Kraft fibre and pulp qualities of 29 trees of New Zealand grown *Eucalyptus nitens*

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There is a need to determine the between tree variation in the wood properties and kraft fibre and pulp qualities of softwoods and hardwoods that grow well in New Zealand. This information will be used in the planning and management of end-product directed plantation forests and tree-breeding programs. Variation among 29 individual trees of *E. nitens* is extremely high; for the individual tree chip samples the basic density range is 390–556kg/m^3, total lignin content 25.1–29.7%, and kraft pulp yield 54–59%. Between tree variation in some important kraft pulp properties are: fibre length (0.780.95mm), fibre perimeter (19.0–21.6mm), wall area (coarseness) (53–70mm^2), and handsheet bulk at 500 PFI mill rev (1.59–1.37cm^3/g).The fibre width:thickness ratio and length combination (r^2 = 0.67), and the chip density and length combination (r^2 = 0.64) are the best predictors of handsheet bulk. Fibres are curled and consequently 'shortened' by pulp bleaching.

Keywords

eucalypt, kraft, fibre dimensions, handsheet properties, chemistry, wood properties, variation

EUCALYPTUS NITENS is a vigorous, frost resistant and relatively disease free eucalypt when grown in New Zealand as a forest plantation tree species (*1*). On the other hand, rather little is known of the between-tree variation in wood and fibre properties of *E. nitens* or its potential for processing into solid wood and reconstituted fibre products such as pulp and paper.

For this reason a comprehensive program was set up to:

- Estimate the extent of within and between tree variation in a comprehensive set of wood, fibre and chemical properties, in a set of 29 trees preselected for a range of wood density from 15 year old *E. nitens* from central Victorian provenances grown in a provenance-progeny trial in Kaingaroa Forest.
- Characterize the fibre and kraft pulp qualities of pulps made from representative whole tree chip samples for the 29 trees.
- Characterize the mechanical pulp qualities of nine of the preselected 29 trees using the cold soda process (CCS).
- Obtain preliminary estimates of solidwood properties and their relationships with wood, fibre and chemical properties by sawing boards from a 1.4 m bolt taken from the base of the butt log of each of the 29 trees.

This report covers the kraft fibre property relationships for 29 individual tree pulps, each representative of the 29 preselected trees.

EXPERIMENTAL METHODS

Sample origin

Twenty-nine 15 year old *E. nitens* trees from central Victorian provenances were taken from the Provenance-Progeny Trial R 1977, Cpt. 1217, Kaingaroa Forest, planted in 1979. The 29 trees were selected from some 100 well grown, dominant or co-dominant trees without forking to cover a full range of basic density, using increment cores taken at breast height. Twenty of these trees were felled in late 1994 and the remaining nine in mid 1995.

The 20-tree sample was made up of six trees of low, six of high and eight of medium density based on five mm diameter increment cores. The corresponding nine-tree sample was made up of three trees of low, three of high and three of medium density. At the time of felling material was taken for wood property assessment as follows: two discs (50 mm thick) were taken from each level (0, 1.4, 5.5, 11.0, 16.5 and 22 m) as well as the roundwood billet below the 1.4 m level. All remaining log segments after taking the discs were chipped in a commercial chipper and the chips used were those that passed through a 40 mm overs screen and were retained on a 10 mm screen. For the 20-tree lot all logs from each tree were chipped; the chips mixed and 5 kg o.d. were taken from each individual tree, to make a well-mixed chip pile for kraft pulping. A different procedure was followed with the nine trees since chip samples were first taken for each log of each of the nine trees (manuscript in preparation), and then the chips of each of 4–5 logs of each tree were well mixed with a front end loader before taking 5 kg o.d. samples.

A bulked chip lot of all 20 trees was made up by taking 300 g o.d. equivalent from each of the 20 samples of 5 kg o.d. chips. A corresponding bulked chip lot of eight of the nine trees was made up by taking 720 g o.d. equivalent from each of the eight samples of 5 kg o.d. chips. These two well mixed bulked lots were divided into three replicate lots of about 2000 g o.d. equivalent and processed separately using the same procedures as for the 29 individual tree lots. The two sets of three replicate chip samples were used to obtain preliminary estimates of experimental error as well as differences between bleached and unbleached pulps. A chip sample for one of the nine trees (tree 98) was not collected until after the chips had been processed for the mechanical pulping studies. Consequently, the chips were kraft-pulped after they had been pre-impregnated with caustic soda in the PAPRO mechanical pulp pilot plant, hence the decrease from nine to eight trees in the number of samples included in the bulk sample. Fortunately, a small quantity (200 g o.d.) of non-impregnated chips was available for basic density and chemical analysis.

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 (*17*).

- Chip basic density was determined in accordance with AS/NZS method P1s-79 except that the fresh green chips were treated as being pre-soaked and not given the specified soaking period (2).

Chemical analyses

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 and 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 these were analysed following TAPPI method T222 om-88 for lignin, TAPPI method um250 for acid soluble lignin, and the method of Pettersen and Schwandt (*3*) for carbohydrates.

