Kraft fibre property variation among 29 trees of 15 year old *Eucalyptus fastigata* and comparison with *E. nitens*

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Variation in wood basic density and chemistry, and fibre and handsheet properties of 29 individual trees of *Eucalyptus fastigata* are assessed and compared to that of 29 *E. nitens* trees of similar age and growing site.

The 29 *E. fastigata* individual tree samples show this species to be of higher wood lignin content and lower pulp yield with wide ranges of fibre collapse and handsheet bulk compared to those of the 29 *E. nitens* trees. Fortunately the high end of the handsheet bulk range and the low end of the fibre collapse range are similar for the two species. Furthermore up to about 20% of the *E. fastigata* and *E. nitens* individual tree pulps can be expected to have handsheet bulk values >1.54 cm^3/g at 500 rev PFI mill and be of good papermaking quality.

Keywords

Eucalypt species, fibre dimensions, handsheets, kraft pulp, variation, wood chemistry, wood density

Eucalyptus fastigata, E. nitens and *E. regnans* are the three eucalypt species considered to be most suitable for growing in New Zealand in commercial plantations for pulp production (*1*). A comprehensive program is underway to quantify the potential of each species for solid wood and/or pulp and paper product end uses as follows:

- To estimate the extent of within and between tree variation in a comprehensive set of wood, fibre and chemical properties.
- To characterize the kraft fibres and pulps, and mechanical cold soda pulps made from representative whole-tree chip samples.

This report covers the kraft pulp and fibre property variation and relationships for 29 individual *E. fastigata* kraft pulps, each representative of trees selected to cover a wide range of breast height, outerwood basic density (396 to 553 kg/m^3). The wood, and kraft and mechanical pulp properties for 29 trees of *E. nitens* are detailed elsewhere (*2,3,4*).

EXPERIMENTAL METHODS

Sample origin

The 29 *E. fastigata* trees were felled and processed in two lots: 20 trees in November 1995 (Stage I) and 9 trees in August 1996 (Stage II). Initially all 29 by 16 year old trees were selected from those in a provenance-progeny trial in Compartment 1207 Kaingaroa Forest (Plot number RO1975). The 29 trees were selected from 625 based on the outerwood basic density of 5 mm increment cores, taken at breast height 1.4 m above ground. Trees were selected with 9 of high, 9 of low and 11 of intermediate density. The nine-tree lot (Stage II) was selected and reserved on the basis of its large volumes with three of high, three of intermediate and three of low density. However the 9 preselected trees of Stage II were not felled but were kept for the breeding program. A replacement 9-tree set was selected from those remaining for the mechanical pulping study with three of high, three of intermediate and three of low density, but these trees were of smaller diameter than the original nine tree set.

The trees selected represented a range of provenances; Natal (South Africa), Vakura (New Zealand), Oberon, Rossi, Robertson, Bombala (Australia). At the time of felling material was removed for wood property assessment as follows: Two discs (50 mm thick) were taken from each height level (0, 1.4, 5.5, 11.0, 16.5 and 22 m above the ground) as well as the roundwood billet below the 1.4 m level. All remaining logs were chipped in a commercial chipper and the chips used passed through a 40 mm overs screen and were retained on a 10 mm screen. All logs of each tree (except the roundwood billets from below 1.4 m) were chipped; the chips mixed and 5 kg o.d of chips taken from each individual tree to make a well-mixed chip pile for kraft pulping.

Replicate chip samples were taken from five of the 20, and all of the 9 individual-tree chip lots. The chip basic density and chemical composition, pulp yield and kraft fibre dimension data, and the handsheet property values at 500 rev PFI mill used in the analyses were those of the 15 unreplicated chip samples. In contrast, graphical presentations of handsheet property regressions are based on the data for each pair of replicate chip samples used in the analyses. The replicate data have been used elsewhere (*4*) to assess the variation in wood, pulp and handsheet test results.

Breast height and chip basic density

- Outerwood breast height basic density was determined on the outer 50 mm of radial 5 mm cores taken at 1.4 m (*6*).
- Chip basic density was determined in accordance with Appita method P1s-79 except that the fresh chips were not given the specified soaking period (*7*).

Chemical analyses

Three hundred g o.d. chip samples were collected for chemical analyses prior to pulping. Unfortunately the 20 individual-tree greenchip samples (300 g o.d.) used for chemical analyses only were stored at 4°C for about three months before drying, and some carbohydrate degradation apparently occurred (Appendix I).

Chips were air dried for three days prior to grinding (20 mesh). Samples were extracted in a Soxtec extractor with dichloromethane – boiling time 30 minutes, rinsing time 60 minutes. Extractives were vacuum dried overnight. Moisture contents were determined on separate samples.

Extracted samples were further ground to 40 mesh for analysis of lignin and carbohydrates. After acid hydrolysis the samples were analysed following TAPPI

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T222 om-88 for lignin, TAPPI T250 cm-85 for acid soluble lignin; the method of Pettersen and Schwandt (*8*) was used for carbohydrates.

Pulping and bleaching

Chips used for kraft pulping passed through the 26 mm; and were 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 the 20-tree sample lot were:

12% effective alkali as Na_2O
30% sulfidity
4:1 liquor to wood ratio
90 minutes to maximum temperature
170°C maximum temperature

Pulps were prepared in 2.0 L pressurized reactors with 300 g o.d. chip charges. Pulps were disintegrated with a propeller stirrer and screened through a 0.25 mm slotted flat screen. After dewatering and fluffing, Kappa number, % rejects and total yield were determined.

