Handsheet property prediction from kraft-fibre and wood-tracheid properties in eleven radiata pine clones

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SUMMARY

There is a prevailing need for non destructive methods to measure wood tracheid properties in standing trees so that large numbers of trees can be screened for their tracheid and potential kraft pulp properties. This report describes handsheet property predictability using kraft fibre, and whole-tree and breast-height tracheid dimension data. The predictions of handsheet properties were evaluated using eleven 16 year old clones of radiata pine; two trees per clone.

Handsheet apparent density, and tensile, tear and burst strength, are predictable from the kraft fibre or wood tracheid (both whole-tree and breast-height) wall thickness and perimeter, and kraft fibre length combination. Other useful handsheet property predictors are the fibre or tracheid perimeter:wall thickness ratio and fibre length combination, and the chip or wood basic density and fibre length combinations. The kraft fibre width:thickness ratio is by itself a good predictor of handsheet properties. Fibre coarseness is a poor predictor of handsheet properties.

KEYWORDS

Eucalypts, growth, wood, cellulose, lignin, pentosans, extractives, fibre, vessels, denity, heartwood.

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The prediction of kraft pulp quality from wood tracheid and pulp fibre properties is only limited by the ability to select and measure the appropriate fibre and/or tracheid properties (*1–5*). In recent years wood density and the fibre properties of length and coarseness have been used extensively as indicators of kraft pulp quality because of their ease of measurement and general applicability (*5–7*). The wood density of outerwood cores of radiata pine can predict whole tree density (*8*). Also estimates of wood density, which have often been shown to be correlated with kraft fibre and pulp qualities (*5,6*), can be determined non-destructively. Unfortunately wood density alone without fibre length can be a poor indicator of kraft pulp quality (*6,7*).

There is a prevailing need for non-destructive methods of measuring wood tracheid properties in standing trees. This would allow large numbers of trees to be screened for their tracheid properties and kraft pulp quality potential. From the point of view of a forest grower and tree breeder this would allow selective breeding programs to be initiated with a knowledge of end product quality requirements. SilviScan, an instrument developed at the Australian CSIRO Forest Products Division, is able to accurately measure tracheid cross-section dimensions and coarseness as well as wood density (*9*). These measurements are essentially non destructive and can be made on pith to bark increment cores taken from standing trees. They can also be combined to give whole tree or part tree estimates of tracheid properties and density.

The present paper describes the prediction of handsheet properties from kraft fibre dimensions (*7*), and from corresponding whole tree and breast height tracheid dimensions measured using SilviScan (*9*). A parallel paper describes correlations between the tracheid and kraft fibre dimensions (*10*). The study involved the assessment of 24 trees of radiata pine, aged 16 years, propagated originally by rooted cuttings. Two trees of each of 10 clones were whole tree chipped individually and 20 kraft pulps made from them, and four trees of an eleventh clone were chipped and bulked from which two kraft pulps were made. Tracheid dimensions were determined for pith to bark cores taken at breast height (1.4 m) and at 5.5 m intervals up each tree (*9*). The kraft fibre cross-section dimensions of each pulp were measured by image analysis of embedded sections (*11*).

EXPERIMENTAL METHODS

Sample selection and preparation

Eleven 16 year old radiata pine clones located in Compartment 327, Kaingaroa Forest (*12*), were selected from a clonal trial of 120 clones of which on average five trees of each survived. Clone selection was based on wood basic density and tracheid length determined from cores taken at breast height. Clones were selected as far as possible to cover the extremes of basic density and tracheid length, namely for high density and long tracheids, high density and short tracheids, low density and short tracheids, low density and long tracheids, as well as medium density and medium length tracheids. Two clones were selected for each density-tracheid length grouping, with each clone represented by two trees. Such an experimental design required a minimum of ten clones with two trees each. An eleventh clone with medium density and tracheid length was selected composed of four trees whose chips were bulked to give a large chip sample used to estimate differences between refiner runs in the mechanical pulping trials (*12*). The ten clones, each of 20 trees were whole tree chipped and pulped separately. Two replicate kraft pulps were prepared from the four-tree bulk sample.

Wood tracheid and kraft fibre dimensions

Wood tracheid cross-section dimensions were measured using SilviScan, (*9,10*). Tracheid dimensions were determined for pith to bark strips (10 × 10 mm) taken at breast height (1.4 m) and at 5.5 m intervals up each tree. Whole tree and weighted breast height tracheid dimension values were calculated by procedures described in (*10*). The kraft fibre cross-section dimensions of each pulp were measured by image analysis of embedded sections (*11*). Tracheid and fibre properties evaluated included width, thickness, perimeter (width + thickness), wall area, wall thickness and selected ratios of these properties (Fig. 1), coarseness and fibre length. Length-weighted-average fibre length and fibre coarseness were determined with a Kajaani FS 200 instrument using TAPPI Method T271 pm-91.

