Kraft handsheet property prediction from the wood and fibre properties of radiata pine seedling and cloned trees

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ABSTRACT
Kraft handsheet properties were predicted from wood properties, including chip density, fibre length, glucose content, fibre coarseness and microfibril angle. Models were developed and compared for one set of 11 radiata pine clones, aged 16 years and another set of 10 clones aged 27/28 years, plus two sets of 25 seedling trees, each derived from the same 25 families, aged 13 and 15 years respectively.

Two sets of wood properties were included as predictor variables in the analyses to allow extensive historical individual-tree data to be utilised, and to broaden the range of age, site and wood-type influences. Thus, handsheet property prediction models using chip density and fibre length alone were compared with models incorporating chip density, fibre length and glucose content, and SilviScan fibre coarseness and microfibril angle.

INTRODUCTION

Wood property variation among and within trees can be very high and is influenced by species, age, growing site and position-in-stem (1, 2). An extensive data set of wood and kraft pulp properties has been built up over the past three decades on individual trees and wood-types (slabwood, topwood and juvenile wood (2)) of New Zealand-grown radiata pine. This data base includes two sets of clones, 11 clones aged 16 and 10 clones aged 27 years, 64 trees in all, (3-5) and two sets of 25 seedling trees, each derived from the same 25 open-pollinated families at ages 13 and 15 years (6, 7). Both conventional properties (chip density, fibre length and glucose content), and SilviScan-generated properties (density, tracheid coarseness, wall thickness, perimeter and microfibril angle (MFA)) (8), as well as kraft pulp evaluation information are available. Additionally, the data base also includes pre-SilviScan (8) historical data for chip density, fibre length and kraft properties, over a wide range of ages (12 - 52 years and wood-types (whole-tree, slabwood, top-corewood and butt-corewood) (9-12). Kraft handsheet prediction models were generated using this data base with two sets of predictor variables, chip density and fibre length, versuschip density, fibre length and glucose content, plus SilviScan coarseness and MFA. Kraft handsheet properties considered are sheet density, log tear index, tensile index, stretch and T.E.A. index.

Each of the individual-tree studies included in the data base of this paper have been reported elsewhere (3-7, 9-12), and all (except that of the clones aged 27 years) consider interrelationships among wood, fibre and chemical (or wood and fibre only) and kraft handsheet properties. The combined data base greatly extends the available range of tree ages, growing sites, and wood-types, and allows "best possible" kraft handsheet prediction models to be developed. Furthermore, the availability of full sets of conventional and SilviScan wood property information confirms and extends handsheet property predictions, particularly those for Tensile index, stretch and T.E.A. index, which have been demonstrated for radiata pine (7) and two eucalypt species (13). These studies also showed that chip density and fibre coarseness predictors are equivalent to SilviScan tracheid perimeter and wall thickness. The inclusion of coarseness along with density ensures fibre number per unit mass is taken into account. The handsheet property prediction models selected in this paper use chip density and SilviScan coarseness as predictor variables rather than SilviScan perimeter and wall thickness. Finally, glucose content is the selected chemical predictor although lignin content would be equally effective (7, 13).

EXPERIMENTAL

Sample selection

Tree-set13 and Tree-set15: Two sets of 25 trees were taken from a preselected population of 200 trees an open-pollinated progeny trial, located in Rotoehu Forest in the Bay of Plenty, New Zealand (37º 57´S, 176º 33´E). These 200 trees represented eight trees from 25 half-sib (open-pollinated)families that had been selected from a total of 180 families in the same progeny trial for growth rate, tree form, and extremes of tracheid wall thickness and perimeter. The first set of 25 trees, cut at age 13 years (Tree-set13), were selected to cover a range of tracheid wall thickness and perimeter values. The second set of 25 trees, cut at age 15 years (Tree-set15), were selected to cover a range of wall thickness, and perimeter values as well as tracheid length. Further details on the selection of the 50 trees are presented elsewhere (6).

Tree-set16: Eleven 16 year-old radiata pine clones were selected from a total of 120 clones in a clonal test at Compartment 327, Kaingaroa Forest, 50km south of Rotorua (lat. 38º 37´S, 176º 21´) (14). Clones were propagated by rooted cuttings from trees aged four years from seed, and were subsequently repropagated into an archive where the mother plants were kept hedged at height one metre. Cuttings were collected from the archive for planting the clonal test. Clone selection was based on wood basic density and tracheid length determined from cores taken at breast height (1.4 m). Clones were selected so as to cover the extreme basic density and tracheid length combinations possible: high density and long tracheids, high density and short tracheids, low density and short tracheids, low density and long tracheids, and medium density and medium length tracheids. Two clones were selected for each of the five wood property combinations, with each clone represented by two trees.