Pulping and bleaching

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

Pulping conditions for the nine-tree sample lot were similar except that sulfidity was 33 %, and effective alkali was 8.9 % (as Na_2O) for the chip sample (tree 98) pre-impregnated with caustic soda (calculated as 3.1 % Na_2O left in pulp).

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, per cent rejects and total yield were determined.

Half of each of three replicate pulps prepared from each of the bulked twenty and eight individual tree chip samples were fully bleached with constant chemical charges in each stage of a DEoD sequence. Bleach conditions were:

D stage: 0.25 active chlorine multiple, 100% industrial chlorine dioxide, 10% stock concentration, 50°C, 60 minutes.

Eo stage: 2.0% NaOH, 0.25 MPa 0_2, 10% stock concentration, 70°C, 60 minutes.

D stage: 1.0% ClO_2, 0.4% NaOH, 10% stock concentration, 70°C, 180 minutes.

Handsheet preparation and evaluation

Handsheets were prepared and pulp physical evaluations made in accordance with AS/NZS standard procedures. The load applied during pulp refining with the PFI mill was 1.77 N/mm. Pulps were refined at 10 % stock concentration for 500, 1000, 2000 and 4000 rev.

Fibre dimension measurement

Cross-section fibre dimensions, (both 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) (*4*). 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. Fibre curl index was measured using the algorithm and procedure described by Miller (*5*).

Statistical calculations

Regression models for the prediction of tree average kraft handsheet properties adjusted to 500 PFI mill rev, 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. Paired-comparison *t*-tests were used to determine the significance of the differences in fibre and handsheet properties between the three unbleached and bleached pulps.

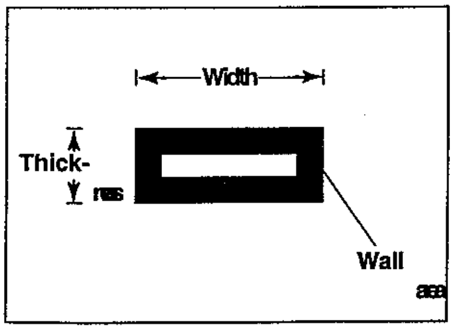

Fig. 1 **Cross-section diagram of a fibre from a handsheet, dried and rewetted .**

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 25.1–29.7 % and total carbohydrates ranging from 59.0–63.4 % (Table 1 and reference *16*). Total lignin and carbohydrate contents in turn influence pulp yield which ranges from 54–59 % for the 29 individual trees (Table 1,2). Pulp yield tends to increase with decreasing chip lignin content and increasing carbohydrate content. Similar wide ranges in property values are obtained for chip density (390–556 kg/m^3), the important fibre dimensions of length (0.78–0.95 mm), perimeter (19.0–21.6 mm), size (width × thickness) (83–106 mm^2), wall area (coarseness) (53–70 mm^2), the width/thickness ratio (1.80–2.09) and handsheet apparent density at 500 PFI mill rev (0.627–0.732 g/cm^3) (Table 1,2).

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

Breast height density is highly correlated with whole tree chip density (r^2=0.70) (*16*). Of the kraft fibre properties, the width:thickness ratio or collapse potential is most strongly correlated with chip density (r^2=0.55), followed by the perimeter:wall thickness ratio (r^2=0.31). These trends are similar to those obtained

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

Property	Range
Chip basic density, kg/m^3	390-556
Chip total lignin, %	25.1-29.7
Chip total carbohydrates, %	59.0-63.4
Pulp yield, %	54-59
Fibre length, mm	0.78-0.95
Fibre perimeter, (W+T) mm	19.0-21.6
Fibre cross-section area, (WxT) mm^2	83-106
Fibre wall area (coarseness), mm^2	53-70
Fibre collapse potential, W:T	1.80-2.09
Handsheet bulk, cm^3/g	1.59 - 1.37
Handsheet apparent density, g/cm^3	0.627-0.732

Table 2 Unrefined *E. nitens* fibre dimensions and handsheet properties at 500 PFI mill rev