Terminology

Fibre and tracheid dimension abbreviations used throughout are:

Tracheid or fibre width	W
Tracheid or fibre thickness	T
Tracheid or fibre wall area	A_w
Tracheid or fibre wall thickness	T_w
Tracheid or fibre perimeter [2 × (W + T)]	P
Fibre length weighted length	L
Pulp yield	Y
Fibre collapse potential (width / thickness)	W/T
Tracheid or fibre perimeter /wall thickness	P/T
Wood or chip density	D

Pulping and pulp processing

All trees were whole tree chipped individually in a commercial chipper. The chips were passed through a 40 mm hole screen, retained on a 10 mm hole screen, and were well mixed. Chips from the four trees of clone 11 were later bulked. A sample of chips, about 5 kg o.d. equivalent, were removed for each individual tree lot and kraft pulps of Kappa number 30 ± 2 were prepared from each by pulping 200 g o.d. of chips using a 15% effective alkali charge at 4:1 liquor to wood ratio for H-factor levels in the range 1500–2000. Further details of pulping procedures can be made available on request (unpublished data). Handsheets were prepared and pulp physical evaluations made in accordance with Appita standard procedures. The load applied during pulp refining with the PFI mill was 3.4 N/mm. Pulps were refined at 10 % stock concentration. Handsheet physical evaluation data are reported on the o.d. bases.

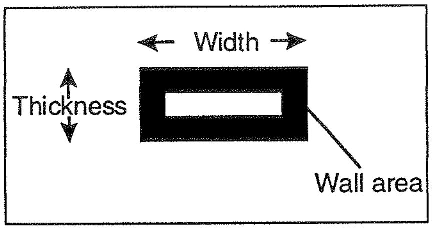

Fig. 1 Tracheid and fibre cross-section dimensions.

Regression analyses

Regression analyses were made with the objective of predicting handsheet properties from kraft fibre and wood tracheid dimensions with 500 PFI mill rev as the basis of comparison (*4,5*). Two trees of each of 10 clones (20 pulps), and the bulked sample of four trees of an additional clone (two pulps) made up the samples used in the analyses. Selected analyses were also made on the 10 clone, 20 individual tree pulps only, and these are presented in an extended version of this paper (13).

Using the data generated by the four different PFI mill refining levels, predicted handsheet properties were calculated for each of the 22 pulps. A simple linear regression of log (PFI mill rev), at four levels, with handsheet properties was used to adjust the handsheet properties of the 22 pulps to the 500 PFI mill rev level.

Correlation coefficient matrices and selected bi-variate plots were used to examine relationships between predicted handsheet properties at 500 rev and individual fibre or tracheid properties. Linear regression was used to develop prediction equations for certain handsheet properties from certain individual fibre or tracheid properties. Multivariate regression analyses using Partial Least Square (PLS) models (*14–18*) were used to develop prediction equations for selected handsheet properties as dependent variables with two or more fibre or tracheid dimensions as independent variables.

Partial least squares regression is used since most of the independent (predictor) variables are passively measured rather than being controlled by experimental design (*14*). Also, the number of independent variables is large compared to the number of pulps, and many are collinear (Tables 2, 7, 8), not exact (large standard errors), and may not be relevant. Stepwise procedures for multiple regression variable selection are claimed to be inferior to PLS regression in these circumstances (*14,15*). The PLS regression models were calculated and cross validated using SIMCA-R4.4 software (*17*). Cross validation is a technique (*17*) for estimating the future prediction error by leaving out some observations (pulps) estimating the regression coefficients from a reduced data set and then predicting the left out observations. The procedure is repeated until all observations have been left out at least once.

Initially, individual handsheet properties (i.e., one response variable) were predicted from groups of predictor variables. PLS models with only one response variable are called PLS1 models (*16*). The groups of predictor variables used were:

- Kajaani FS 200 length data (proportion of fines, length weighted length, weight weighted length, and coarseness) and kraft fibre cross-section dimensions (including various combinations and ratios).
- Kajaani FS 200 length data (proportion of fines, length weighted length, weight weighted length, and coarseness) and breast height wood tracheid dimensions.
- Kajaani FS 200 length data (proportion of fines, length weighted length, weight weighted length, and coarseness) and whole tree wood tracheid dimensions.
- The above three blocks and chip basic density.

