had a similar mean, which was well predicted by wood density or by the level of fibre collapse in handsheets. *Eucalyptus regnans* trees had a good pulp yield, similar to those of *E. nitens*. For a market kraft pulp, *E. regnans* grown for 15 years could be expected to give a kraft pulp very deficient in handsheet bulk.

Keywords: handsheet properties; wood density; fibre dimensions; chemical composition; *Eucalyptus fastigata*; *Eucalyptus nitens*; *Eucalyptus regnans*.

INTRODUCTION

Eucalyptus regnans, *E. fastigata*, and *E. nitens* are the three eucalypt species that have been planted in New Zealand for pulp production. A substantial resource of eucalypts of over 7000 ha was established by Carter Holt Harvey Forests Ltd in Kinleith Forest in the 1970s and early 1980s, in which *E. regnans* was the main species (Miller *et al.* 2000). However, this species has been badly affected by a complex infection by several leaf fungi known as the "Barron Road syndrome" (Kay 1993), which is apparently induced by climatic factors (B.Murphy & T.Payn unpubl. data) and which has resulted in progressive decline of stands. Although well regarded in the past, *E. regnans* is no longer planted commercially and its place has been taken by increased planting of *E. nitens*, as well as continued use of *E. fastigata*.

The *E. regnans* stands represent a large standing resource in spite of this, and this species was therefore included in a comprehensive programme which has now been completed, for evaluating each species for both kraft and chemi-mechanical pulping. This has involved characterising kraft fibres and pulps, and mechanical cold soda pulps made from individual, whole-tree chip samples of 29 trees of each species, chosen for a range of wood basic density, and estimating within- and between-tree variation in wood, fibre, and chemical properties (Kibblewhite et al. 1997; Kibblewhite & McKenzie 1998; Jones & Richardson 1999a, b, 2000).

The kraft pulp and fibre property variation and relationships for 29 trees of *E. regnans* aged 20–21 years, preselected for a range of breast-height outerwood density, are reported here. The wood and kraft pulp properties for 29 trees each of *E. nitens* and *E. fastigata,* aged 15–16 years, are also compared here with those of *E. regnans*.

EXPERIMENTAL

Sample Origin

A provenance/progeny trial of *E. regnans,* was planted in 1977 in Cpt 37, Kaingaroa Forest, which is located 50 km south-west of Rotorua in the central North Island (latitude 38°30′S, altitude 415 m). In 1997, at age 20 years, 100 trees in the trial were screened for outerwood basic density by breast-height increment cores. Twenty-nine trees were then selected for a range of outerwood density (from 349 to 519 kg/m^3) with nine of high, nine of low, and 11 of intermediate density. Initially nine trees, with outerwood densities covering the range, were felled and whole-tree chipped for a cold soda mechanical pulping study as well as for this kraft pulping study. Nearly a year later the remaining 20 trees were felled and chipped individually for the kraft pulping study, and the chips of all 20 trees were then bulked for a mechanical process study. Trees were chosen without regard to their provenance and family origin, but derived almost equally from Tasmanian and Victorian provenances. They were amongst the dominants and codominants in the stand, ranging in diameter at breast height from 39 to 51 cm for the first nine trees and from 30 to 64 cm for the remainder.

Discs were collected from the butt, 1.4 m, 5.5 m, and at consecutive 5.5-m intervals to a small-end diameter (s.e.d.) of 100 mm for determining whole-tree weighted mean basic density. All logs of each tree were then chipped in random order in a commercial chipper and the chips were passed through a 58-mm overs screen and retained on a 6-mm screen. The screened chips were mixed by taking and mixing repeated small samples from the conveyor, as it emptied into a truck, and 5 kg (o.d.) of these chips were taken for kraft pulping.

Breast Height and Individual-tree Chip Basic Density

Outerwood breast-height basic density was determined on the outer 50 mm of two radial 5-mm cores taken at 1.4 m (Smith 1954). Chip basic density was determined in accordance with Appita method P1s-79, except that the fresh chips were not given the specified soaking period (Cown 1980). Whole-tree basic density was determined, using log volume weighting, from discs taken at the butt and at 5.5-m intervals up the stem, to a s.e.d. of 100 mm, with an additional disc at 1.4 m.

Chemical Analyses

Three hundred grams (o.d.) chips from each of 29 trees were removed from the 5-kg individual-tree samples for chemical analyses prior to pulping, and were air-dried for 3 days prior to grinding (20 mesh). Dichloromethane solubles content was determined in a Soxtec extractor—30 min boiling, 60 min rinsing—and extractives were determined gravimetrically after vacuum drying overnight.

Extracted samples were further ground to 40 mesh for analysis of lignin and carbohydrates. After acid hydrolysis these were analysed following Tappi T222 om-88 for lignin, Tappi um250 for acid-soluble lignin, and the method of Pettersen & Schwandt (1991) for carbohydrates. Reported Klason lignin values could include some non-lignin polyphenolic substances not extracted by dichloromethane (Appita P11s-78) (J.A.Lloyd unpubl. data).

Pulping and Bleaching

Chip samples for kraft pulping were those passing through the 26-mm screen but retained on the 9-mm holes of a Williams laboratory round-hole screen. One kraft pulp of kappa number 20±2 was prepared from each chip sample by varying the H-factor at constant alkali charge. The pulping conditions for each of the 29 tree samples were: 12% effective alkali as Na_2O on o.d. chips, 30% sulphidity, 4:1 liquor-to-wood ratio, and 90 minutes to 170°C maximum temperature.

Pulps were prepared in 2-litre pressurised reactors with 300-g o.d. chip charges. Pulps were then disintegrated with a propeller stirrer and screened through a 0.25-mm slotted flat screen. After de-watering and fluffing, kappa number, percentage rejects, and total yield were determined.