Individual	Handsheet properties at 500 rev PFI mill**				Wood properties				Total	Unrefined kraft pulp fibre properties										
tree pulp	Apparent density g/cm³	Tensile index N.m/g	Stretch %	Light scattering coefficient m²/kg	Breast height density kg/m³ D_h	Chip density kg/m³ D_c	Chip total lignin g/100g	Chip carbo-hydrate g/100g	yield at Kappa 20 Y	Length mm L	Width µm W	Thickness µm T	Perimeter µm $W+T$	Width x Wall thick. µm² WxT	Wall area µm² A_w	Wall thick. µm T_w	Width / thick. W/T	$W+T/T_w$	$W+T/A_w$	Relative number of fibres
1	0.627	84	2.58	36.0	532	556	27.8	60.4	57	0.83	12.7	7.1	19.8	91	60	2.43	1.86	8.5	0.35	113
2	0.631	93	2.15	32.5	466	533	27.1	61.7	57	0.88	12.6	7.2	19.9	93	64	2.70	1.80	7.6	0.33	100
3	0.641	85	2.48	33.9	479	492	26.5	61.0	59	0.87	12.6	6.9	19.5	88	59	2.51	1.88	8.1	0.35	110
4	0.642	91	2.22	32.2	475	498	27.3	61.0	56	0.87	13.1	7.3	20.4	98	61	2.32	1.85	9.1	0.35	106
5	0.648	100	2.37	32.7	432	484	25.1	63.4	58	0.95	12.9	6.9	19.8	91	61	2.52	1.94	8.2	0.34	97
6	0.643	91	2.39	32.3	496	497	26.9	61.7	56	0.93	12.4	6.7	19.0	83	53	2.14	1.91	9.2	0.38	114
7	0.649	95	2.55	33.6	435	456	28.1	59.9	56	0.90	13.4	7.2	20.5	96	62	2.33	1.95	9.1	0.35	101
8	0.651	97	2.45	33.3	427	480	27.8	60.7	57	0.87	13.1	7.1	20.2	95	65	2.62	1.91	8.0	0.33	100
9	0.657	102	2.56	31.7	400	475	26.4	61.5	59	0.90	13.5	7.1	20.6	97	64	2.45	1.96	8.7	0.34	98
10	0.668	96	2.56	32.6	479	494	27.8	59.0	55	0.83	12.9	6.9	19.9	90	59	2.40	1.95	8.6	0.36	115
11	0.671	104	2.65	33.0	435	492	28.1	59.5	56	0.85	12.7	6.9	19.6	88	59	2.47	1.93	8.3	0.35	112
12	0.673	112	2.51	31.6	460	466	26.9	61.2	59	0.94	12.7	6.6	19.3	84	56	2.31	2.00	8.7	0.36	107
13	0.678	101	2.41	31.2	396	454	27.9	61.0	54	0.85	13.8	7.0	20.8	97	65	2.54	2.07	8.7	0.34	102
14	0.677	110	2.59	31.4	434	488	27.8	59.7	56	0.85	13.4	7.0	20.5	95	66	2.76	2.00	7.8	0.33	100
15	0.681	89	2.72	32.4	525	542	27.9	59.7	55	0.82	12.9	7.3	20.2	95	64	2.68	1.84	7.8	0.33	107
16	0.678	102	2.75	32.8	427	431	27.4	60.0	56	0.88	13.5	7.1	20.6	96	63	2.43	1.99	8.8	0.34	102
17	0.677	101	2.67	34.2	388	406	27.0	60.3	57	0.95	13.2	6.8	20.0	90	56	2.11	2.02	9.7	0.37	106
18	0.681	103	2.65	31.5	430	464	27.6	60.2	56	0.92	12.9	6.8	19.7	88	59	2.44	1.96	8.4	0.35	104
19	0.685	106	2.80	30.4	428	490	28.0	59.1	55	0.84	13.5	6.7	20.3	93	62	2.24	2.07	8.7	0.35	108
20	0.693	93	2.36	30.7	456	506	27.1	61.8	59	0.85	12.6	6.9	19.5	87	57	2.40	1.90	8.3	0.35	116
21	0.693	111	2.47	30.1	430	479	27.5	60.4	56	0.87	14.1	7.4	21.6	106	70	2.65	1.96	8.5	0.32	92
22	0.694	109	2.58	31.1	382	456	27.4	61.7	56	0.81	13.4	6.9	20.3	93	61	2.37	2.05	9.0	0.36	114
23	0.700	98	2.49	31.6	385	435	28.0	60.7	57	0.87	13.7	7.1	20.8	99	66	2.52	2.00	8.7	0.34	98
24	0.702	106	2.96	33.4	431	484	27.7	60.7	55	0.82	13.3	6.7	20.0	90	57	2.15	2.04	9.7	0.37	120
25	0.705	106	2.70	28.6	433	494	27.5	60.1	55	0.81	13.4	6.9	20.4	95	62	2.47	2.01	8.7	0.35	112
26	0.715	114	2.55	31.1	392	462	27.8	59.8	55	0.82	13.3	6.7	20.0	90	59	2.32	2.03	9.0	0.36	116
27	0.716	107	3.11	33.8	390	411	29.0	59.7	55	0.83	13.0	6.6	19.7	88	57	2.32	2.03	8.8	0.36	119
28	0.732	121	3.23	29.9	404	437	29.7	59.1	54	0.86	13.4	6.7	20.1	91	59	2.35	2.06	9.0	0.36	111
29	0.731	117	2.63	30.3	376	390	28.0	59.3	56	0.78	13.6	6.8	20.3	93	60	2.32	2.09	9.1	0.35	120
Mean	0.677	102	2.59	32.1	435	474	27.6	60.5	56	0.86	13.2	6.9	20.1	92	61	2.42	1.97	8.6	0.35	108
Std Dev	28.6	9.28	0.232	1.54	41.2	38.2	0.815	1.01	1.44	0.0443	0.419	0.218	0.528	4.82	3.71	0.164	0.0766	0.513	0.0137	7.65
CV%	4.22	9.10	8.96	4.80	9.47	8.06	2.95	1.67	2.57	5.15	3.17	3.16	2.63	5.24	6.08	6.78	3.89	5.97	3.91	7.08
LSD*										0.03	0.6	0.3	0.70	7	4	0.11	0.11	0.40	0.012	

* LSD: Least significant difference between means at the 95 % level of significance

** Interpolated values based on the regression between the handsheet properties and log(rev) for each of four PFI mill refining levels per pulp, including 500 rev.

for radiata pine individual tree pulps prepared from eleven 16 year old clones (*6*), and from 25, 13 year old trees selected for extremes of tracheid perimeter and wall thickness (*7*). 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 ratio.