Handsheet preparation and evaluation

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

Fibre dimension measurement

Cross-section kraft fibre dimensions (means and distributions) of thickness, width, wall area, wall thickness, perimeter, cross-section area and the width:thickness ratio were measured using image processing procedures described previously (Fig. 1) (*9*). Measurements were made on dried and rewetted fibres reconstituted from handsheets. Length weighted average fibre lengths were determined with a Kajaani FS 200 instrument using TAPPI method T271 pm-91.

Statistical calculations

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

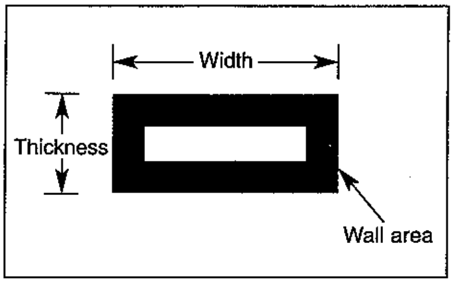

Fig. 1 Cross-section diagram of a fibre dried and rewetted from a handsheet.

Terminology

Fibre and dimension abbreviations used throughout are:

Fibre width	W
Fibre thickness	T
Fibre wall area	AW
Fibre size – cross section area (WxT)	A
Fibre wall thickness	TW
Half fibre perimeter (W+T)	P
Fibre length weighted length	L
Fibre collapse potential (width thickness)	W/T
Half fibre perimeter/wall thickness	P/TW
Chip density	Dc
Breast height core density	Db
Lignin	Lg

RESULTS AND DISCUSSION

Wood chip, kraft fibre and handsheet property variation

Chemical compositions of the 29 individual-tree chip samples show marked between-tree variation with total lignin contents ranging from 28.7 to 31.9% and pulp yield ranging from 48 to 57% for the individual trees (Tables 1, 2 and reference *19*). Pulp yield tends to increase with decreasing chip lignin contents and increasing carbohydrate contents.

Table 1
Variation in selected chip, fibre and handsheet properties for the 29 individual trees.

Property	Range
Chip basic density, kg/m³	404-534
Chip total lignin, %	28.7-31.9
Pulp yield, %	48-57
Fibre length, mm	0.76-0.92
Half fibre perimeter, (W+T) mm	18.5-21.1
Fibre cross section area, (WxT) µm²	78-100
Fibre wall area (coarseness), µm²	54-65
Fibre collapse potential, (W/T)	1.81-2.30
Handsheet bulk, cm³/g	1.58-1.29
Handsheet apparent density, g/cm³	0.632-0.773

Unfortunately, carbohydrate contents are consistently low for the first set of 20 trees compared to those of the second set of 9 trees, with mean total carbohydrate contents of 56.1 and 60.2% respectively (Table 2 and reference 19). Hence, some carbohydrate degradation probably occured in the green 20-tree chip samples stored for about three months at 4°C before chemical analysis. Although similar trends can be expected with corresponding lignin contents actual differences are less obvious. Carbohydrate degradation occurred only in the 20-tree chip samples used for chemical analysis. Corresponding chip samples used for pulping probably had minimal degradation because they were processed soon after chipping.

Wide ranges in property values are also obtained for chip density (404 to 534 kg/m³), the important fibre dimensions of length (0.76 to 0.92 mm), half perimeter (18.5 to 21.1 µm), size (width by thickness) (78 to 100 µm²), wall area (coarseness) (54 to 65 µg/m), the width: thickness ratio (1.81 to 2.30) and handsheet apparent density at 500 rev PFI mill (0.632 to 0.773 g/cm³) (Tables 1,2).

Correlations of individual-tree wood chip, kraft fibre and handsheet properties

Breast height outerwood density is highly correlated with whole-tree chip density (r^2=0.78) (Table 2 and reference 19). Of the kraft fibre properties, the width: thickness ratio or collapse potential is most strongly correlated with chip density (r^2=0.78), followed by the perimeter:wall thickness ratio (r^2=0.60). These trends are similar to those obtained for 29 trees of *E. nitens* (*2,3*), and for radiata pine individual-tree pulps prepared from eleven 16 year old clones (*10*), and from 25 by 13 year old trees selected for extremes of tracheid perimeter and wall thickness (*3*). Other fibre properties are generally poorly correlated with chip density except width by itself which is accounted for as a component of the width:thickness and perimeter:wall thickness ratios.

Handsheet apparent density, tensile strength and light scattering coefficient are important eucalypt pulp quality determinants (*3,11,12*). Handsheet property predictions are made at 500 rev PFI mill as the basis of comparison for reasons described elsewhere (*10,13*). Predictive relationships for these handsheet properties from chip and kraft fibre properties are indicated in Tables 3 and 4. The kraft fibre width:thickness ratio is consistently the best predictor of the selected handsheet properties – apparent density (r^2=0.81), tensile index (r^2=0.62) and light scattering coefficient (r^2=0.43). The fibre peri-

Table 2
Unrefined *E. fastigata* dimensions and handsheet properties @ 500 PFI mill rev.