Such an experimental design required a total of ten clones and twenty trees. An eleventh clone with medium density and tracheid length was selected and consisted of 4 trees which were bulked to give a bulked chip sample used to estimate differences between refiner runs in the mechanical pulping trials (14).

Two trees of each of the chosen ten clones, and a bulked four-tree sample from one clone were selected for kraft pulp quality assessment. For the ten clones each tree was chipped and pulped separately. Two replicate kraft pulps were prepared from the four-tree bulk sample.

Tree-set27 and Tree-set28: A unique early clonal test, planted 1968, provided the material for these studies (5). Initial propagation by rooted cuttings was from trees, aged 6-7 years from seed. Ten clones were selected for a range of the four traits, diameter at breast height, wood density, branch diameter and internode length. Selected trees were required to show a range of qualities, typical as far as possible of the genetically unimproved crop being harvested in 1995. Two trees of each of the 10 clones were felled at age 27 years (Tree-set 27) and used in sawn-timber studies (15), where the uppermost sawn log (5.5m long) ranged from the 3rd log for a small tree to the 7th log for a large tree. The remaining toplogs above the uppermost sawn log and the slabwood residues from the 1st, 2nd, and 3rd or 4th logs were chipped and kraft pulped separately, by individual trees. The toplog chips were also pulp by the TNP process (16). A further two trees of each clone were felled the following year (Tree-set28) and used in a peeling and slicing study (Harding and Orange, unpubl.). The remaining toplogs of each tree of Tree-set 28 were chipped and kraft pulped.

Toplog specifications for Tree-set 27 and Tree-set 28 were very different (5). The wood used for toplog chips for Tree-set 28 begins on average at 19 m, which is 6.3 m lower down the tree than the average height of 25.3m for Tree-set 27. The large difference between tree-sets in the height at which the first toplog starts, is reflected in the much larger average diameters and higher numbers of large-end growth layers for Tree-set 28. The individual-tree toplog chips of Tree-set27 are, therefore, designated toplogs whereas those of Tree-set28 are designated (Mid+top)logs (5).

Tree/log processing
Discs of thickness ca2.5 cm were taken from each tree at 5.5 m intervals, from the base of the butt-log to the top of the uppermost saw- or peeler-log (Tree-sets 27 and 28 (5)), as well as from 1.4 m and to a ca10 cm top (Tree-sets 13, 15 and 16 (4, 7)).
The logs of each individual tree (Tree-sets 13, 15 and 16), the toplogs (Tree-sets 27 and 28) and the slabwood (Tree-set27), were chipped in a commercial chipper as a batch and in random order, and the chips well mixed with a front-end loader. Bulk samples (5kg o.d.) were taken for kraft pulping. Each sample was passed through a Williams round-hole screen, with acceptable chips passing through the 26 mm hole screen and retained on the 9 mm hole screen.

Chemical analyses
300 g (o.d. equivalent) of chips from each tree were air-dried for three days prior to grinding (20 mesh). Samples were extracted in a Soxtec extractor with dichloromethane - boiling time of 30 min., and rinsing time of 60 min. 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. These were analysed after acid hydrolysis following Tappi T222 om-88 for lignin, Tappi um 250 for acid soluble lignin, and the method of Pettersen and Schwandt (17) for carbohydrates.

Chemical analyses were made on all 25 Tree-set13 chip samples, and on 21 of the 25 Tree-set15 samples. Chemical analyses were also made on all Tree-set16, Tree-set27 and Tree-set28 chip samples.

Chip basic density
Chip basic density was determined in accordance with Appita method P1s-79, except that the fresh chips were not given the specified soaking period.

Pulp fibre length
Length weighted average kraft fibre length was determined with a Kajaani FS 200 instrument, using Tappi T271 pm-91.