Handsheet Preparation and Evaluation

Handsheets were prepared and pulp physical and optical evaluations were made in accordance with Appita standard procedures. The load applied during pulp refining with the PFI mill was 1.77 N/mm. Pulp charges (24 g o.d) were refined at 10% stock concentration for 500, 1000, 2000, and 4000 rev.

Fibre Dimension Measurement

Cross-sectional kraft-fibre dimensions of thickness, width, wall area, wall thickness, perimeter, cross-sectional area, and width/thickness ratio were measured using image-processing procedures described previously (Fig. 1) (Kibblewhite & Bailey 1988). Measurements were made on dried and re-wetted fibres reconstituted from handsheets. The

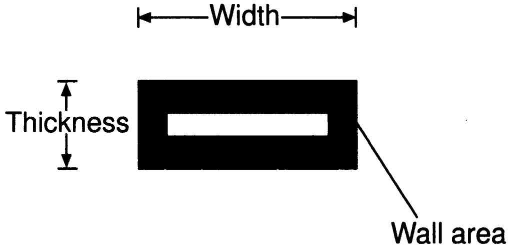

FIG. 1–Cross-section diagram of a fibre dried and re-wetted from a handsheet

ratio, width/thickness, is an indicator of the level of collapse of the dried and re-wetted fibres — the greater the width and the smaller the thickness of a fibre cross-section, the greater is the extent of collapse. Relative numbers of fibres per unit mass of pulp were calculated using the reciprocal of the length × wall area product. Length-weighted average fibre lengths were determined with a Kajaani FS 200 instrument, using Tappi T271 pm-91.

Statistical Calculations

Regression models were calculated using simple linear regression for the prediction of individual-tree kraft handsheet properties at 500 PFI mill rev. from kraft fibre dimensions (of unrefined pulp), chip basic density, and lignin content. For models with two or more predictor variables, multiple linear regression was used.

Terminology

Fibre and dimension abbreviations used throughout are as follows:

Fibre width	W
Fibre thickness	T
Fibre wall area	A_w
Fibre size – cross-section area (W×T)	A
Fibre wall thickness	T_w
Half fibre perimeter (W+T)	P
Fibre length weighted length	L
Fibre collapse (width/thickness)	W/T
Half fibre perimeter/wall thickness	P/T_w
Chip density	D_c
Breast-height core density	D_b
Lignin	Lg

RESULTS AND DISCUSSION

E. regnans

Wood chip, kraft fibre, and handsheet property variation

Chemical compositions of the 29 individual-tree chip samples of *E. regnans* showed marked between-tree variation, with total lignin contents ranging from 26.3 to 31.6%, glucose contents ranging from 39.2 to 46.2%, and pulp yields ranging from 53 to 59% for the 29 individual trees (Tables 1 and 2). Wide variation between trees in wood and fibre properties was also evident for chip density (365–509 kg/m^3), fibre dimensions of length (0.79–1.01 mm), half perimeter (20.0–22.5 μm), wall area (coarseness) (54–68 μm^2), width/thickness ratio (1.95–2.71), and relative number of fibres (85–119). Handsheet apparent density at 500 PFI mill rev. also showed wide between-tree variation (619–791 kg/m^3) (Tables 1 and 2).

Relationships among individual-tree wood chip, kraft fibre, and handsheet properties

Breast-height outerwood density was highly correlated with whole-tree chip density (r=0.93) (Table 3). Of the kraft fibre properties, the width/thickness ratio or fibre collapse

TABLE 1–Variation in selected chip, fibre, and handsheet properties for the 29 individual trees of *E. regnans*

	Mean	Range
Chip basic density (kg/m^3)	438	365–509
Chip total lignin (%)	29.1	26.3–31.6
Chip glucose (%)	43.6	39.2–46.2
Pulp yield (%)	56	53–59
Fibre length (mm)	0.91	0.79–1.01
Half fibre perimeter (W+T) (μm)	21.4	20.0–22.5
Fibre wall area (coarseness) (μm^2)	61	54–68
Fibre collapse (W/T)	2.27	1.95–2.71
Relative fibre number	102	85–119
Handsheet bulk* (cm^3/g)	1.44	1.62–1.26
Handsheet apparent density* (g/cm^3)	0.696	0.619–0.791
Tensile index * (N·m/g)	103	83–125

* @ 500 PFI mill rev.

was most strongly correlated with basic wood density of the tree and the resulting chips ($r=-0.78$). Other fibre properties were generally poorly correlated with chip density, except width and thickness themselves and fibre wall thickness.

Pulp yield tended to increase with decreasing chip lignin contents, and increasing glucose and carbohydrate contents (Table 3).

Handsheet apparent density, tensile strength, and light-scattering coefficient are important eucalypt pulp quality determinants (Levlin 1986; Kibblewhite & Shelbourne 1997). Handsheet apparent density is a measure of fibre packing density and web structural organisation, and is therefore expected to be predictable from mean fibre dimensions and/or fibre dimension populations (Kibblewhite & Shelbourne 1997). Handsheet property predictions were made at 500 PFI mill rev. as the basis of comparison, for reasons described elsewhere (Kibblewhite & Shelbourne 1997).

Predictive relationships for these handsheet properties from chip and kraft fibre properties are indicated in Table 4 and the Appendix. For the 29 *E. regnans* pulps, handsheet apparent density was well predicted by the fibre width/thickness ratio and length, or even better, by the chip density and kraft fibre length combinations (Table 4). Chip density and chip lignin themselves, the chip density and lignin combination, and the kraft fibre perimeter, wall thickness, and length combination, are also moderate-to-strong predictors of handsheet apparent density. Prediction equations are given in the Appendix. Handsheet apparent density but not tensile index predictions were slightly improved by the inclusion of fibre length in these relationships. The prediction of handsheet light-scattering coefficient from wood or kraft fibre properties was generally poor and non-significant for *E. regnans* (Tables 3 and 4), as was found also in *E. nitens* and *E. fastigata* (Kibblewhite *et al.* 1997; Kibblewhite & McKenzie 1998).