Handsheet apparent density, tensile strength and light scattering coefficient are important eucalypt pulp quality determinants (*8,9*). Handsheet property predictions are made at 500 PFI mill rev as the basis of comparison for reasons described elsewhere (*6,10*). Correlations between these handsheet properties from chip and kraft fibre properties are indicated in Table 3 and reference *16*. The kraft fibre width:thickness ratio is consistently the best predictor of the selected handsheet properties; apparent density (r^2=0.57), tensile index (r^2=0.64) and light scattering coefficient (r^2=0.19). The fibre perimeter:wall thickness ratio, chip basic density and chip lignin content are also correlated to some degree with the three handsheet properties.

Table 3
Prediction of individual-tree handsheet properties adjusted to 500 PFI mill rev by kraft fibre dimensions and some wood properties

Dependent variable	Independent variables	r^2
Apparent density	T_w, and P	ns*
	L	0.24
	T_w + P,	0.16
	T_w + P + L	0.37
	W/T	0.57
	W/T + L	0.67
	P/T_w	0.13
	P/T_w + L	0.37
	D_c	0.36
	D_c + L	0.64
	D_c + Lg	0.53
	D_c + Lg + L	0.66
	D_b**	0.40
	D_b + L	0.60
	Lg	0 .31
	Lg + L	0.36
Tensile index	T_w, L and P/T_w	ns*
	T_w + P	0.14
	T_w + P + L	0.16
	W/T	0.64
	W/T + L	0.64
	P/T_w + L	0.14
	D_c	0.37
	D_c + L	0.43
	D_c + Lg	0.42
	D_c + Lg + L	0.44
	D_b	0.51
	D_b + L	0.53
	Lg	0.14
	Lg + L	0.14
Light scattering coefficient	W/T	0.19
	W/T + L	0.21

* No correlation at the 95 % level of significance if $r^2 < 0.12$ width (W), thickness (T), perimeter (P), chip density (D_c), breast-height density (D_b), lignin (Lg) and length (L).

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. Multiple linear regression techniques are used to estimate the combined influence of two or more fibre properties. For the 29 *E. nitens* pulps, handsheet apparent density is best 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 (*16*). 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 potentials would give high and low sheet densities respectively (*6*).
- 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 (*11,12*).
- Chip basic density is a measure of the total mass and volume of a chip sample. It is evidently strongly influenced by the dimensions and coarseness of the fibres, the tissue component which makes up the largest part of the wood chip mass.
- The added influence of fibre length on handsheet apparent density when in combination with the width:thickness ratio, the perimeter:wall thickness ratio or chip density can be readily explained; for handsheets made up of fibres of the same cross-section dimensions, short fibres will increase and long fibres could be expected to decrease packing and handsheet density.

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. nitens* individual tree pulps. While such trends are indicated for these three variables, particularly when in combination one with another (r^2=0.37), their reliability of prediction are 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 (Table 3 and reference *16*). Fibre length is 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 which in turn is determined by fibre packing densities and arrangements in handsheets (Table 2 and reference *7*). Tensile strength prediction with the wall thickness, perimeter and length combination is poor (Table 3).

Handsheet light scattering coefficient is poorly predicted by kraft fibre properties or chip density. The best fibre property predictor of light scattering coefficient is the width:thickness ratio although the coefficient of determination is relatively low (Table 3). Fibre perimeter shows some correlation with light scattering coefficient (*16*) in agreement with trends obtained with radiata pine individual tree pulps (*6,7*).

Handsheet property predictions from fibre properties for the 29 *E. nitens* individual trees are overall similar to those obtained for eleven radiata pine clones (two trees per clone) (*6*). The chip basic density and length, and the kraft fibre width:thickness ratio and length combinations are again found to be the best predictors of handsheet apparent density. Similarly, fibre length is again shown to be unimportant in the prediction of handsheet tensile strength, either by itself or when in combination with chip density or the fibre width:thickness ratio.

The prediction of handsheet properties adjusted to 500 PFI mill rev 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 (*7,12*). 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 using the apparent density of 'unrefined' pulps (500 PFI mill rev) as the base against which other 'unrefined' handsheet properties are compared (*7*).