SilviScan wood density and tracheid properties
Transverse wood tracheid dimensions and microfibril angle were determined on SilviScan using image analysis, and x-ray densitometry and diffraction (8, 18, 19). A single radius was cut from each disc, then solvent-exchanged in ethanol and dried. Thin pith-to-bark strips (2mm wide x 7mm high) were cut from each dried disc. Wood density, and tracheid radial and tangential diameters were measured at 50 μm intervals along the strip. Tracheid coarseness, outer perimeter (from radial and tangential diameters) and average wall thickness were generated from these primary measures. All SilviScan samples were conditioned to 20°C and 40% relative humidity.

Individual-tree (3, 20) SilviScan property values were calculated as volume-weighted averages using data from all sampling heights. Toplog SilviScan property values were calculated as the area-weighted average for the uppermost disk sampled (i.e. the disk taken from the top of the uppermost sawlog or equivalently the bottom of the toplogs). Slabwood SilviScan values were volume weighted averages for the outer 5 complete growth layers for all sawlog logs.

Pulping
Kraft pulps kappa numbers ranged from around 30±2 (Tree-sets 13, 16 and 27(4, 5, 7)), and around 27±2 (Tree-sets 15 and 27 (5, 7)). Kappa number was controlled by

varying the H-factor at constant alkali charge. The pulping conditions were:

- 16% effective alkali as Na_2O
- Sulfidity 30-32 %
- 4:1 liquor-to-wood ratio
- 90 minutes to maximum temperature
- 170°C maximum temperature

Pulps were prepared in 2.0 L Stalsvets reactors with 300 g (o.d. wt.) chip charges. Pulps were disintegrated with a propeller stirrer and screened through a 0.25 mm slotted flat screen. Kappa number was determined after pulp dewatering and fluffing.

Handsheet preparation and evaluation

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.

Statistical Analysis

Linear regression analysis was used to calculate models for individual tree sets (wood-types) and for combined data sets where no wood-type classification variable is used in the model (Tables 1, 2, 5, and 9). Analysis of covariance (ANCOVA) was used to calculate equal-slopes models that included a classification term (wood-type) to account for differences between wood types, in addition to the continuous predictor variables used (Tables 4, 7, 8). The least squares means for each wood-type were compared statistically (Tables 3, 6, 10). The least squares mean is the model-predicted value for a wood-type at the mean value of all model covariates (predictor variables) of all the data (all wood-types). No separate-slopes models were calculated to test for statistical significance of wood-type by predictor variable interactions.

For each Figure, the data from all wood-types was combined into one dataset and a multiple linear regression model fitted for each handsheet property. This combined dataset regression model was used to calculate the combined model predicted values for all points from all wood-types in a Figure. Regression lines were calculated for actual versus combined model predicted values for each wood-type included in a figure. Note these are not the individual tree-set regression models given in the Tables. These regression lines and points indicate the relative position and spread of points for each wood-type when a combined data set model is fitted. The combined model solution is generally not provided in the report tables, since these combined models were only calculated to generate predicted values to allow graphic illustration of the relative positions of the wood-type and data points when all wood-types are treated as one.

RESULTS AND DISCUSSION

Handsheet density prediction from chip density and pulp fibre length

Handsheet density is used here as the base against which other sheet properties are compared. It is a measure of the spatial arrangements and packing densities of the fibres within a web. These are in turn influenced by fibre length, cross-section dimensions, collapse and straightness (2, 21). Handsheet density prediction models for the four wood-types from clones are first examined using chip density (which is controlled by the fibre wall thickness/perimeter ratio (2, 21)) and fibre length as predictor variables (Table 1). It is noteworthy that chip density and fibre length together are insufficient to indicate the suitability of a fibre resource for particular paper grades. To do this, either fibre coarseness or fibre cross-section dimension values (perimeter and wall thickness) is also necessary (7, 13, 21).

Chip density alone is a moderate to strong predictor of handsheet density (at 500 PFI mill rev) for all four wood-types (Table 1). The relatively high residual error (root-mean-square-error (RMSE)) obtained with the Tree-set16 data could be partly explained by the tree selection process used (4). Clones (and ramets) were selected to cover the

Table 1: Clone-tree handsheet density prediction models using chip density alone, and chip density and fibre length as predictor variables, for each of the four wood types from clones; Tree-set28 ((Mid+top)log), Tree-set27 (slabwood and toplog), and Tree-set16 (Whole-tree). Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