The ratio fibre width/thickness reflected the collapsed configuration of the kraft fibres in handsheets, and the high correlation with apparent density could be expected since high and low resistance to collapse would give low and high sheet densities respectively (Kibblewhite & Shelbourne 1997).

TABLE 2–Unrefined *E. regnans* dimensions and handsheet properties @ 500 PFI mill rev.

Tree No.	Handsheet properties adjusted to 500 rev. PFI mill					Wood/chip properties					Pulp yield		Kraft fibre dimensions								
	Apparent density (g/cm^3)	Tensile index (N·m/g)	Stretch (%)	Light-scattering coefficient (m^2/kg)	Weighted whole-tree basic density (discs) (kg/m^3)	Breast-height density (kg/m^3)	Chip basic density (kg/m^3)	Total lignin (g/100 g)	Glucose (g/100 g)	Carbohydrate (g/100 g)	Rejects (%)	Total @ Kappa 20 (%)	Length (mm)	Width (µm)	Thickness (µm)	Perimeter (µm)	Width × thickness ($µm^2$)	Wall area ($µm^2$)	Wall thickness (µm)	Width / thickness	Relative number
						D_b	D_c	Lg				Y	L	W	T	W+T	WxT	A_w	T_w	W/T	
1	0.619	86	2.14	33.8	476	466	468	28.1	45.8	62.2	1.8	58	0.96	14.19	7.09	21.3	101	62	2.18	2.11	95
2	0.621	88	2.17	33.5	511	499	505	29.0	44.5	61.4	1.9	56	0.93	14.04	7.20	21.3	102	64	2.29	2.04	95
3	0.624	83	2.00	29.0	520	519	509	26.3	46.2	62.9	0.9	58	0.98	13.97	7.35	21.3	103	68	2.52	1.99	85
4	0.629	91	2.32	33.3	503	493	502	29.3	44.8	60.0	1.4	57	0.93	13.42	7.22	20.7	97	63	2.34	1.95	96
5	0.642	93	2.45	34.1	467	463	467	28.5	45.2	61.3	1.3	57	0.93	14.72	6.78	21.5	101	62	2.11	2.25	98
6	0.646	88	2.54	34.0	473	482	477	29.0	44.6	60.9	3.7	56	0.87	14.33	6.60	21.0	95	57	2.02	2.25	114
7	0.650	99	2.33	28.5	484	493	462	28.1	44.1	61.1	1.2	57	0.97	14.32	7.01	21.4	102	66	2.40	2.13	88
8	0.655	94	2.28	33.1	482	485	470	27.5	43.8	62.5	2.5	57	0.92	13.87	6.59	20.5	92	58	2.13	2.19	106
9	0.659	93	2.53	34.1	462	472	453	28.2	43.9	61.7	3.9	55	0.96	14.92	6.69	21.6	100	61	2.07	2.31	96
10	0.673	93	2.84	33.0	501	505	480	29.2	43.7	60.6	6.7	59	0.92	13.43	6.55	20.0	88	55	2.05	2.13	112
11	0.677	97	2.52	31.7	399	386	408	28.4	45.2	61.7	1.5	56	0.94	15.10	7.03	22.1	107	64	2.10	2.23	94
12	0.681	99	2.49	30.7	450	421	434	28.4	44.3	61.2	0.8	58	0.89	14.21	6.94	21.2	100	64	2.26	2.16	99
13	0.687	103	2.68	32.5	438	412	424	28.7	46.0	61.4	1.4	58	0.98	14.66	6.27	21.0	93	56	1.93	2.40	103
14	0.703	100	2.46	31.5	472	444	461	28.6	41.8	60.5	1.6	55	0.85	14.55	6.68	21.2	98	62	2.15	2.28	107
15	0.705	104	2.73	33.0	434	425	429	30.7	42.2	59.7	2.8	54	0.88	15.45	6.59	22.1	103	61	2.02	2.41	105
16	0.708	118	2.64	31.5	409	412	378	28.2	45.9	61.8	1.9	57	0.95	13.97	6.38	20.4	90	54	1.92	2.25	110

TABLE 2–cont.