Multiple regression models were also calculated for each of the above four groups of independent variables. All possible one, two, three and four regressor models were calculated and ranked according to their r^2 values, for each set of regressors (*18*). This was used as an exploratory model building exercise, and to compare the multiple and PLS regression models. Prediction using multiple regression had similar r^2 values to prediction using PLS models for the important fibre property combinations of wall thickness and perimeter, and wall thickness, perimeter and length.

The overall objective of the analyses is to obtain relationships between limited numbers of meaningful kraft fibre and wood tracheid dimensions and dimension combinations, and handsheet properties. The PLS analyses on these blocks of predictors produced statistics which showed the most important predictor variables (*17*). The number of predictor variables was reduced by a combination of *ad hoc* backward elimination and by trying additional predictors with some of the best linear regression predictors. PLS models with few predictor variables (down to 2) were able to be calculated with minimal lowering of r^2 values. These models with few predictor variables are used to calculate the biased regression coefficients (*17, 18*) used here.

One of the strengths of the PLS method is that any new object (pulp) is first classified to ascertain its similarity with the calibration data set, and predictions for the new object are only made if the new object is similar to the calibration data set. If the objective of the analyses is to make predictions for new pulps, it would be preferable if PLS models with all available predictor variables (e.g. including other pulping variables such as cooking time and Kappa number) are used since they would be better at detecting pulps that are not similar to the calibration set.

RESULTS AND DISCUSSION

Handsheet property prediction at 500 PFI mill rev

Since the rate and effectiveness of pulp refining can vary greatly with fibre quality (*4*), any comparison of handsheet and pulp properties needs to be based on the dimensions of unrefined fibres. For this reason handsheet property values used are based on minimal amounts of pulp refining, at 500 PFI mill rev. To achieve this the pulps are processed at four levels of refining and their handsheet property values determined by interpolation at 500 rev (*4*).

The decision to predict handsheet properties at 500 PFI mill rev is supported by the pulps having different slopes for the tensile, tear and burst indices versus log (PFI mill rev) regressions (Table 1). Slopes of the handsheet apparent density and light scattering coefficient versus PFI mill rev regressions, on the other hand, are similar and comparisons can be made at any refining level within the range 500 to 4000 rev. A homogeneity-of-slopes model was fitted to the handsheet data set (22 pulps, 4 beating points for each pulp) using the SAS/STAT General Linear Models procedure (*19*).

Table 1
Handsheet property–refining level regressions.

Handsheet property	Null hypothesis that all slopes equal	
	at 5%	at 1%
Apparent density	accept	accept
Tensile index	reject	accept
Tear index	reject	reject
Light scattering coefficient	accept	accept
Burst index	reject	reject

Kraft pulp fibre dimensions

Selected handsheet property values at 500 PFI mill rev, chip basic density, and selected kraft fibre dimensions and dimension ratios of the 11 clones and individual trees, as well as the correlation coefficient matrix for the various handsheet and kraft fibre combinations, are presented in an extended version of this paper (*10, 13*). The 22 pulps were made from two trees of each of 10 clones (20 pulps), and the bulked sample of four trees of an additional clone (two pulps).

Wall thickness, width/thickness, perimeter, and the perimeter:wall thickness ratio are the kraft fibre dimension properties relatively highly correlated with handsheet properties at 500 PFI mill rev (*13*). Any influence of fibre width is covered by its inclusion in combination with fibre thickness (perimeter and width/thickness). Chip basic density is also consistently highly correlated with the selected handsheet properties. Fibre wall area and the related property of fibre coarseness (*6*), are poorly correlated with handsheet properties, as is fibre length. These low correlations result from the 22 pulps being composed of individual trees of the same age (*7*), rather than from a wide range of individual tree, part individual tree and bulked tree pulps from trees of widely different basic density and age that have formed the basis of other studies (*4,6*).

Partial least square regressions are used to predict handsheet properties from kraft fibre wall thickness, perimeter and length (Table 2). Coefficients of determination (r^2) for each equation give estimates of the correlation between actual and predicted handsheet properties.

Table 2
Kraft fibre dimension prediction of handsheet properties at 500 PFI mill rev—wall thickness, T_w, perimeter, P, and length weighted length, L.

	r^2	Standard error*
Apparent density	0.46	17.2
	0.57	15.3
	0.46	17.2
	0.62	14.4
Tensile index	0.15	5.41
	0.23	5.14
	0.23	5.14
Tear index	0.36	1.44
	0.68	1.02
	0.33	1.47
	0.72	0.95
Light scattering coefficient	0.06	0.78
	0.37	0.64
	0.43	0.61
	0.43	0.61
Burst index	0.40	0.36
	0.56	0.31
	0.34	0.38
	0.54	0.38

* [RSS / (N-A-1)] with N=22, and A the number of PLS components which is always 1 in this report.