Sheet density at 500 PFI mill rev (kg/m^3)	Tree-set28	Tree-set27		Tree-set16	All
	(Mid+top)log	Slabwood	Toplog	Whole-tree	
Intercept	1078	980	1091	878	1073
Chip density (kg/m^3)	-1.03 **	-0.895 **	-1.091 **	-.523 **	-1.06 **
R^2	0.81	0.79	0.79	0.49	0.81
RMSE	15.3	15.5	15.2	17.0	22.3
Intercept	1156	1095	1178	1121	1118
Chip density (kg/m^3)	-0.775 **	-0.864 **	-0.699 **	-0.558 **	-0.675 **
Fibre length (mm)	-68.0 *	-41.2	-98.4 **	-93.2 **	-74.0 **
R^2	0.87	0.82	0.90	0.79	0.91
RMSE	13.4	14.8	10.5	11.2	15.2
Correlation coefficient between chip density and fibre length	0.71	0.18	0.68	-0.09	0.72

range and combinations of individual-tree outerwood densities and tracheid lengths available. The variation accounted for by the Tree-set16 model is greatly increased with the inclusion of fibre length as a predictor variable. Sheet density predictions for the Tree-set27 and Tree-set28 wood-types are also improved by the inclusion of fibre length in the models, although to a considerably lesser extent. The fibre length effect is non-significant for the slabwood, moderate for the (mid+top) log, and high for the toplog wood-types. Respective fibre length ranges are 2.9-3.3 mm, 2.4-2.9 mm and 2.2-2.6 mm (5), suggesting that it is the fibre length in shorter-fibred pulps which most strongly influence sheet density. In contrast to the tree-set16 model, however, chip density and fibre length are moderately correlated and possibly confounded one with another in the (mid+top) log and toplog models for the 27-year-old clones. The combined models predict sheet density with an RMSE of about 15 kg/m^3.

Handsheet property prediction using chip density and glucose content, and pulp fibre length

Handsheet property prediction models for sheet density and tensile index (at PFI mill 500 rev), and log tear index (at PFI mill 1000 rev) using as predictors chip density and glucose content, and pulp fibre length, are listed in Table 2. PFI mill refining at 500 rev is a minimal pulp processing treatment and one that is taken to leave pulps close to their unrefined condition. The same cannot be said for PFI mill refining at 1000 rev which was necessary to develop the log tear index linear regression models. A 1000 rev treatment was sufficient to move tear index values beyond maxima which normally occur with most radiata pine kraft pulps from slabwood (22). Overall the prediction models account for at least 77% of the variation in sheet density within each wood type.

Chip density is by far the dominant predictor of sheet density, tensile index and tear index in each of the four wood-type and combined models (Table 2). There are significant effects of fibre length in the Tree-set16 models for sheet density, tensile index and log tear index. This moderate to strong effect of fibre length has been partially explained by the clone and tree selection procedure used for Tree-set16 (Table 1). Chip glucose content is a poor predictor of the three sheet properties for each of the four wood-types when considered separately. For the combined wood-type models, however, the glucose content effect can be highly significant but with an increased RMSE values.

Actual versus predicted sheet density, tensile index and tear index regressions for the four wood-types show that the 'odd-man-out' is the (mid+top) log wood-type (Figures 1-3). Kappa numbers for the (mid+top) log pulps are consistently lower than those of the other wood-types by 2.5 units. When kappa number is included as a predictor variable in the models differences between the (mid+top) log and other wood-type regressions are moderately diminished for tensile index and tear index, and slightly diminished for sheet density (Figure 1-3). Differences between wood types can be statistically significant (0.05 level ANCOVA model) both without and with kappa number included in the models (Table 3).

Actual versus model-predicted (chip density + fibre length + glucose content + kappa number) relationships, with the seedling-tree values of 50 individual trees (7, 21) superimposed over the four clone wood-types regressions, are shown in Figure 4. It is clear that relationships between the clone and seedling tree pulps are very similar, a conclusion confirmed by the statistics of Table 3.