Tree No.	Handsheet properties adjusted to 500 rev. PFI mill					Wood/chip properties					Pulp yield		Kraft fibre dimensions									
	Apparent density (g/cm³)	Tensile index (N·m/g)	Stretch (%)	Light-scattering coefficient (m²/kg)	Weighted whole-tree basic density (discs) (kg/m³)	Breast-height density (kg/m³)	Chip basic density (kg/m³)	Total lignin (g/100 g)	Glucose (g/100 g)	Carbohydrate (g/100 g)	Rejects (%)	Total @ Kappa 20 (%)	Length (mm)	Width (μm)	Thickness (μm)	Perimeter (μm)	Width × thickness (μm²)	Wall area (μm²)	Wall thickness (μm)	Width / thickness	Relative number
						D_b	D_c	Lg				Y	L	W	T	W+T	WxT	A_w	T_w	W/T	
17	0.712	103	2.58	29.7	472	450	452	29.5	42.9	61.0	1.1	55	0.89	14.99	7.14	22.2	108	66	2.18	2.18	96
18	0.716	112	2.58	29.9	425	417	424	28.9	43.6	61.1	1.9	55	0.98	14.43	6.86	21.3	101	62	2.16	2.17	93
19	0.720	117	2.95	32.1	412	402	409	29.4	42.6	61.0	1.0	52	0.88	14.74	6.40	21.2	96	57	1.92	2.36	113
20	0.724	109	2.81	29.6	443	423	425	30.4	42.8	59.8	3.7	55	0.86	13.75	6.59	20.4	91	55	1.99	2.17	119
21	0.725	114	2.85	31.3	444	410	427	28.0	45.2	62.2	1.0	56	1.01	14.35	6.28	20.7	91	56	1.96	2.36	100
22	0.726	112	2.80	30.8	423	435	423	30.2	40.4	58.6	1.5	56	0.90	14.89	6.69	21.6	101	65	2.21	2.30	97
23	0.730	108	2.96	32.5	420	380	416	29.4	44.9	61.2	1.7	56	0.87	14.44	6.27	20.7	91	55	1.95	2.38	118
24	0.733	99	2.55	28.4	436	403	429	30.5	42.9	59.6	2.2	55	0.87	15.53	6.95	22.5	109	65	2.08	2.31	100
25	0.746	113	2.95	28.9	390	378	402	29.7	41.8	59.9	1.0	54	0.79	15.76	6.52	22.3	103	66	2.17	2.55	108
26	0.746	120	2.78	29.4	393	379	384	29.9	43.1	59.9	1.0	57	0.98	15.12	6.71	21.9	102	61	2.00	2.33	95
27	0.757	121	2.67	30.2	419	388	406	29.5	41.8	61.2	0.8	54	0.84	15.36	6.32	21.7	98	62	2.09	2.52	108
28	0.767	119	2.80	29.1	403	374	400	30.7	42.3	59.3	0.2	53	0.84	15.68	6.84	22.5	108	65	2.11	2.38	103
29	0.791	125	3.07	29.3	367	349	365	31.6	39.2	57.5	1.0	53	0.82	15.76	6.01	21.8	96	60	1.96	2.71	115
Mean	0.696	103	2.60	31.3	446	433	438	29.1	43.6	60.8	1.84	56	0.91	14.62	6.71	21.35	99	61	2.11	2.27	102
Std. Dev.	0.047	11.9	0.266	1.89	39.6	46.5	37.9	1.12	1.71	1.19	1.30	1.71	0.056	0.671	0.334	0.665	5.79	4.04	0.148	0.166	8.88
CV%	6.78	11.5	10.2	6.03	8.88	10.7	8.65	3.83	3.92	1.96	70.7	3.07	6.16	4.59	4.98	3.12	5.85	6.61	7.00	7.30	8.67

TABLE 3–Correlation coefficient matrix — 29 × *E. regnans*.

	Handsheet properties @ 500 rev PFI mill							Wood/chip properties				Unrefined kraft pulp fibre properties								
	Apparent density (g/cm^3)	Tensile index (N·m/g)	Stretch (%)	Light-scattering coefficient (m^2/kg)	Whole-tree basic density (kg/m^3)	Breast-height density* (kg/m^3) D_b	Chip basic density (kg/m^3) D_c	Total lignin (g/100 g) Lg	Glucose (g/100 g)	Carbohydrates (g/100 g)	Pulp yield (%) Y	Length (mm) L	Width (μm) W	Thickness (μm) T	Perimeter (μm) W+T	Width × thickness (μm^2) WxT	Wall area (μm^2) A_w	Wall thickness (μm) T_w	Width / thickness W/T	Relative number of fibres
Apparent density (kg/m^3)	1.00																			
Tensile index (N.m/g)	0.92	1.00																		
Stretch (%)	0.83	0.79	1.00																	
Light-scattering coefficient (m^2/kg)	−0.59	−0.51	−0.24	1.00																
Whole-tree basic density (kg/m^3)	−0.84	−0.85	−0.76	0.40	1.00															
Breast-height density (kg/m^3)	−0.87	−0.84	−0.74	0.43	0.95	1.00														
Chip density (kg/m^3)	−0.86	−0.90	−0.76	0.44	0.97	0.93	1.00													
Chip lignin (g/100 g)	0.70	0.58	0.68	−0.28	−0.58	−0.59	−0.54	1.00												
Chip glucose (g/100 g)	−0.69	−0.57	−0.55	0.42	0.48	0.44	0.45	−0.75	1.00											
Chip carbohy-drates (g/100 g)	−0.62	−0.50	−0.59	0.37	0.50	0.46	0.45	−0.91	0.81	1.00										
Pulp yield (%)	−0.65	−0.59	−0.52	0.29	0.57	0.57	0.50	−0.61	0.69	0.49	1.00									
Fibre length (mm)	−0.52	−0.33	−0.46	0.23	0.38	0.42	0.31	−0.64	0.69	0.60	0.62	1.00								
Fibre width (μm)	0.66	0.53	0.46	−0.41	−0.71	−0.70	−0.63	0.57	−0.59	−0.50	−0.67	−0.48	1.00							
Fibre thickness (μm)	−0.61	−0.65	−0.78	−0.05	−0.59	0.57	0.63	−0.35	0.34	0.26	0.33	0.30	−0.26	1.00						
Width + thickness (μm)	0.36	0.21	0.08	−0.44	−0.42	−0.42	−0.32	0.40	−0.42	−0.38	−0.51	−0.33	0.88	0.24	1.00					
Width × thickness (μm^2)	0.02	−0.10	−0.28	−0.38	−0.08	−0.09	0.01	0.16	−0.18	−0.17	−0.27	−0.11	0.58	0.63	0.90	1.00				
Fibre wall area (μm^2)	−0.12	−0.21	−0.43	−0.43	0.14	0.13	0.23	−0.03	−0.19	−0.12	−0.09	−0.09	0.36	0.70	0.72	0.88	1.00			
Fibre wall thickness (μm)	−0.54	−0.54	−0.73	−0.20	0.61	0.60	0.64	−0.42	0.16	0.20	0.33	0.18	−0.26	0.81	0.14	0.46	0.78	1.00		
Width / thickness	0.79	0.73	0.76	−0.24	−0.80	−0.79	−0.78	0.57	−0.60	−0.49	−0.62	−0.53	0.79	−0.79	0.40	−0.04	−0.18	−0.63	1.00	
Relative number of fibres	0.47	0.40	0.66	0.13	−0.37	−0.39	−0.39	0.47	−0.34	−0.33	−0.36	−0.63	0.04	−0.76	−0.34	−0.62	−0.71	−0.72	0.51	1.00

* Based on the outer 50 mm of 5 mm cores taken at breast height (1.4 m).