Summarized details are:

- The predictions of handsheet apparent density, tear index and burst index from wall thickness using linear regression are progressively improved by the inclusion of perimeter and length in PLS regressions.
- Burst index is influenced by wall thickness and perimeter, but not by fibre length.
- Handsheet light scattering coefficient, on the other hand, is best predicted from perimeter using linear regression, and is improved by the inclusion of wall thickness but not length in PLS regressions.
- Tensile index is poorly predicted by the three fibre properties either together in PLS models or by themselves using linear regression.

The mean fibre properties of length, wall thickness and cross-section perimeter together should describe the size, shape and coarseness of the fibres of a given pulp. Hence, their relatively good prediction of handsheet packing density and structure through the measurement of apparent density (r^2= 0.62) is to be expected (Table 2).

Table 3
Fibre dimension ratio and chip basic density prediction of handsheet properties at 500 PFI mill rev—width, *W*, thickness, *T*, perimeter, *P* and length, *L*.

Dependant variable	Independent variables	r^2	Standard error*
Apparent density	W/T	0.59	15.0
	W/T, L	0.66	13.6
	P/T_w	0.50	16.5
	P/T_w, L	0.61	14.6
	$D^†$	0.53	16.0
	$D^†$, L	0.83	9.6
Tensile index	W/T	0.49	4.19
	W/T, L	0.46	4.31
	P/T_w	0.26	5.04
	P/T_w, L	0.27	5.01
	$D^†$	0.69	3.26
	$D^†$, L	0.76	2.87
Tear index	W/T	0.72	0.95
	W/T, L	0.70	0.98
	P/T_w	0.31	1.49
	P/T_w, L	0.35	1.45
	$D^†$	0.66	1.05
	$D^†$, L	0.81	0.78
Light scattering coefficient	W/T	0.18	0.73
	W/T, L	0.17	0.74
	P/T_w	0.24	0.70
	P/T_w, L	0.24	0.70
	$D^†$	0.22	0.71
	$D^†$, L	0.22	0.71
Burst index	W/T	0.71	0.25
	W/T, L	0.67	0.27
	P/T_w	0.35	0.38
	P/T_w, L	0.34	0.38
	$D^†$	0.78	0.22
	$D^†$, L	0.82	0.20

* [RSS / (N-A-1)] with N=22, and A the number of PLS components which is always 1 in this report.
† Chip basic density

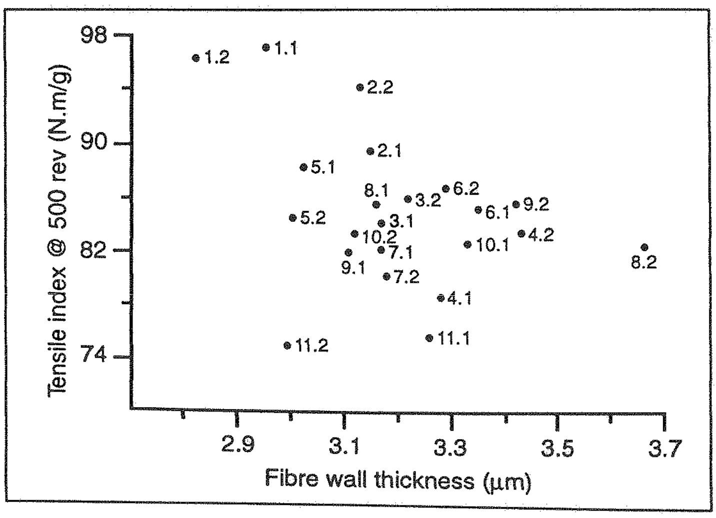

Fig. 2 Tensile index at 500 rev versus kraft fibre wall thickness.