Handsheet property relationships

Eucalypt market kraft pulps are known to combine the most important pulp and paper properties in a particularly favourable way (*8,9,13*). 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. The pulps from 29 trees of *E. nitens* show a wide range of handsheet bulk values at 500 PFI mill rev (1.59–1.37 cm^3/g), which is the reciprocal of the apparent density range of 0.627–0.732 g/cm^3 of 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 (*8,9*)

The 29 individual tree *E. nitens* pulps are numbered 1 to 29 in ascending order of sheet density in Table 2 and reference (*16*). Handsheet property data are presented in (*16*). The effect of the large 0.627–0.732 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 refinining 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 1–7 with their

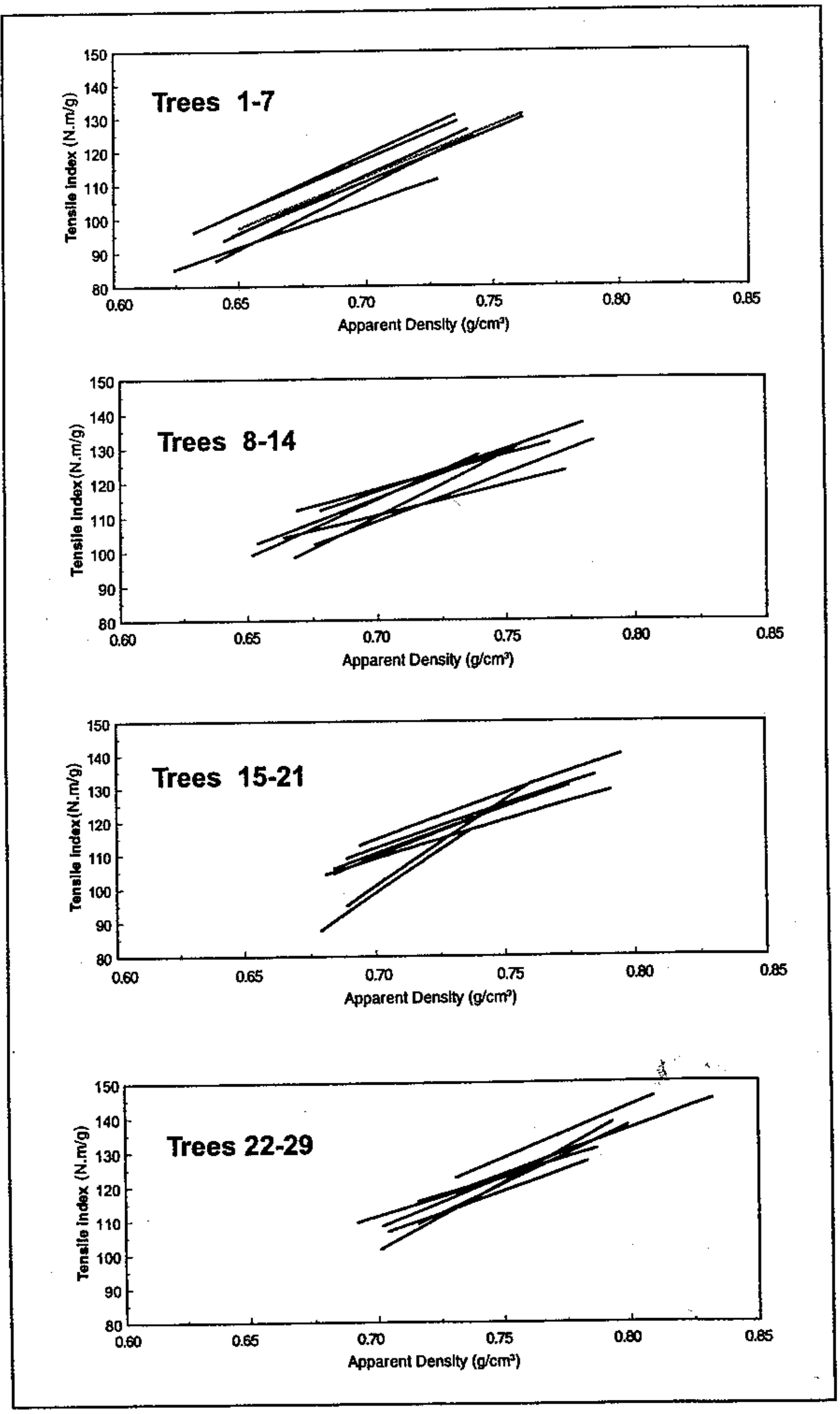

Fig. 2 Tensile index and apparent density relationships.

low apparent density (high bulk) and good potential to develop tensile strength with refining would be suitable for the manufacture of wood free tissue, and printings and writing grades (*7*). Pulps 22–29, on the other hand, are deficient in bulk and unsuitable for such an end use despite a high potential to develop tensile strength.

Handsheet bulk is highest for the *E. nitens* pulps with the lowest fibre width:thickness ratio, or the better combinations of low width:thickness and long fibres (Table 2). The fibre width : thickness ratio is measured from fibres which are first pressed and dried in the handsheeting process (*4*). 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 dependent on the apparent density value of the unrefined pulps (Fig. 3). Hence, at 0.7 g/cm^3 apparent density, average light scattering coefficients of the refined pulps are about 27 m^2/kg for trees 1–7, about 29 m^2/kg for trees 8–14, about 31 m^2/kg for trees 15–21, or out of range for trees 22-29.