TABLE 4—Prediction of handsheet properties at 500 PFI mill rev. from kraft fibre dimensions and wood density* in *E. regnans*

Dependent variable	Independent variables	r^2†
Individual-tree chip density (D_c)	D_b	0.87
Apparent density	T_w	0.29
	P	0.13
	T_w + P	0.49
	T_w + P + L	0.57
	W/T	0.63
	W/T + L	0.65
	D_c	0.74
	D_c + L	0.82
	D_b	0.76
	D_b + L	0.80
	D_c + Lg	0.83
	D_c + Lg + L	0.84
	Lg	0.49
	Lg + L	0.50
Tensile index	T_w	0.30
	T_w + P	0.38
	T_w + P + L	0.40
	W/T	0.53
	W/T + L	0.53
	D_c	0.80
	D_c + L	0.81
	D_b	0.70
	D_b + L	0.70
	D_c + L_g	0.82
	D_c + L_g + L	0.82
	Lg	0.33
	Lg + L	0.33
Light-scattering coefficient	W/T	0.06
	W/T + L	0.07
	D_c	0.20
	D_c + L	0.21

* Wall thickness (T_w), perimeter (P), chip density (D_c), lignin (Lg) and length weighted length (L) breast height outer wood density (D_b), fibre width/thickness (W/T).

† No correlation at the 95% level of significance if r^2 <0.12

The mean fibre properties of length, wall thickness, and cross-sectional perimeter together can be expected to describe the size, shape, and coarseness of the fibres of a given tree's pulp and, in turn, handsheet packing densities and structures. Hence, it could be expected that the fibre length, wall thickness, and perimeter combination should be a good predictor of handsheet apparent density for the 29 *E. regnans* individual-tree pulps. While such trends were indicated for these three variables, particularly when in combination (r^2=0.57), they were less precise predictors than the width/thickness ratio (Table 4).

Chip basic density is a measure of the total mass and volume of a chip sample (Kibblewhite & Shelbourne 1997). It is evidently strongly influenced by the dimensions and coarseness of the fibres, the tissue component which makes up the largest proportion of the wood chip mass, and for *E. regnans* was the best single predictor of handsheet apparent density.

Handsheet tensile index was also best predicted by chip basic density individually (Table 4). Fibre length is generally unimportant in this context either by itself or when in combination with chip density. Hence, tensile strength appears to be influenced more by fibre bonding than by length-related network reinforcement properties. Such a statement ignores the clear dependence of tensile strength on apparent density (or bulk) which in turn is influenced by fibre dimensions, packing densities, and arrangements in handsheets (Kibblewhite & Shelbourne 1997).

Handsheet properties (adjusted to 500 PFI mill rev.) may be partly predicted from unrefined fibre properties. However, the prediction of combinations of handsheet properties is required to fully characterise papermaking furnishes/systems. For example, while the tensile strengths of a range of kraft pulps can be similar, their apparent density and light-scattering coefficient values can be very different (Kibblewhite & Shelbourne 1997). The direct prediction of combinations of handsheet properties from fibre properties is, however, associated with a number of problems. These derive from the effects of wide ranges in fibre and handsheet properties, pulp refining levels and conditions, and the bases of comparison selected. Some of these difficulties have been overcome in the selection of individual-tree fibre types for different paper and pulp grades by using the apparent density of "unrefined" pulps (500 PFI mill rev.) as the base against which other "unrefined" handsheet properties are compared (Kibblewhite & Shelbourne 1997).

Relationships among handsheet properties

Eucalypt market kraft pulps are known to combine the most important pulp and paper properties in a particularly favourable way (Levlin 1986; Kibblewhite & Shelbourne 1997; Cotterill & Macrae 1997). They give good strength and formation, with excellent bulk and optical properties. Handsheet bulk is particularly important since strength can normally be developed by refining, provided the resulting bulk meets the requirements of the product being manufactured (Kibblewhite & Shelbourne 1997). The pulps from the 29 trees of *E. regnans* showed a wide range of handsheet bulk values at 500 PFI mill rev. (1.62–1.26 cm^3/g), which is the reciprocal of the apparent density range of 0.619–0.791 g/cm^3 (Tables 1 and 2). Excellent optical properties (opacity and light-scattering coefficient) and formation are normally obtained with eucalypt market kraft pulps because their fibres are short, of low coarseness, stiff, and uncollapsed, and are present in large numbers compared to other hardwood fibres (Levlin 1986; Kibblewhite *et al.* 1991; Brindley & Kibblewhite 1996).

The 29 individual-tree *E. regnans* pulps are numbered 1 to 29 in ascending order of apparent sheet density in Table 2. The effect of the large 0.619–0.791 g/cm^3 apparent sheet density range on the tensile strength/apparent density relations for the 29 pulps is indicated in Fig. 2 where the two graphs separately show the regressions for the seven trees of highest apparent sheet density and those for the rest. Each pulp's regression line was based on handsheet data determined at each of four refining levels — 500, 1000, 2000, and 4000 rev. All pulps are able to be refined to high tensile index although refining requirements can be very different. Also, the lower the handsheet apparent density (or higher the bulk) of the unrefined pulps the lower are their tensile strengths. Pulps 1–7, with their low apparent density (<0.650 g/cm^3) and good potential to develop tensile strength with refining, would be suitable for the manufacture of wood-free tissue, and printing and writing grades (Kibblewhite & Shelbourne 1997). Pulps 8–29, on the other hand, would be considered to be deficient in bulk and generally unsuitable for such end uses, despite their high initial tensile strength.