Handsheet apparent density can also be predicted by linear regression from the kraft fibre ratios width:thickness (r^2=0.59) and perimeter:wall thickness (r^2=0.50), and by chip basic density (r^2=0.53) (Table 3). The three r^2 values are respectively increased by 7, 11 and 30 % with the inclusion of fibre length in PLS models. Chip basic density and fibre length together account for 83 % of the variation in handsheet density for the individual tree pulps from 11 × 16 year old radiata pine clones. In previous studies an equivalent r^2 value was obtained for chip basic density alone but with an extreme range of individual tree and part individual tree pulps from trees of widely different basic density and age (*4*). Summarized details are:

- The ratio width:thickness reflects the collapsed configuration of the kraft fibres in handsheets and the high correlation with apparent density is therefore to be expected since high and low collapse potentials can be expected to 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 (*6,7*).
- Chip basic density is a measure of the total mass and volume of a chip sample. It is obviously strongly influenced by the dimensions and coarseness of the tracheids, the tissue component that makes up more than 90% of the wood chip mass. It is fortunate for the New Zealand pulp and paper industry (*20*) that such good predictive equations are obtained with basic density, particularly with the inclusion of fibre length in the prediction equation.

The prediction of handsheet tensile index is particularly poor for the PLS models using kraft fibre length, wall thickness and perimeter (r^2=0.23), and for the perimeter:wall thickness ratio and length equation (r^2=0.27) (Tables 2,3).

One reason for this poor prediction of tensile index is the low tensile strengths obtained with the two pulps of clone 11 (Fig. 2). The fibre width:thickness ratio or collapse potential is a reasonable predictor of tensile strength but less than that of chip basic density either by itself or in combination with fibre length.

Chip basic density, the ratio width: thickness, and to a lesser extent the ratio perimeter:wall thickness, are also relatively good predictors of handsheet tear index and burst index (Table 3). The chip basic density predictions are markedly improved with the inclusion of fibre length in the relationships.

Wood tracheid dimensions

Selected handsheet property values at 500 PFI mill rev for breast height and whole tree basic density, and tracheid dimensions and dimension ratios, and the correlation coefficient matrices for the various handsheet and wood tracheid combinations are presented in an extended version of this paper (*10, 13*). Handsheet property prediction equations show roughly comparable slopes, intercepts and coefficients of determination for the breast height and whole tree data (Table 4) (*13*).

Handsheet property prediction from kraft fibre and wood tracheid wall thickness, perimeter and length weighted length show remarkably similar trends, except for the prediction of tensile strength (Table 5) (*13*):

- Apparent density and tear index predictability and coefficients of determination are progressively improved with the inclusion of wall thickness, perimeter and length in the prediction equation.
- Light scattering coefficient is most strongly influenced by fibre or tracheid perimeter alone.
- Burst index and tensile index are influenced by wall thickness and perimeter, but not by fibre length.
- Tensile index and tracheid wall thickness are strongly correlated one with another (Table 4) whereas tensile index and kraft fibre wall thickness are poorly correlated (Table 2). This discrepancy is explained by the clone 11 kraft fibres having relatively thin walls and low tensile strengths (Fig. 2).

Chip basic density or derived breast height and whole tree density, and length weighted fibre length, are together consistently good predictors of hand-

Table 4
Breast height and whole tree wood tracheid dimension prediction of handsheet properties at 500 PFI mill rev—wall thickness, T_w and perimeter, P, and kraft fibre length weighted length, L.

	Fibre/tracheid property	Breast height tracheids		Whole tree tracheids	
		r^2	Standard error*	r^2	Standard error*
Apparent density	T_w	0.61	14.6	0.37	18.6
	T_w, P	0.65	13.8	0.47	17.0
	T_w, L	0.62	14.4	0.45	17.3
	T_w, P, L	0.79	10.7	0.67	13.4
Tensile index	T_w	0.66	3.41	0.64	3.51
	T_w, P	0.69	3.26	0.74	2.99
	T_w, P, L	0.69	3.26	0.75	2.93
Tear index	T_w	0.49	1.28	0.34	1.46
	T_w, P	0.70	0.98	0.63	1.09
	T_w, L	0.43	1.35	0.34	1.46
	T_w, P, L	0.80	0.80	0.77	0.86
Light scattering coefficient	T_w	0.04	0.79	0.00	0.80
	P	0.42	0.61	0.46	0.59
	T_w, P	0.40	0.63	0.46	0.59
	T_w, P, L	0.41	0.62	0.47	0.59
Burst index	T_w	0.52	0.32	0.46	0.34
	T_w, P	0.65	0.28	0.64	0.38
	T_w, L	0.47	0.34	0.42	0.36
	T_w, P, L	0.67	0.27	0.66	0.27

* [*RSS* / (*N*-*A*-1)] with *N*=22, and *A* the number of PLS components which is always 1 in this paper.

Table 5
Kraft fibre and wood tracheid dimension prediction of handsheet properties at 500 PFI mill rev—wall thickness, T_w, perimeter, P, length, L and pulp yield, Y.