The wide handsheet apparent density range of 0.627–0.732 g/cm^3 for the 29 individual tree pulps suggests a high potential for tree selection based on this pulp quality determinant. The problem is the availability of non-destructive tests for screening individual forest trees to find those with the desired fibres. While breast height basic density is relatively strongly correlated with whole-tree chip density ($r^2 = 0.70$) for the 29 tree *E. nitens* sample, corresponding correlations with handsheet density are relatively low at $r^2 = 0.36$ and $r^2 = 0.40$ respectively (Table 3). Breast height density together with fibre length are required to give more realistic estimates of handsheet apparent density $r^2 = 0.60$ (Table 3). Unfortunately, breast height and whole tree fibre length relationships have yet to be determined (*7*).

Unbleached and bleached fibre and handsheet property relationships

Estimates of the fibre and pulp quality differences between unbleached and bleached eucalypt kraft pulps are assessed using two sets of paired bleached and unbleached pulps. Each set of three pulps

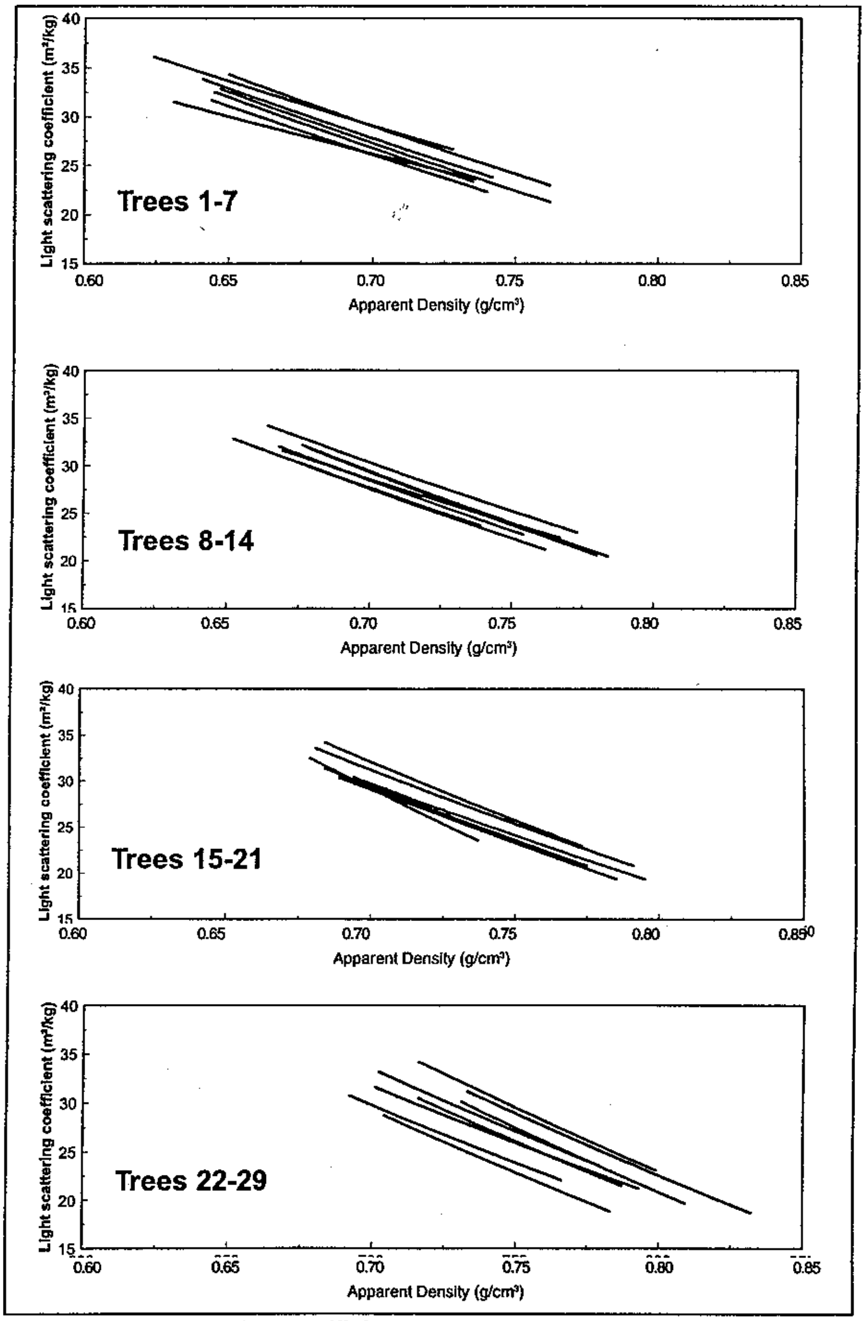

Fig. 3 Light scattering coefficient and apparent density relationships.