The higher tensile index/apparent density regression slopes, lower initial apparent densities (≤0.650 g/cm^3) and easy development of tensile index with refining, separate Pulps 1–7 from all others (Fig. 2) The rate of increase in tensile index with refining progressively decreases with increasing handsheet density of the lightly refined pulps (500 rev. PFI mill) (Fig. 2). This is the result of tensile index tending towards maximum values at high apparent densities.

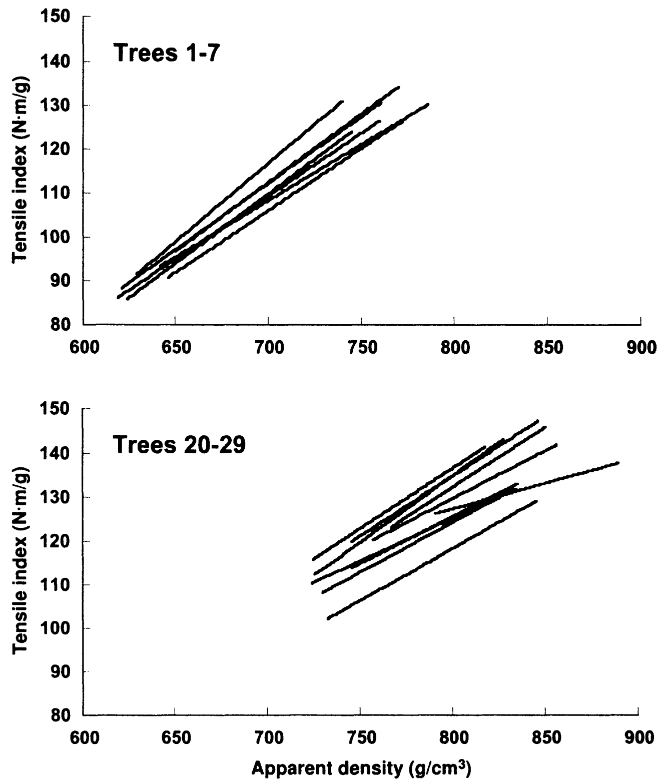

FIG. 2–Tensile index *vs* apparent density regressions for individual tree pulps of *E. regnans*. Each regression is based on four PFI mill refining levels—500, 1000, 2000, and 4000 rev.

Comparison of *E. regnans* with *E. nitens* and *E. fastigata*

Trees used in the three 29-tree eucalypt pulping studies came from sites in northern Kaingaroa Forest, ranging in altitude from 230 m (*E. nitens*), to 270 m (*E. fastigata*), to 415 m for *E. regnans*. The *E. regnans* trees were felled at ages 20 and 21 years, some 5 years older than the *E. nitens* and *E. fastigata* samples. Comparisons of wood, fibre, and handsheet properties among these three species were thus confounded with differences among the environments under which the trees were growing as well as their different ages, both of which can greatly affect the whole-tree wood and fibre properties. A densitometry study of discs taken at 5.5-m intervals of nine of the 29 trees of *E. regnans* (R.McKinley unpubl. data) showed density increasing beyond the fifteenth ring from the pith. Wood density, kraft fibre length, and coarseness of individual trees of *E. regnans* could therefore be expected to be somewhat higher than those of the same trees had they been felled at age 15 or 16 years (Raymond *et al.* 1998; Nicholls & Griffin 1978). Comparisons of chip, wood, and fibre properties of the trees from the three stands, and corresponding pulp handsheet properties (Table 5), can be statistically tested but are not **species** comparisons, and these must therefore be made with caution, bearing in mind the confounding of species with tree-age and site effects.

For the *E. regnans*, *E. nitens* (Kibblewhite *et al.* 1997), and *E. fastigata* (Kibblewhite & McKenzie 1998) 29 individual-tree samples (Table 5), mean property values indicate that *E. regnans* was of lower wood basic density than *E. nitens* and *E. fastigata*, of intermediate lignin content, and with kraft pulp yield as high as *E. nitens*. *Eucalyptus regnans* had kraft fibres which were longer, wider, of larger perimeter, thinner-walled, coarser, and more

TABLE 5–Variation in selected chip, fibre, and handsheet properties for the 29 individual trees of *E. regnans*, *E, nitens*, and *E. fastigata*..

	E. regnans Tree age 20/21		*E. nitens* Tree age 15/16		*E. fastigata* Tree age 15/16	
	Mean	Range	Mean	Range	Mean	Range
Chip basic density (kg/m^3)	438	365–509	474	390–556	458	404–534
Glucose (%)	43.6	39.2–46.2	42.8	40.5–46.6	41.4	37.8–46.1
Xylose (%)	14.3	12.4–15.7	15.3	14.2–16.7	13.2	10.8–15.2
Chip total lignin (%)	29.1	26.3–31.6	27.6	25.1–29.7	30.5	28.7–31.9
Pulp yield (%)	56	53–59	56	54–59	53	48-57
Fibre length (mm)	0.91	0.79–1.01	0.86	0.78–0.95	0.85	0.76–0.92
Fibre width (μm)	14.6	13.4–15.8	13.2	12.4–14.1	13.3	12.1–14.4
Fibre thickness (μm)	6.7	6.0–7.4	6.9	6.6–7.4	6.7	6.2–7.2
Half fibre perimeter (W+T) (μm)	21.4	20–22.5	20.1	19.0–21.6	20.0	18.5–21.1
Fibre rectangular area (W×T) (μm^2)	98.9	88–109	92.4	83–106	90.3	78–100
Fibre wall area (μm^2)	61.1	54–68	60.9	53–70	58.8	54–65
Fibre wall thickness (μm)	2.11	1.92–2.52	2.42	2.11–2.76	2.30	2.01–2.59
Fibre collapse resistance (W/T)	2.27	1.95–2.71	1.97	1.80–2.09	2.08	1.81–2.30
Relative fibre number	102	85–119	108	92–120	112	96–130
Handsheet bulk (cm^3/g)*	1.44	1.62–1.26	1.48	1.59–1.37	1.42	1.58–1.29
Handsheet density (g/cm^3)*	0.696	0.619–0.791	0.696	0.627–0.732	0.705	0.632–0.773
Handsheet tensile index (N·m/g)*	104	83–125	102	84–121	103	85–124