Handsheet property	Fibre/tracheid property	Coefficient of determination (r^2)		
		Whole tree kraft fibres	Breast height tracheids	Whole tree tracheids
Apparent density	T_w	0.46	0.61	0.37
	T_w, P	0.57	0.65	0.47
	T_w, L	0.46	0.62	0.45
	T_w, P, L	0.62	0.79	0.67
	T_w, P, L, Y	0.71	0.91	0.87
Tensile index	T_w	0.15	0.66	0.64
	T_w, P	0.23	0.69	0.74
	T_w, P, L	0.23	0.69	0.75
	T_w, P, L, Y	0.27	0.71	0.87
Tear index	T_w	0.36	0.49	0.34
	T_w, P	0.68	0.70	0.63
	T_w, L	0.33	0.43	0.34
	T_w, P, L	0.72	0.80	0.77
	T_w, P, L, Y	0.74	0.84	0.87
Light scattering coefficient	T_w	0.06	0.04	0.00
	P	0.37	0.42	0.46
	T_w, P	0.43	0.40	0.46
	$T_w, P; L$	0.43	0.41	0.47
	T_w, P, L, Y	0.58	0.53	0.59
Burst index	T_w	0.40	0.52	0.46
	T_w, P	0.56	0.65	0.64
	T_w, L	0.34	0.47	0.42
	T_w, P, L	0.54	0.67	0.66
	T_w, P, L, Y	0.58	0.75	0.82

Table 6
Kraft fibre and wood tracheid dimension ratios, and wood density prediction of handsheet properties at 500 PFI mill rev

Handsheet property	Fibre/wood property	Coefficient of determination (r^2) Whole tree kraft fibres	Breast height tracheids	Whole tree tracheids
Apparent density	*W/T*	0.59	0.29	0.35
	W/T, L	0.66		
	P/T_w	0.50	0.61	0.45
	$P/T_w, L$	0.61	0.82	0.71
	*D**	0.53	0.59	0.45
	D, L*	0.83	0.82	0.73
Tensile index	*W/T*	0.49	0.15	0.22
	W/T, L	0.46		
	P/T_w	0.26	0.66	0.67
	$P/T_w, L$	0.27	0.69	0.74
	*D**	0.69	0.61	0.66
	D, L*	0.76	0.65	0.73
Tear index	*W/T*	0.72	0.34	0.40
	W/T, L	0.70		
	P/T_w	0.31	0.72	0.62
	$P/T_w, L$	0.35	0.81	0.76
	*D**	0.66	0.69	0.62
	D, L*	0.81	0.80	0.78
Light scattering coefficient	*W/T*	0.18	0.07	0.36
	W/T, L	0.17		
	P/T_w	0.24	0.21	0.20
	$P/T_w L$	0.24	0.27	0.21
	*D**	0.22	0.25	0.21
	D, L*	0.22	0.25	0.21
Burst index	*W/T*	0.71	0.06	0.11
	W/T, L	0.67		
	P/T_w	0.35	0.67	0.62
	$P/T_w, L$	0.34	0.69	0.66
	*D**	0.78	0.66	0.64
	D, L*	0.82	0.68	0.69

* Chip density for kraft fibre analyses. Derived wood density for wood tracheid breast height and whole tree analyses.

sheet apparent density and tensile, tear and burst indices (Table 7). The predictions of handsheet apparent density are markedly and consistently improved by the inclusion of fibre length in the equation, by some 23 to 30%.

The fibre width:thickness ratio by itself is a relatively good predictor of handsheet apparent density, and tensile, tear and burst indices (Table 7). Corresponding tracheid width:thickness ratios are poor predictors of handsheet properties since the tracheids are in an uncollapsed configuration compared with fibres from handsheets (*6*).

The fibre or tracheid perimeter:wall thickness ratio is consistently a good predictor of handsheet apparent density (Table 7). Predictability is markedly improved by 11 to 26% with the inclusion of fibre length in the relationship. For handsheet apparent density the perimeter:wall thickness ratio and length, and the density and length, relationships are very similar based on their r^2 values. Unfortunately the same cannot be said for the corresponding tensile, tear and burst indices relationships.

Coefficients of determination for the perimeter:wall thickness ratio are consistently lower for the kraft fibres than for the wood tracheids. This is explained in part by the poor kraft fibre and wood tracheid wall thickness correlations (Fig. 3) (*10*).

Perimeter is the best fibre or tracheid property predictor of handsheet light scattering coefficient at 500 PFI mill rev (Tables 6,7). Chip and wood density are also poor predictors.