	Handsheet properties @ 500 PFI mill rev					Wood properties				Unrefined kraft pulp fibre properties										
Individual tree pulp	Apparent density g/cm³	Tensile index N.m/g	Stretch %	Light scattering co-efficient m²/kg	Breast-height density ** kg/m³ D_b	Chip density kg/m³ D_c	Chip total lignin g/100 g	Chip carbo-hydrate g/100 g	Pulp yield at Kappa 20* % Y	Length mm L	Width µm W	Thickness µm T	Perimeter µm W+T	Width x thickness µm² WxT	Wall area µm² A_W	Wall thickness µm T_W	Width/thickness W/T	W+T/T_W	W+T/A_W	Relative number of fibres
1	0.632	85	2.67	34.2	553	517	29.2	54.7	52	0.84	12.5	7.1	19.6	89	59	2.40	1.84	8.4	0.35	114
2	0.648	88	2.48	32.1	530	534	30.1	57.3	52	0.88	12.5	7.2	19.7	94	61	2.55	1.81	8.0	0.34	103
3	0.648	93	2.55	32.8	535	507	29.6	59.9	54	0.92	12.3	6.8	19.1	84	56	2.35	1.91	8.4	0.36	109
4	0.649	92	2.55	33.8	511	502	29.8	58.1	52	0.85	12.3	7.0	19.3	87	59	2.59	1.83	7.6	0.34	112
5#	0.663	92	2.83	35.0	484	476	30.9	59.8	55	0.85	12.8	6.7	19.5	87	55	2.16	1.98	9.3	0.37	118
6#	0.673	88	2.55	32.8	515	492	30.5	60.0	55	0.84	12.8	6.7	19.5	87	56	2.21	1.99	9.1	0.37	118
7#	0.675	91	2.59	31.6	511	478	31.4	59.1	55	0.86	13.0	6.6	19.6	88	56	2.21	2.05	9.1	0.37	115
8#	0.676	93	2.76	31.5	510	492	31.3	58.8	54	0.89	12.9	6.7	19.6	87	56	2.25	2.00	9.0	0.37	109
9	0.680	97	2.80	31.5	533	465	30.1	56.0	53	0.87	13.3	6.9	20.2	92	63	2.54	2.03	8.2	0.34	103
10#	0.689	100	2.63	31.8	475	444	28.7	61.8	55	0.88	13.6	7.0	20.6	96	60	2.19	2.02	9.6	0.36	105
11	0.690	93	2.96	33.3	415	439	30.4	57.1	53	0.77	14.1	7.1	21.1	100	65	2.43	2.09	9.1	0.34	114
12#	0.690	100	2.57	31.7	406	421	29.0	61.4	57	0.89	13.5	6.5	20.1	90	56	2.13	2.15	9.7	0.38	111
13	0.690	98	2.93	32.5	466	442	30.3	55.2	55	0.88	13.9	7.1	21.0	99	65	2.43	2.04	8.9	0.34	98
14	0.694	102	2.60	31.6	491	474	29.6	55.5	51	0.79	13.0	6.7	19.6	87	57	2.28	2.01	8.8	0.36	125
15	0.699	102	2.71	32.3	460	474	31.4	55.6	48	0.87	13.5	6.9	20.4	94	64	2.48	2.04	8.5	0.34	101
16	0.713	110	3.04	33.0	498	496	31.3	56.1	53	0.84	12.1	6.4	18.5	78	54	2.44	1.95	7.8	0.36	124
17#	0.714	106	2.68	31.6	423	430	29.1	61.8	55	0.87	13.1	6.6	19.8	88	56	2.12	2.05	9.6	0.37	113
18	0.718	100	2.65	30.8	476	471	31.3	54.8	52	0.81	13.9	6.9	20.8	98	65	2.46	2.10	8.8	0.35	109
19	0.718	111	3.08	31.9	424	459	30.5	54.6	51	0.81	13.3	6.9	20.2	93	63	2.54	2.02	8.3	0.34	110
20	0.727	109	2.95	30.9	446	431	30.7	55.3	55	0.86	13.5	6.5	20.0	88	57	2.18	2.18	9.5	0.37	115
21	0.728	103	3.13	27.2	464	454	31.9	54.2	50	0.81	14.1	6.7	20.8	94	61	2.25	2.20	9.4	0.35	114
22#	0.731	110	2.93	31.9	465	431	31.5	59.0	53	0.84	13.7	6.6	20.3	91	57	2.12	2.16	9.8	0.37	115
23	0.732	112	3.17	30.5	423	433	29.8	58.1	54	0.90	13.4	6.2	19.5	83	55	2.23	2.27	9.1	0.37	96
24	0.739	109	3.15	31.5	445	432	31.2	56.6	53	0.78	13.4	6.7	20.1	90	60	2.39	2.09	8.7	0.35	120
25	0.762	118	3.09	30.3	396	422	29.8	56.8	52	0.87	14.4	6.5	21.0	95	61	2.17	2.30	10.0	0.36	106
26	0.762	119	3.19	31.3	428	438	31.6	55.2	51	0.88	14.0	6.5	20.5	91	59	2.20	2.26	9.5	0.37	109
27	0.768	113	3.40	31.9	406	412	31.4	53.5	50	0.78	14.0	6.4	20.5	91	58	2.13	2.28	9.9	0.37	124
28#	0.769	126	3.12	29.2	424	404	31.6	60.1	53.0	0.86	13.8	6.4	20.2	90	55	2.01	2.24	10.3	0.39	117
29	0.773	114	3.41	30.8	404	406	31.8	55.7	50	0.76	13.7	6.3	20.0	87	57	2.21	2.26	9.3	0.36	130
Mean	0.705	103	2.87	31.8	466	458	30.5	57.3	53	0.85	13.3	6.7	20.0	90	59	2.30	2.07	9.0	0.36	112
Std dev	0.39.8	10.5	0.270	1.49	46.1	34.8	0.938	2.43	2.03	0.0418	0.615	0.264	0.620	4.87	3.39	0.159	0.138	0.679	0.0140	8.11
CV%	0.5.65	10.3	9.42	4.68	9.89	7.61	3.07	4.23	3.84	4.93	4.61	3.93	3.09	5.39	5.77	6.92	6.65	7.52	3.89	7.22
LSD*										0.03	0.60	0.30	0.71	6.4	3.8	0.10	0.12	0.39	0.012	