Table 2: Clone-tree, wood-type prediction models for sheet density, tensile index and log tear index, with chip density, fibre length and glucose content as predictor variables. Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

	Tree-set28	Tree-set27		Tree-set16	Combined
	(Mid+top)logs	Slabwood	Toplogs	Whole-tree	
Sheet density at 500 rev (kg/m³)					
Intercept	1159	1285	1195	1183	1212
Chip density kg/m³	-0.775**	-0.745**	-0.690**	-0.535**	-0.657**
Fibre length mm	-67.3	-36.9	-97.8**)	-91.1**	-68.2**
Glucose %	-0.118	-5.85	-0.514	-1.78	-2.77*
R^2	0.87	0.83	0.90	0.80	0.92
RMSE	13.8	14.6	10.8	11.2	14.9
Tensile index at 500 rev (N.m/g)					
Intercept	159	170	212	158	216
Chip density kg/m³	-0.264**	-0.219**	-0.226**	-0.158**	-0.163**
Fibre length mm	-9.02	-11.6	3.42	-12.6*	-13.1**
Glucose %	1.34	0.532	-1.26	0.354	-0.909
R^2	0.80	0.83	0.74	0 .71	0.79
RMSE	4.38	3.53	4.12	3.47	5.97
Log tear index at 1000 rev (mN.m²/g)					
Intercept	-0.355	-0.204	-0.126	-0.308	-0.800
Chip density kg/m³	0.00177**	0.00249**	0.00156**	0.00149**	0.00147**
Fibre length mm	0.131	0.0760	0.212**	0.174**	0.182**
Glucose %	0.00835	0.00383	0.000935	0.00886*	0.0197**
R^2	0.85	0.88	0.83	0.85	0.90
RMSE	0.0370	0.0341	0.0336	0.0251	0.0448

The combined four clone- and single seedling-tree wood-type models of Table 4 show markedly increased coefficients of determination with very acceptable RMSE values, compared to those of the individual wood-type models alone (Table 2). This trend is to be expected in view of the greatly increased range and numbers in the combined data-set. The inclusion in the models of wood-type as a classification variable, and kappa number as an additional continuous variable, further decreases the unexplained variation (increases coefficient of determination) and decreases RMSE values (Table 4). The low coefficients of determination (or high unexplained variation) of the tensile index prediction models (Tables 2, 4), compared with sheet density and log tear index, are consistent with previous literature values (9-12).

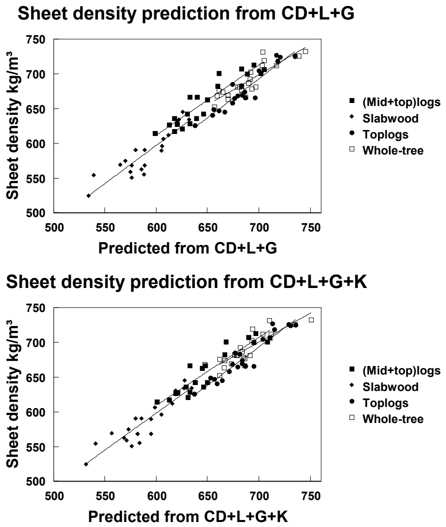

Figure 1: Actual versus predicted sheet density regressions for each of the four wood-types, without and with the inclusion of pulp kappa number as a predictor variable.

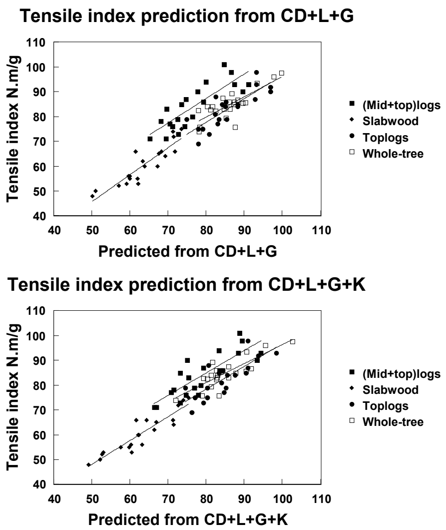

Figure 2: Actual versus predicted sheet tensile index regressions for each of the four wood-types, with out and with the inclusion of pulp kappa number as a predictor variable.

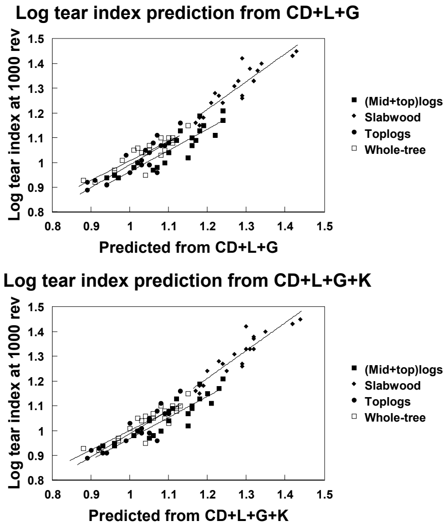

Figure 3: Actual versus predicted sheet log tear index regressions for each of the four wood-types, with out and with the inclusion of pulp kappa number as a predictor variable.