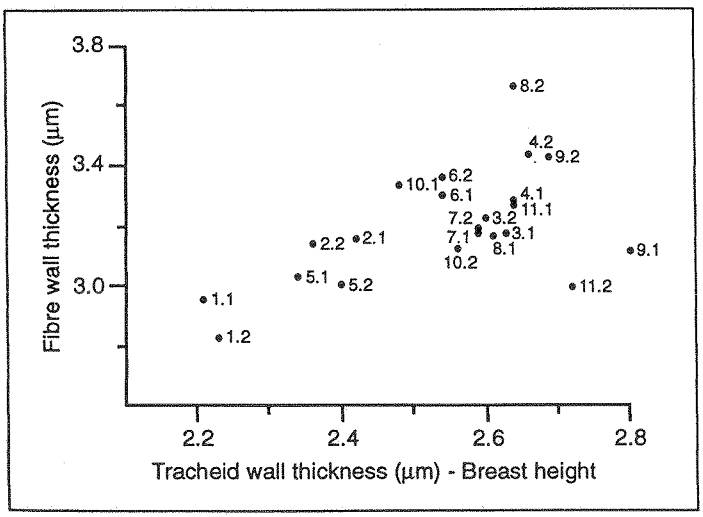

Fig. 3 Kraft fibre wall thickness versus breast height tracheid wall thickness (r^2=0.29).

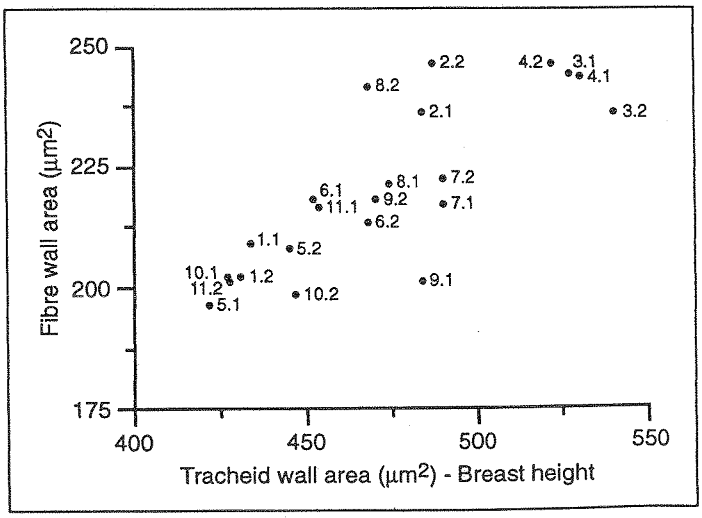

Fig. 4 Kraft fibre wall area versus breast height tracheid wall area (r^2=0.65).

Table 7
Kraft fibre and wood tracheid dimension prediction of handsheet properties at 500 PFI mill rev—wall area, A_w, perimeter, P, length, L.

Handsheet property	Fibre/tracheid property	Coefficient of determination (r^2)		
		Whole tree kraft fibres	Breast height tracheids	Whole tree tracheids
Apparent density	A_w	0.01	0.02	0.00
	P	0.11	0.20	0.16
	A_w, P	0.65	0.64	0.45
	A_w, P, L	0.71	0.80	0.72
Tensile index	A_w	0.00	0.03	0.03
	P	0.08	0.19	0.18
	A_w, P	0.28	0.65	0.75
	A_w, P, L	0.29	0.65	0.76
Tear index	A_w	0.02	0.00	0.02
	P	0.32	0.40	0.38
	A_w, P	0.74	0.71	0.62
	A_w, P, L	0.79	0.85	0.84
Light scattering coefficient	A_w	0.15	0.17	0.33
	P	0.36	0.42	0.46
	A_w, P	0.40	0.43	0.46
	A_w, P, L	0.42	0.54	0.64
Burst index	A_w	0.00	0.00	0.00
	P	0.17	0.31	0.27
	A_w, P	0.63	0.60	0.62
	A_w, P, L	0.64	0.68	0.64

Influence of pulp yield

Tracheid and kraft fibre dimension correlations (*10*), and handsheet property predictions from tracheid dimensions can be expected to be influenced by pulp yield. Yield values for the 22 pulps are listed elsewhere (*10, 13*). Coefficients of determination (r^2) for the handsheet property prediction equations are listed in Table 5 with pulp yield as well as tracheid wall thickness and perimeter, and fibre length as the independent variables. Corresponding r^2 values for whole tree kraft fibres are also listed even though in reality they can have little meaning since measurements refer to pulps of given Kappa number irrespective of yield. They do, however, increase in all cases as do those of the whole tree and breast height tracheids. This marked increase in r^2 brought about by including pulp yield in the handsheet apparent density-tracheid dimension regressions is noteworthy. Packing arrangements of fibres within handsheets must strongly determine apparent density which in turn must be most closely correlated with tracheid dimensions corrected for pulp yield.