*LSD: Least significant difference between means at the 95% level of significance
** Based on the outer 50 mm of 5 mm cores taken at breast height (1.4 m)
# From second set of 9 trees.

Table 3
Prediction of handsheet properties at 500 rev PFI mill based on individual-tree fibre dimension and chip basic density data from 29 *E. fastigata* – width (W), thickness (T), perimeter (P), chip density (D_c), lignin (Lg) and length (L).

Dependant variable	Independent variables	r^2	Dependant variable	Independent variables	r^2	Dependent variable	Independent variables	r^2
Apparent density	Tw	0.23	Tensile index	Tw	0.19	Light scattering coefficient	W/T	0.43
	P	0.18		Tw+P	0.25		W/T+L	0.44
	Tw+P	0.38		Tw+P+L	0.27		P/T_w,	0.21
	Tw+P+L	0.48		W/T	0.62		P/T_w+L	0.22
	W/T	0.81		W/T+L	0.62		D_c	0.24
	W/T+L	0.84		P/Tw,	0.27		D_c+L	0.25
	P/TW	0.37		P/Tw+L	0.29		Others	#ns
	P/TW+L	0.49		Dc	0.58			
	Dc	0.69		Dc+L	0.58			
	Dc+L	0.71		Dc+Lignin	0.63			
	Dc+Lg	0.81		Dc+Lignin+L	0.65			
	Dc+Lg+L	0.81		Lg	0.13			
	Lg	0.25		Lg+L	0.13			
	Lg+L	0.28						

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

meter:wall thickness ratio, chip basic density, chip lignin content are also correlated with handsheet apparent density and tensile index.

Handsheet apparent density is a measure of fibre packing density and web structural organization, and therefore expected to be predictable from mean fibre dimensions and/or fibre dimension populations (*3*). Techniques of multiple linear regression are used to estimate the combined influence of two or more fibre properties. For the 29 *E. fastigata* pulps, handsheet apparent density is strongly predicted by either the fibre width: thickness ratio and length, or the chip density and kraft fibre length combinations (Table 3). Chip lignin by itself, the chip density and lignin combination, and the kraft fibre perimeter:wall thickness ratio and length combination, are also moderate to strong predictors of handsheet apparent density. Prediction equations together with their r^2 and standard error values are listed in Table 4. Further explanatory notes follow:

- The ratio fibre width:thickness reflects the collapsed configuration of the kraft fibres in handsheets, and the high correlation with apparent density could therefore be expected since high and low collapse potential would give high and low sheet densities respectively (*3*).
- The ratio perimeter:wall thickness is a measure of the interactive influences of fibre perimeter and wall area or coarseness, since for a given wall area a thick walled fibre will be of small perimeter and resist collapse, and a thin walled fibre will be of larger perimeter and collapse more easily. Hence, the perimeter:wall thickness ratio can be expected to influence handsheet apparent density values (*3*).
- Chip basic density is a measure of the total mass and volume of a chip sample (*3*). It is evidently strongly influenced by the dimensions and coarseness of the fibres, the tissue component which makes up the largest portion of the wood chip mass.

The mean fibre properties of length, wall thickness and cross-section perimeter together can be expected to describe the size, shape and coarseness of the fibres of pulp from a given tree 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. fastigata* individual-tree pulps. While such trends are indicated for these variables, paticularly when in combination one with another (r^2=0.60), their reliability of prediction is low compared to the width:thickness ratio (Table 3).

Handsheet tensile strength is best predicted by the kraft fibre width:thickness ratio or chip basic density individually (Tables 3,4). Fibre length is

Table 4
Prediction of handsheet properties at 500 rev PFI mill based on individual tree kraft fibre dimension data from 29 *E. fastigata* – width (W), thickness (T), perimeter (P), chip density (D_c), lignin (Lg), and length (L).

Prediction equation					r^2	Standard error#
Apparent density	= 259W/T			+ 167.8	0.805	17.9
	= 249W/T	- 173L		+ 336.0	0.837	16.7
	= 35.9P/T_w			+ 381.1	0.374	32.1
	= 35.5P/T_w	- 322L		+ 657.6	0.488	29.6
	= -0.950D_c*			+ 1140	0.689	22.6
	= -0.906D_c	- 145L		+ 1243	0.711	22.2
	= -0.874D_c	+ 15.1Lg		+ 643.6	0.812	18.0
	= -0.869D_c	+ 14.7Lg	- 22.9L	+ 671.8	0.812	18.3
	= 21.1Lg			+ 59.28	0.248	35.2
	= 18.1Lg	- 175L		+ 301.3	0.277	35.2
Tensile index	= 60.1W/T			- 22.19	0.622	6.58
	= 60.2W/T	+ 0.233L		- 22.42	0.622	6.71
	= -0.231D_c			+ 208.1	0.583	6.92
	= -0.234D_c	+ 10.1L		+ 200.9	0.584	7.04
	= -0.218D_c	+ 2.49Lg		+ 126.2	0.630	6.64
	= -0.226D_c	+ 3.06Lg	+ 35.5L	+ 82.52	0.647	6.62
Light scattering coefficient	= -7.09W/T			+ 46.47	0.433	1.14
	= -7.24W/T	- 2.59L		+ 48.99	0.438	1.16