Table 4
Fibre cross-section dimensions of pulps made from replicate bulked chip samples from 20 and 8 individual trees – Comparison of bleached and unbleached pulps

Pulp		Length mm	Width mm	Thick. mm	Perimeter mm	Width x thick. mm²	Wall area mm²	Wall thick. mm	Width/ thick
Bulk20/1	Unbl.	0.86	13.2	6.8	20.0	90	59	2.33	2.00
Bulk20/2	Unbl.	0.85	13.2	7.3	20.4	97	64	2.46	1.88
Bulk20/3	Unbl.	0.86	13.0	6.7	19.7	88	57	2.26	2.01
Bulk20/1	Blch.	0.79	13.0	6.5	19.5	85	55	2.17	2.09
Bulk20/2	Blch.	0.78	13.0	6.6	19.7	87	57	2.25	2.08
Bulk20/3	Blch.	0.79	13.0	6.6	19.5	86	57	2.28	2.08
Bulk08/1	Unbl.	0.92	12.8	6.7	19.5	88	57	2.29	1.98
Bulk08/2	Unbl.	0.91	13.0	6.8	19.8	89	56	2.20	1.99
Bulk08/3	Unbl.	0.89	12.7	6.9	19.6	88	57	2.24	1.93
Bulk08/1	Blch.	0.81	12.6	6.8	19.4	86	58	2.42	1.95
Bulk08/2	Blch.	0.81	13.1	6.6	19.7	86	58	2.35	2.08
Bulk08/3	Blch.	0.80	13.2	6.6	19.8	87	58	2.30	2.09

Table 5
Curl index for replicate unbleached and bleached pulps made from the same chip source

Pulp	Curl index	Standard deviation
Bulk20/1 Unbleached	0.1307	0.0695
Bulk20/2 Unbleached	0.1338	0.0653
Bulk20/3 Unbleached	0.1308	0.0627
Bulk20/1 Bleached	0.1655	0.0754
Bulk20/2 Bleached	0.1536	0.0676
Bulk20/3 Bleached	0.1601	0.0756
LSD*	0.0122	

* Least significant difference between means at the 5 % level of significance

Table 6
Handsheet properties of two sets of replicate unbleached (U) and bleached (B) pulps

Pulp	PFI mill rev	Pulp freeness CSF	Apparent density g/cm³	Bulk cm³/g	Tensile index N.m/g	Stretch %	Light scat. coef. m²/kg
Bulk20/1-U	500	520	0.676	1.48	105	2.57	32.0
Bulk20/2-U	500	515	0.667	1.50	101	2.46	33.7
Bulk20/3-U	500	525	0.656	1.52	101	2.59	32.7
Bulk20/1-B	500	445	0.687	1.46	94	3.03	34.9
Bulk20/2-B	500	415	0.689	1.45	94	3.05	35.0
Bulk20/3-B	500	435	0.685	1.46	96	3.08	34.9
Bulk08/1-U	500	520	0.664	1.51	101	2.60	34.0
Bulk08/2-U	500	525	0.675	1.48	105	2.69	33.7
Bulk08/3-U	500	520	0.674	1.48	101	2.53	33.9
Bulk08/1-B	500	520	0.680	1.47	97	3.27	35.4
Bulk08/2-B	500	470	0.683	1.46	94	3.16	35.6
Bulk08/3-B	500	495	0.687	1.45	93	3.40	34.8

was produced from the same chip source (bulk 08 and bulk 20).

Fibre property data for the two sets of three replicate bulked samples show that the bleached fibres are 'shorter', more collapsed and correspondingly smaller in cross section area (width x thickness) compared to unbleached fibres (Table 4), as expected (*15*). Corresponding changes in fibre wall dimensions (perimeter, wall area and wall thickness) expected to be brought about by bleaching cannot be detected because of the small size and mass of eucalypt fibres. The shortening effect of the bleaching process is explained by the development of increased fibre curl resulting from pulp mixing at medium stock concentration (Table 5) (*14*). The measured increase in fibre collapse is in agreement with the removal of residual lignin and other wall material by the bleaching process. Paired comparison *t*-tests were used to compare the two sets of three replicate pulps before and after bleaching. Pulp average length weighted fibre length and cross-section area (width x thickness) are decreased, and fibre collapse potential (width: thickness) and curl are increased by bleaching to significant extents (Table 4,5). Fibre wall dimensions were statistically unchanged by bleaching at the 95% level of significance.

Handsheet apparent density, stretch and light scattering coefficient are increased, and tensile strength is decreased by the bleaching treatment when compared at 500 PFI mill rev (Table 6) (*16*). Paired comparison *t*-tests were used to compare the two sets of three replicate pulps before and after bleaching. At 500 PFI mill rev pulp freeness, apparent