Prediction from kraft fibre and wood tracheid properties

Handsheet property predictions from kraft fibre dimension combinations that include wall thickness are often somewhat lower than those from corresponding wood tracheid values (Tables 5,6). This occurs most strongly with tensile index and with wall thickness and the perimeter:wall thickness ratio. Fibre and tracheid wall thicknesses are poorly correlated one with another (r^2=0.29) (Fig. 3) whereas those for fibre and tracheid wall area are relatively high (r^2=0.65) (Fig. 4) (*10*). In the measurement of kraft fibre dimensions wall thickness is derived from the wall area and the wall centre line length (*11*). Estimates of mean kraft fibre wall thickness are therefore considered to be somewhat less reliable than the primary measurements of fibre wall area and fibre perimeter.

Tracheid and fibre wall area and perimeter by themselves are generally poor predictors of handsheet properties, although perimeter by itself can be a moderate predictor of light scattering coefficient (Table 7). When in combination, however, wall area and perimeter are good predictors and equivalent to those of wall thickness and perimeter (Table 5). Such relationships are to be expected since wall thickness is determined by perimeter and wall area and vice versa. Unfortunately, the poor prediction of tensile index from kraft fibre properties is unchanged by the replacement of wall thickness with wall area and remains unexplained. Multiple regression models were used to calculate the r^2 values of Table 7 since the PLS models were constrained by the high correlation between wall area and perimeter (Appendix I). Both the fibre and tracheid perimeter:wall thickness ratios, either by themselves or together with fibre length, are good predictors of handsheet apparent density (Table 5). Furthermore, coefficients of determination for the ratio, and the ratio and length combinations, are generally equivalent to corresponding density, and density and length combinations. Hence, wood or chip density, and the fibre or tracheid perimeter: wall thickness ratio can be considered as being equivalent for the prediction of packing arrangements within handsheets. Such relationships do not hold for handsheet properties where fibre bonding and interfibre interactions are important as is the case with tensile, tear and burst indices (Table 3). Again the reason is probably related to the poor correlation between fibre and tracheid wall thickness (10).

The kraft fibre width:thickness ratio is strongly correlated with handsheet properties, other than light scattering coefficient (Table 6). There is no equivalent wood tracheid dimension or ratio. Fibre width/thickness is a direct measure of fibre collapse which, together with fibre length, directly influences packing arrangements within handsheets. The influence of fibre length is apparently unimportant when bonding is a primary determinant of a handsheet property e.g., tensile, tear and burst indices (Table 6).

CONCLUSIONS

A minimal level of pulp refining (in this case 500 PFI mill rev) is considered the most meaningful basis of comparison for the prediction of handsheet properties from tracheid and unrefined kraft fibre dimensions. With this basis of comparison general conclusions are:

- The width:thickness ratio of the unrefined dried and rewetted kraft fibres is a good predictor of handsheet apparent density (r^2=0.59) and tensile (r^2=0.49), tear (r^2=0.72) and burst (r^2=0.71) indices. Inclusion of fibre length in the four relationships improves the prediction of apparent density only (r^2=0.66). Such an effect is explained by the major influence of sheet structure in determining apparent density, and the major influence of bonding and bonded area in determining strength properties. Corresponding wood tracheid width: thickness ratios are generally poorly correlated with handsheet properties, as expected.
- Kraft fibre or wood tracheid wall thickness and perimeter, and fibre length together are good predictors of handsheet apparent density (r^2=0.62–0.79), light scattering coefficient (r^2=0.43–0.47), and tear (r^2=0.72–0.80) and burst (r^2=0.54–0.67) indices.
- The wood tracheid properties of wall thickness, perimeter, and kraft fibre length together are good predictors of handsheet tensile index (r^2=0.69–0.75). Tensile index is however poorly predicted by these three kraft fibre properties (r^2=0.23), probably because of some anomalous kraft fibre wall thickness values.
- Fibre and tracheid wall area when in combination with perimeter is able to replace wall thickness as a predictor of handsheet properties. Wall area (or coarseness) by itself is a poor predictor.
- Chip or wood basic density, and kraft fibre length together are good predictors of handsheet apparent density (r^2=0.73–0.83) and tensile (r^2=0.65–0.76), tear (r^2=0.78–0.81) and burst (r^2=0.68–0.82) indices.

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