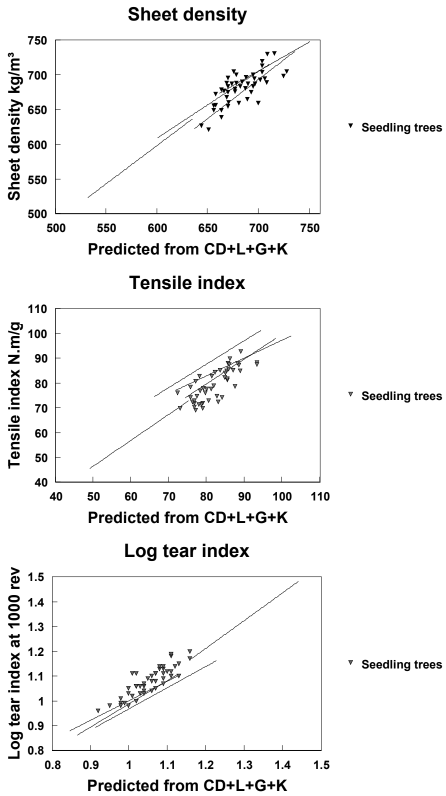

Figure 4: Actual versus predicted sheet density, tensile index and log tear index relationships for each of the four wood-types from clones (regressions (Figures 1-3)), and for seedling trees (data points (7)). Model predictor variables are chip density, kraft fibre length, glucose content and pulp kappa number.

Table 3: Comparison of wood-type means from ANCOVA with chip density, fibre length, glucose content and kappa number as predictor variables. Comparisons are made among four wood-types from clones (Table 2), and among these clones and a set of 50 seedling-trees (7, 21). Note: Wood-type least square mean values with the same letter following are not significantly different one from another (0.05 level).

	Sheet density (kg/m^3)	Tensile index (Nm/g)	Log tear index (log (mNm/g)
Toplog	655 a	80.4	1.06
Slabwood	659 ab	74.8 a	1.11 ab
Seedling	663 ab	75.2 a	1.12 b
(Mid+top)log	668 bc	87.8	1.03
Whole-tree	675 c	79.6	1.09 a

Table 4: Combined wood-type model with and without wood-type (classification variable) and kappa number (continuous variable) included, for sheet density tensile index and log tear index.

	Sheet density (kg/m^3)		Tensile index (N.m/g)		Log tear index ($mN.m^2/g$)	
	With	Without	With	Without	With	Without
Wood-type	**		**		**	
Chip density kg/m^3	-0.649 **	-0.617 **	-0.186 **	-0.184 **	0.00188 **	0.00168 **
Fibre length mm	-62.4 **	-70.4 **	-5.61 *	-9.97 **	0.136 **	0.157 **
Glucose %	-4.63 **	-3.85 **	-0.39	-0.78 *	0.0093 **	0.0179 **
Kappa number	-1.84		-0.621 *		0.00838**	
R^2	0.93	0.88	0.89	0.86	0.95	0.92
RMSE	13.0	16.1	3.82	4.16	0.029	0.035

Historical data (9-12): Handsheet property prediction using chip density and pulp fibre length alone

Sheet density and tensile index at 500 PFI mill rev, and log tear index at 1000 PFI mill rev, linear regression models (using chip density and fibre length only as predictor variables) are presented in Table 5 for a wide range of radiata pine seedling-tree, wood-types and tree ages (9-12).

The sheet density prediction models are strongly influenced by the chip density effect which is significant or highly significant for all wood-types. Both chip density and fibre length are highly significant effects in the combined wood-type, sheet density prediction ANCOVA model with its high coefficient of determination (Table 7). The separate and combined log tear index prediction

models show similar trends to those of the corresponding sheet density models (Tables 5-7).