RMS error for each regression equation.

generally unimportant in this context either by itself or when in combination with either the width:thickness ratio or chip density. Hence, tensile strength appears to be determined more by the development of 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 determined by fibre packing densities and arrangements in handsheets (*3*).

Handsheet light scattering coefficient is poorly predicted by kraft fibre properties or chip density except for the width:thickness ratio (Table 3).

Handsheet property predictions from fibre properties for the 29 *E. fastigata* individual-trees are generally better than those obtained for 29 *E. nitens* trees of similar age (*2*). The added influence of fibre length on fibre width:thickness or chip density prediction of handsheet bulk is, however, minimal for *E. fastigata* compared to *E. nitens*, most probably because of their high prediction values when alone; $r^2 = 0.81$ and 0.69 respectively. Fibre length is again shown to be unimportant in the prediction of handsheet tensile strength, either by itself (*19*) or when in combination with chip density or the fibre width:thickness ratio (Table 3) (*2*).

The prediction of handsheet properties at 500 rev PFI mill from unrefined fibre properties represents an effective way of partly describing fibre and handsheet property relationships. It is however the prediction of combinations of handsheet properties which is required to fully characterize papermaking furnishes and systems. For example, while the tensile strengths of a range of kraft pulps can be similar their apparent density, light scattering coefficient, and tearing resistance values can be very different (*14,15*). The direct prediction of combinations of handsheet properties from fibre properties is, however, associated with a number of problems because of the effects of wide ranges in fibre and handsheet properties, pulp refining levels and conditions, and the bases of comparison selected, as well as a need to interpolate or extrapolate data. Some of these difficulties have been overcome in the selection of fibre types for different paper and pulp grades by