* For handsheets made from pulps refined for 500 PFI mill rev.

collapsible than the other species (Table 5). Furthermore, there was a strong indication that the similar mean pulp yields of *E. regnans* and *E. nitens* were the result of higher glucose (cellulose) and lower xylose contents in the *E. regnans* pulps (Table 5) (Kibblewhite & Riddell in press). The higher chip lignin content and lower pulp yield of the *E. fastigata* material, compared to that of *E. nitens*, has been reported elsewhere (Kibblewhite & McKenzie 1998).

Eucalyptus regnans, on average, was of lower wood density than the *E. nitens* and *E. fastigata* trees sampled (and most eucalypts used for kraft pulping) and could be expected to give kraft handsheets with higher mean apparent density or lower bulk (Cotterill & Macrae 1997; Kibblewhite *et al.* 1991). Its handsheet apparent density could be expected to be even higher, if the trees had been of the same age as those of the other two species (Table 5). The wide range of handsheet bulk or apparent density values for the 29 individual-tree *E. regnans* pulps is noteworthy (Tables 2 and 5) with tree 29 having the extreme high value of 0.791 g/cm^3 (and the lowest chip density of 365 kg/m^3). Handsheet apparent density is determined by fibre dimensions, fibre collapse, and configuration and packing arrangement in handsheets (Kibblewhite & Shelbourne 1997). This broad range of handsheet apparent density for *E. regnans* is associated with an equally wide range of pulp yield, wood basic density, and glucose content. Mean handsheet tensile index values for given apparent density were higher for the *E. nitens* than for the *E. regnans* or *E. fastigata* 29 individual-tree data sets (Fig. 3).

It is considered that eucalypt kraft pulps prepared in the laboratory require handsheet apparent density values of £0.650 g/cm3 in order to be suitable for most market kraft pulp end-uses (3,12). Seven of the 29 trees of *E. regnans* (which were aged 20/21 years) met this criterion compared with 7 out of 29 trees of *E. nitens* and 4 out of 29 of *E. fastigata* (both latter species aged 15/16 years). At age 15 years, fewer *E. regnans* trees would have made the grade. Indeed, in a recent pulping study of 8-year-old and 11-year-old *E. nitens* (22), mean handsheet apparent densities were 0.751 and 0.735 g/cm^3 respectively, and virtually no trees at these ages would be suitable for market kraft.

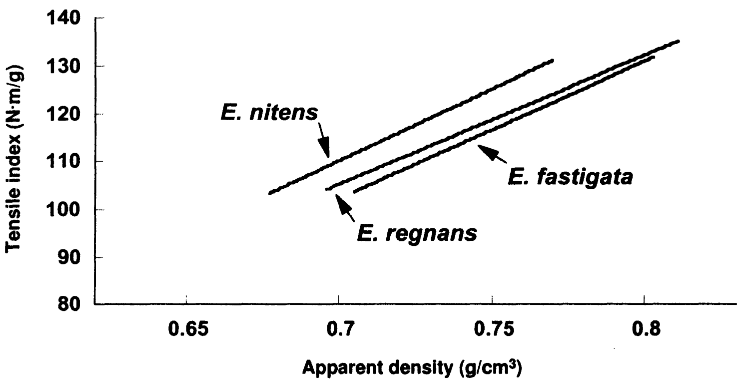

FIG. 3—Mean handsheet tensile index and apparent density relationships for 29 individual-tree pulps for each eucalypt species. Regression lines based on four PFI mill-refining levels — 500, 1000, 2000, and 4000 rev.

Handsheet property predictions from wood and fibre properties for E. regnans, E. nitens, and E. fastigata

Whole-tree wood basic density was well predicted by density of outerwood cores taken from standing trees at breast height (1.4 m) for *E. regnans, E. nitens*, and *E. fastigata* (Table 6). Furthermore, the basic density of both whole-tree chips and outerwood cores at 1.4 m was a good predictor of handsheet apparent density for *E. regnans* and *E. fastigata* but not so good for *E. nitens* (r^2 =0.36 and 0.40), a result that has no ready explanation. Prediction of handsheet apparent density was enhanced by inclusion of kraft fibre length, especially for *E. nitens*. The kraft fibre property of collapse (indicated by the width/thickness ratio (Fig. 1)) was a good predictor of handsheet apparent density for all three eucalypt species (Table 6), and was strongly correlated with wood basic density for *E. regnans* (Table 3) and for the other species (Kibblewhite 1999). Levels of prediction of handsheet apparent density were increased slightly by inclusion of fibre length with width/thickness.