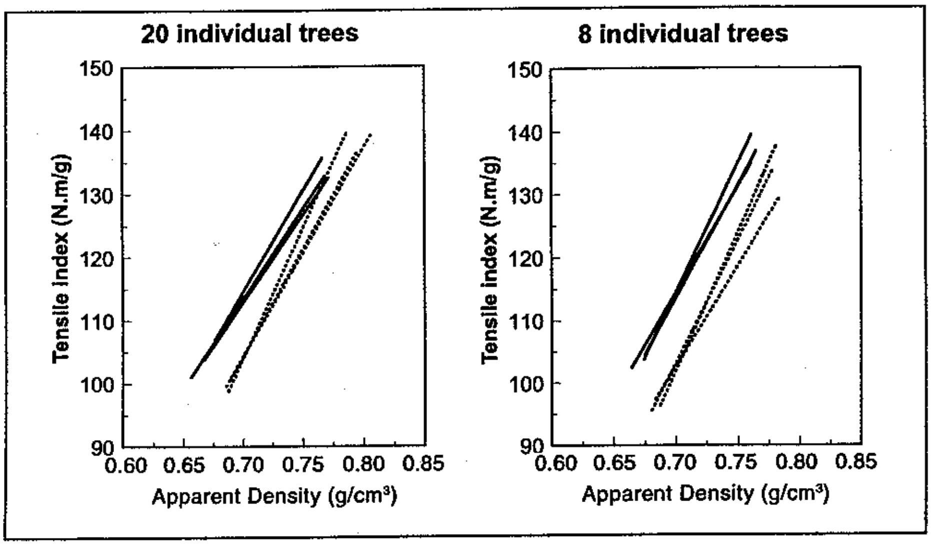

Fig. 4 Handsheet tensile index and apparent density for unbleached (—) and bleached (——) replicate bulk pulps.

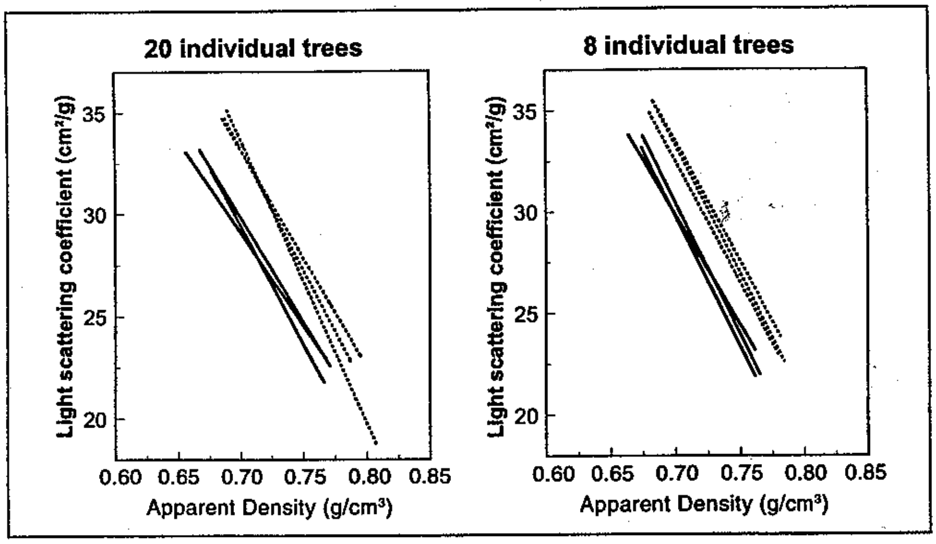

Fig. 5 Handsheet light scattering coefficient and apparent density for the unbleached (----) and bleached (——) replicate bulk pulps.

density and tensile index are decreased, and handsheet stretch and light scattering coefficient are increased by bleaching to significant extents (5% level). The increase in apparent density and the decrease in tensile index that occur with bleaching are retained with pulp refining (Fig. 4). Note: Bleached pulp 'Bulk 20/2' was inadvertently refined for 7000 rather than 4000 rev (Fig. 4,5).

Handsheet light scattering coefficient is higher for the bleached than for the unbleached pulps when compared at given apparent densities (Fig. 5). Relative light scattering coefficient differences between the bleached and unbleached pulps are unchanged by refining (Fig. 5).

CONCLUSIONS

The range of individual tree and kraft fibre and pulp properties for the 29 *E. nitens* trees is extremely wide: chip density 390–556 kg/m^3, pulp yield at 20 Kappa 54–59%, fibre length 0.78–0.95 mm, and handsheet apparent density at 500 PFI mill rev 0.627–0.732 g/cm^3.

Breast height chip density is strongly correlated with individual-tree chip density ($r^2 = 0.70$), but both show only poor to moderate correlation with the important handsheet properties; apparent density ($r^2 =$ 0.36 and 0.40) and tensile strength ($r^2 =$ 0.37 and 0.51).

The kraft fibre width:thickness ratio or collapse potential is the best individual property predictor of the important handsheet properties; apparent density ($r^2 = 0.57$), tensile strength ($r^2 = 0.64$) and light scattering coefficient ($r^2 = 0.19$).

Handsheet bulk, the reciprocal of apparent density, is an important quality determinant of *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 and optical properties can normally be developed by refining provided the resulting bulk meets the requirements of the product being manufactured. The fibre width: thickness ratio and length combination, and the chip density and length combination are the best predictors of handsheet bulk or apparent density.

Pulp bleaching at medium stock concentration causes fibres to curl and consequently to appear 'shortened' compared to unbleached pulps. Bleached fibres collapse more readily than unbleached fibres, but expected changes in wall dimensions cannot be detected due to the small size and mass of eucalypt fibres. Unrefined handsheet apparent densities are increased and tensile strengths decreased by the pulp bleaching process.

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