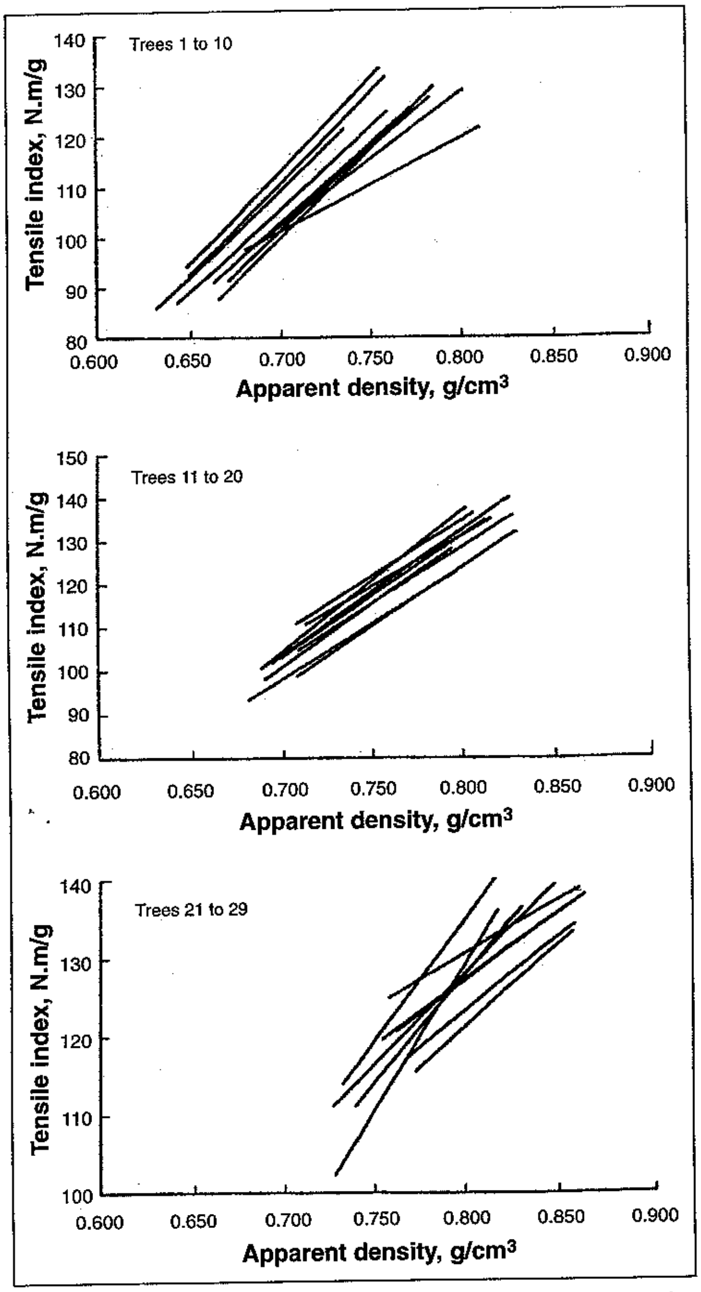

Fig. 2 Tensile index and apparent density relationships/

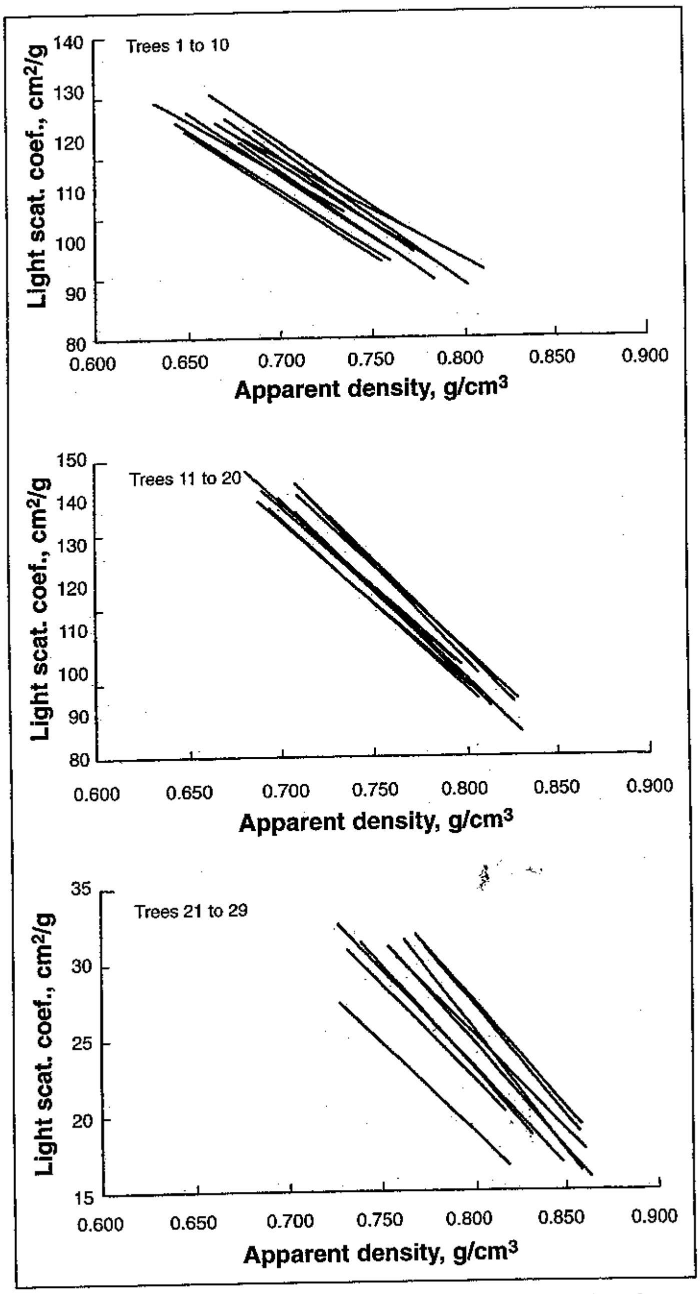

Fig. 3 Light scattering coefficient and apparent density relationships.

using the apparent density of 'unrefined' pulps (500 rev PFI mill) as the base against which other 'unrefined' handsheet properties are compared (*3*).

Handsheet property relationships

Eucalypt market kraft pulps are known to combine the most important pulp and paper properties in a particularly favourable way (*3,11,16,17*). They give good strength and formation with excellent bulk and opacity 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 (*3*). The pulps from 29 trees of *E. fastigata* show a wide range of handsheet bulk values at 500 rev PFI mill (1.58 to 1.29 cm^3/g) which is the reciprocal of the apparent:density range of 0.632 to 0.773 g/cm^3 (Table 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 present in large numbers compared to other hardwood fibres (*11,12*).

The 29 individual-tree *E. fastigata* pulps are numbered 1 to 29 in ascending order of sheet density in Table 2. The effect of the large 0.632 to 0.773 g/cm^3 apparent density range on the tensile strength apparent density relations for the 29 pulps is indicated in Figure 2. Each regression line is based on handsheet data determined at each of four refining levels – 500, 1000, 2000 and 4000 rev. All pulps can 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 to 4 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 woodfree tissue, and printing and writing grades (*3*). Pulps 5 to 29, on the other hand, are deficient in bulk and generally unsuitable for such end uses despite their high initial tensile strength.

The highest tensile index:apparent density regression slopes, low initial apparent densities (<0.650 g/cm^3) and easy development of tensile index with refining, separate pulps 1 to 4 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).

Regression coefficients of determination (r^2) fall below 0.90 for pulps 25 to 29 indicating that tensile strength maxima are reached with the selected levels of PFI mill refining (*19*).

Fibre width:thickness ratios are also lowest for pulps 1 to 4 which in turn are of acceptable market pulp bulk and fibre length (Table 2) (*3*). The fibre width: thickness ratio is measured from fibres which are first pressed and dried in the handsheeting process (*9*). Hence the width:thickness ratio is a direct measure of the collapse potential of the fibres within a pulp.

Light scattering coefficient decreases with increasing apparent density but with light scattering values at a given density development on the apparent density value of the unrefined pulps (Fig. 3). Hence at 0.700 g/cm^3 apparent density, average light scattering coefficients of the refined pulps are about 20 m^2/kg for trees 1 to 10, about 32 m^2/kg for trees 11 to 20, or out of range for trees 21 to 29. It is noteworthy that regression slopes remain generally constant for all 29 pulps (Fig. 4,5) compared to those of the tensile strength:apparent density regressions (Fig. 2). For trees 25 to 29 tensile strength maxima are reached with refining although corresponding minima are absent for light scattering coefficient.