TABLE 6–Comparison of prediction of handsheet apparent density and tensile index (@ 500 PFI mill rev.) from fibre dimension (W/T + L) and chip (D_c) and breast-height (D_b) basic density for three eucalypt species

Dependent variable	Independent variables	*E. regnans*		*E. nitens*		*E. fastigata*	
		R^2	Standard error	R^2	Standard error	R^2	Standard error
Chip density (D_c) (kg/m^3)	D_b	0.87	13.7	0.70	21.4	0.78	16.5
Handsheet apparent density (g/cm^3)	W/T	0.63	0.0292	0.57	0.0190	0.81	0.0179
	W/T + L	0.65	0.0292	0.67	0.0169	0.84	0.0167
	D_c	0.74	0.0243	0.36	0.0233	0.69	0.0226
	D_c + L	0.82	0.0210	0.64	0.0178	0.71	0.0222
	D_b	0.76	0.0233	0.40	0.0227	0.66	0.0235
	D_b + L	0.80	0.0222	0.60	0.0188	0.67	0.0234
Handsheet tensile index (N.m/g)	W/T	0.53	8.34	0.64	5.66	0.62	6.58
	W/T + L	0.53	8.46	0.64	5.76	0.62	6.71
	D_c	0.80	5.37	0.37	7.49	0.58	6.92
	D_c + L	0.81	5.42	0.43	7.29	0.58	7.04
	D_b	0.70	6.65	0.51	6.65	0.57	6.92
	D_b + L	0.70	6.77	0.53	6.64	0.57	7.02

Chip density and kraft fibre width/thickness are also good predictors of handsheet tensile index, but the r^2 were unchanged by the inclusion of fibre length. There was, however, a clear dependence of tensile index on apparent density (Fig. 2) which in turn was determined by fibre packing densities and arrangements in handsheets (Kibblewhite & Shelbourne 1997).

CONCLUSIONS

The range of individual-tree wood and kraft fibre and pulp properties for the 29 *E. regnans* trees was extremely wide: chip density 368–509 kg/m^3, chip lignin content 26.3–31.6%, pulp yield at 20 kappa 53–59%, fibre length 0.79–1.01 mm, and handsheet apparent density at 500 PFI mill rev. 0.619–0.791 g/cm^3.

For the three eucalypt species — *E. regnans*, *E. nitens*, and *E. fastigata* — breast-height outerwood density and individual-tree chip density were strongly correlated one with another, and also well correlated with the important handsheet properties of apparent density and tensile strength (less well for *E. nitens*). While such correlations could therefore be used to select standing trees for wood density and thus handsheet apparent density, neither indicate fibre quality nor paper product suitability (Kibblewhite & Shelbourne 1997). Hence, non-destructive and economical test methods are needed which give estimates of the wood fibre cross-sectional and length dimensions in standing trees. This will facilitate selection of individual trees for tree breeding that are suited to pulp product requirements (Kibblewhite & McKenzie 1998), and also evaluation of plantation stands for forest management. It is recommended in the meantime that trees and provenances be screened and selected for breeding and planting programmes on the basis of breast-height outerwood density. Such practice will allow these selections to be further screened for lignin/cellulose content and fibre quality when suitable testing technologies become available.

Kraft fibre collapse (indicated by width/thickness ratio) was the most reliable individual-tree pulp property predictor (across the three species) of the important handsheet property of the apparent density of "unrefined" pulp (@ 500 PFI mill rev.). "Unrefined" apparent density is considered to be the critical property, the base against which all other handsheet properties are compared (Kibblewhite & Shelbourne 1997). Handsheet apparent density is an important quality determinant of *E. regnans*, *E. nitens*, and *E. fastigata* kraft pulps since the lower the apparent density of the unrefined pulp, the higher is the potential to develop useful tensile strength with refining, while retaining bulk. Other handsheet properties can normally be developed by refining, provided the resulting apparent density meets the requirements of the product being manufactured. For the three eucalypts, the prediction of handsheet apparent density was consistently improved by inclusion of kraft fibre length in the chip density and kraft fibre width/thickness equations.

The 29 *E. regnans* individual-tree wood samples averaged lower wood density than those of *E. nitens* and *E. fastigata* (maybe accentuated by the higher elevation of the *E. regnans* stand) resulting in higher handsheet apparent density values, despite an additional 5 years' growth of higher density outerwood. Mean property values for the three species showed that *E. regnans* had, in addition to lower chip basic density, an intermediate lignin content and good kraft pulp yield, with kraft fibres which are longer, broader, thinner-walled, and of higher collapse than the other two species (Table 5). Mean pulp yields were similar for *E. regnans* and *E. nitens*, with the *E. regnans* pulps containing more glucose and less xylose. Mean handsheet apparent density for the 29-tree samples of *E. regnans*, *E. nitens*, and *E. fastigata* all exceeded the critical level of 0.650 g/cm^3 needed for most market kraft end-uses, though each population had a proportion of trees that were suitable.

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APPENDIX

TWENTY-NINE INDIVIDUAL-TREE *E. REGNANS* KRAFT FIBRE DIMENSION AND CHIP DENSITY PREDICTIONS OF HANDSHEET PROPERTIES AT 500 PFI MILL REV.

(wall thickness (T_w), perimeter (P), chip density (D_c), lignin (Lg), and length weighted length (L))

	Prediction equation	r^2	Standard error*
Apparent density	$= 0.226W/T + 0.182$	0.630	0.0292
	$= 0.204W/T - 0.123L + 0.344$	0.645	0.0292
	$= -0.001D_{c^*} + 1.17$	0.744	0.0243
	$= -0.001D_c - 0.239L + 1.34$	0.817	0.0210
	$= -0.001D_c + 0.014Lg + 0.652$	0.825	0.0205
	$= -0.001D_c + 0.009Lg - 0.138L + 0.919$	0.841	0.0199
	$= 0.030Lg - 0.169$	0.493	0.0342
	$= 0.026Lg - 0.102L + 0.019$	0.502	0.0346
Tensile index	$= 52.2W/T - 15.0$	0.527	8.34
	$= 55.0W/T + 15.4L - 35.3$	0.531	8.46
	$= -0.282D_c + 227$	0.804	5.37
	$= -0.276D_c - 12.6L + 236$	0.807	5.42
	$= -0.260D_c + 1.43Lg + 176$	0.817	5.29
	$= -0.259D_c + 1.55Lg + 3.80L + 168$	0.817	5.39
Light-scattering coefficient	$= -2.74W/T + 37.5$	0.058	1.87
	$= -1.86W/T + 4.95L + 31.0$	0.073	1.89

* RMS error for each regression equation.