The wide handsheet apparent density range of 0.632 to 0.773 g/cm^3 for the 29 individual-tree pulps suggests a high potential for tree selection based on this pulp quality determinant. It is noteworthy that breast height core basic density is a good predictor of both whole-tree chip density (r^2 = 0.78) and handsheet apparent density (r^2 = 0.65) (Table 3). While such correlations could therefore be used to screen standing trees into potential wood density and handsheet bulk categories, they indicate neither fibre quality nor paper product suitability (*3*). Hence non-destructive test methods are required which give estimates of the fibre cross-section and length dimensions in standing trees. This will ensure that tree breeding and plantation forest management programs are in tune with both solid- and reconstituted-wood product requirements (*3*).

E. fastigata versus *E. nitens* comparison

The 29 *E. fastigata* individual-tree wood samples are of similar basic density, higher lignin content, and give lower pulp yields than corresponding *E. nitens* samples (*2*). (Table 5). The high lignin contents and low pulp yields (low alpha cellulose contents) of the *E. fastigata* trees confirms other recent research findings (*18*). The fibre properties of length and relative number per unit mass of pulp

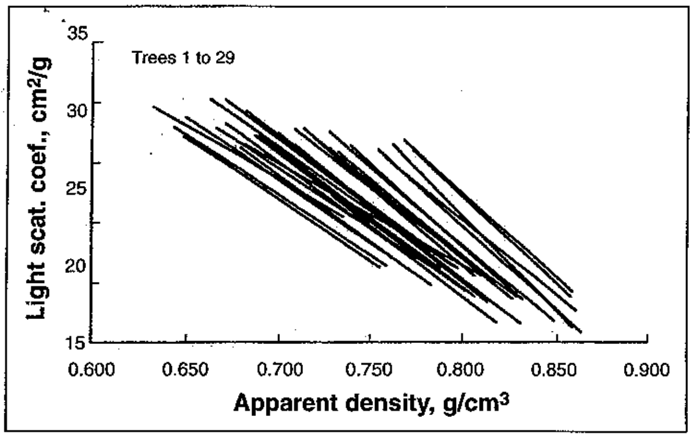

Fig. 4 Light scattering coefficient and apparent density relationships – 29 individual-tree pulps.

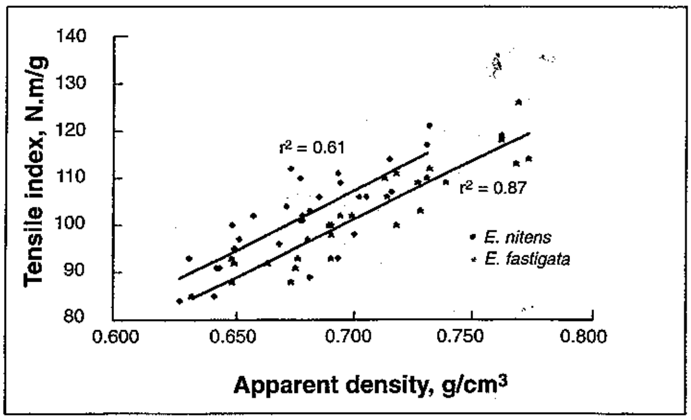

Fig. 5 Handsheet tensile index versus apparent density for 29 *E. fastigata* and 29 *E. nitens* individual-tree pulps each refined 500 rev PFI mill.

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

	29 x *E. nitens*		29 x *E. fastigata*	
	Mean	Range	Mean	Range
Chip basic density, kg/m^3	474.0	390–556	458.0	404–534
Chip total lignin, %	27.6	25.1–29.7	30.5	28.7–31.9
Pulp yield, %	56.0	54–59	53.0	48–57
Fibre length, mm	0.86	0.78–0.95	0.85	0.76–0.92
Fibre collapse potential, (W/T)	1.97	1.80–2.09	2.08	1.81–2.30
Number fibres/unit mass	108.0	92–120	112.0	96–130
Handsheet bulk, cm^3/g	1.48	1.59–1.37	1.42	1.58–1.29

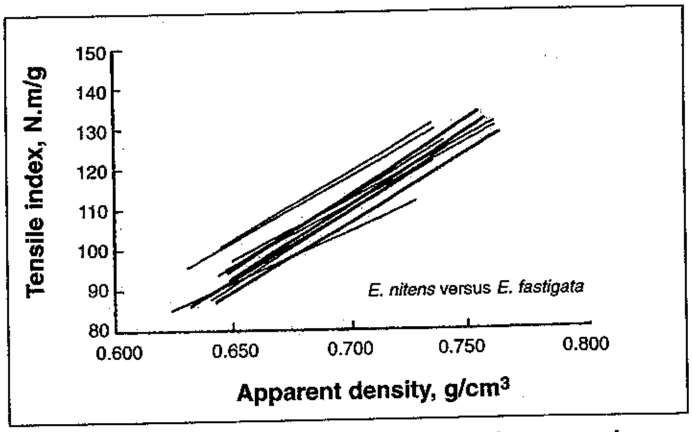

Fig. 6 Tensile index versus apparent density regressions for individual-tree pulps of apparent density <0.650 g/cm^3 at 500 rev PFI mill. The four *E. fastigata* pulps are indicated by the dark regression.

are similar for the two eucalypt species, although mean fibre collapse is greater and mean handsheet bulk is lower for the *E. fastigata* individual-tree pulps. The wide range of bulk and collapse values of the 29 *E. fastigata* pulps is the cause of the apparent low and high values respectively. At desired eucalypt bulk levels for papermaking (>1.54 cm^3/g) (*3*), fibre and handsheet bulk properties are similar for four of the 29 *E. fastigata* pulps (14%) and seven of 29 *E. nitens* pulps (24%) (2) (Table 6). The apparent low proportion of *E. fastigata* pulps of 'high' bulk may be partly related to the changed tree selection criteria for the 9-tree *E. fastigata* sample.

Handsheet property predictions from chip density and kraft fibre collapse (W/T), and their kraft fibre length combinations, are higher for the 29 *E. fastigata* than the 29 *E. nitens* individual-tree samples (Table 7). Furthermore fibre collapse and handsheet bulk variation are highest for the *E. fastigata* pulps (Table 5). Thus, the similar standard errors for the two eucalypt species are to be expected, despite the high r^2 values of the *E. fastigata* regressions (Table 7).

For individual-tree pulps, each lightly refined to 500 rev PFI mill, tensile strengths at given apparent densities are marginally higher for *E. nitens* than *E. fastigata*, although the *E. nitens* data are well scattered (Fig. 5). The two eucalypt species, however, show similar tensile index:apparent density regressions for individual-tree pulps of good bulk for papermaking (viz. bulk ≥1.54 cm^3/g or apparent density ≤0.650 g/cm^3 at 500 rev PFI mill (*3*)). (Fig. 6).

CONCLUSIONS

The range of individual-tree and kraft pulp fibre and pulp properties for the 29 *E. fastigata* trees is extremely wide: chip density 404 to 534 kg/m^3, chip lignin content (28.7 to 31.9%) pulp yield at 20 Kappa 48 to 55%, fibre length 0.76 to 0.92 mm, and handsheet apparent density at 500 rev PFI mill 0.632 to 0.773 g/cm^3.

Breast height outerwood density and individual-tree chip density are strongly correlated one with another (r^2 = 0.78) and with the important handsheet property of apparent density or bulk (r^2 = 0.65 and 0.69 respectively) and tensile strength (r^2 = 0.56 and 0.58). While such correlations could therefore be used to select standing trees for wood density and handsheet bulk, neither indicate fibre quality nor paper product suitability (*3*). Hence non-destructive test methods are required which give estimates of the wood fibre cross-section and length dimensions in standing trees. This will ensure that evaluation of individual trees for tree breeding and of plantation stands for forest management, is in tune with both solid- and reconstituted wood product requirements (*3*). It is recommended in the meantime that trees be screened and selected for breeding and planting programs on the basis of breast height outerwood density. Such practice will allow these selections to be further screened for lignin content and fibre quality when suitable testing technologies become available.

The kraft pulp fibre width:thickness ratio or collapse potential is the best individual-tree property predictor of the important handsheet property of bulk

Table 6
Variation in selected chip, fibre and handsheet properties for individual-tree pulps of handsheet bulk >1.54 cm^3/g.

	7 x *E. nitens*		4 x *E. fastigata*	
	Mean	Range	Mean	Range
Chip basic density, kg/m^3	509.0	456–556	514.0	502–529
Chip total lignin, %	27.0	25.1–28.1	29.6	29.2–30.0
Pulp yield, %	57.0	56–59	53.0	52–54
Fibre length, mm	0.89	0.83–0.95	0.87	0.84–0.92
Fibre collapse potential, (W/T)	1.88	1.80–1.95	1.87	1.81–0.92
Number fibres/unit mass	106.0	97–114	108.0	98–114
Handsheet bulk, cm^3/g	1.56	1.59–1.54	1.56	1.58–1.54

Table 7
Chip density and kraft-fibre width:thickness prediction of important handsheet properties at 500 rev PFI mill for 29 *E. fastigata* and 29 *E. nitens* individual trees.

		29 *E. nitens*		29 *E. fastigata*	
		r^2	Std error#	r^2	Std error#
Apparent density	W/T	0.57	19	0.81	18
	W/T+L	0.68	17	0.84	17
	D_c	0.36	23	0.69	23
	D_c+L	0.64	18	0.71	22
Tensile index	W/T	0.64	5.7	0.62	6.6
	W/T+L	0.64	5.8	0.62	6.7
	D_c	0.37	7.5	0.58	6.9
	D_c+L	0.43	7.3	0.58	6.7
Light scattering coefficient	W/T	0.19	1.4	0.43	1.1
	W/T+L	0.21	1.4	0.44	1.2

RMS error for each regression equation.

(r^2 = 0.84), the base against which all other handsheet properties are compared. Handsheet bulk is an important quality determinant of *E. fastigata* (and *E. nitens*) kraft pulps since the higher the bulk of the unrefined pulp the higher is the potential to develop useful tensile strength with refining. Other handsheet strength properties can normally be developed by refining provided the resulting bulk meets the requirements of the product being manufactured. The added influence of fibre length on fibre width:thickness or chip density prediction of handsheet bulk is minimal for *E. fastigata* compared to *E. nitens*, most probably because of their high prediction values when alone; *E. fastigata* width:thickness r^2 = 0.86 and chip density 0.74.

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