Tensile index predictions for the eight wood-types of Table 5 are markedly different one from another compared to those of sheet density and log tear index (Tables 5-7). While some of this tensile index variation among wood-types could be attributed to testing error as suggested by the poor predictions of the new-crop slabwood and butt-corewood models (Table 5), other factors such as microfibril angle could account for the low slope of the thinnings and butt-corewood regressions compared to that of the top-corewood regression (Figure 5))2, 23). Tensile index predictions are consistently weaker than those for sheet density and log tear index for the two data sets considered here (Tables 2-4 and 5-7). The clone- (Table 2) and seedling-tree (Table 5) prediction models are generally similar one to another as indicated by the superimposed seedling-tree data of Figure 4 (Tree-set13 + Tree-set15) and Figures 5 and 6 (Tree-set13 only). The Tree-set13 tensile index data envelope is of a somewhat higher magnitude with a similar flat profile compared to the thinnings and butt-corewood regressions (Figure 5). Note that Tree-set15 has been excluded from Figures 5 and 6 because pulp kappa numbers are more than 2 units lower than those of all other wood-types (Table 5) (7).

Table 5: Individual-tree prediction models for sheet density, tensile index and log tear index with chip density and fibre length as predictor variables. Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

	9 old-crop trees aged 52 years (11)		**9 new-crop trees aged 24 years (10)**			**9 new-crop trees aged 12 years (9)**	**2 trees from each of 25 families aged 13 & 15 years (7)**	
	OC top-corewood	OC butt-slabwood	NC top-corewood	NC butt-corewood	NC slabwood	Thinnings	Tree-set 13	Tree-set 15
Sheet Density at 500 rev (kg/m³)								
Intercept	1091	901	1076	919	757	1068	1084	1014
Chip density kg/m³	-0.859 *	-0.399 *	-1.04 **	-0.419 *	-0.517 **	-0.658 **	-0.686 **	-0.560 **
Fibre length mm	-43.9	-48.9 *	-20.0	-46.3	16.7	-58.6 *	-65.5 **	-45.2
R^2	0.55	0.82	0.91	0.76	0.91	0.91	0.75	0.32
Root MSE	20.9	12.1	9.4	11.7	7.4	7.8	13.2	17.4
Tensile index at 500 rev (N.m/g)								
Intercept	203.9	152.9	230	68.4	69.1	113.4	164.0	139.9
Chip density kg/m³	-0.148 *	-0.092	-0.528 **	-0.115	-0.124	-0.210 **	-0.185 **	-0.170 **
Fibre length mm	-23.0 *	-14.2	17.2	16.4	15.9	13.6	-6.51	0.69
R^2	0.71	0.59	0.78	0.20	0.25	0.85	0.73	0.33
Root MSE	3.5	5.4	7.1	8.9	9.7	3.0	3.5	5.0
Log tear index at 1000 rev (mN.m²/g)								
Intercept	-0.33	0.18	0.083	0.769	0.871	0.682	0.030	-0.154
Chip density kg/m³	0.00168 *	0.00117	0.00255 **	0.00130 **	0.00151 *	0.00183 **	0.00174 **	0.00223 **
Fibre length mm	0.292 *	0.220 *	0.056	-0.007	-0.042	-0.0707	0.164 **	0.160 *
R^2	0.74	0.78	0.85	0.76	0.58	068	0.84	0.57
Root MSE	0.092	0.049	0.031	0.027	0.059	0.043	0.025	0.040

Table 6: Comparison of wood-type means from ANCOVA with chip density and fibre length as predictor variables. Comparisons are made among eight wood-types from seedling-trees (Table 5). Note: wood-type least square mean values with the same letter following are not significantly different one from another (0.05 level).

	Sheet density (kg/m³)	**Tensile index (N.m/g)**	**Log tear index (mN.m²/g)**
OC butt- slabwood	626 a	76.8 b c	1.25 b
NC slabwood	627 a	71.7 a b	1.28 b
NC top-corewood	632 a	82.0 c d	1.19
NC butt-corewood	634 a	69.4 a b	1.24 b
OC top- corewood	638 a	82.3 d	1.13 a
Tree-set13	653	77.1 b c d	1.12 a
Thinnings	672 b	65.8 a	1.26 b
Tree-set15	679 b	76.3 b	1.12 a

Table 7: ANCOVA model with wood-type (classification variable) and chip density and fibre length (continuous variables) included, for sheet density, tensile index and log tear index. Model data are the eight wood-types from seedling-trees (Table 5). Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

	Sheet density (kg/m³)	**Tensile index (N.m/g)**	**Log tear index (mN.m²/g)**
Wood-type	**	**	**
Chip density kg/m³	-0.581**	-0.165**	0.00162**
Fibre length mm	-38.6**	0.461	0.108**
R^2	0.93	0.66	0.92
RMSE	14.30	6.04	0.040

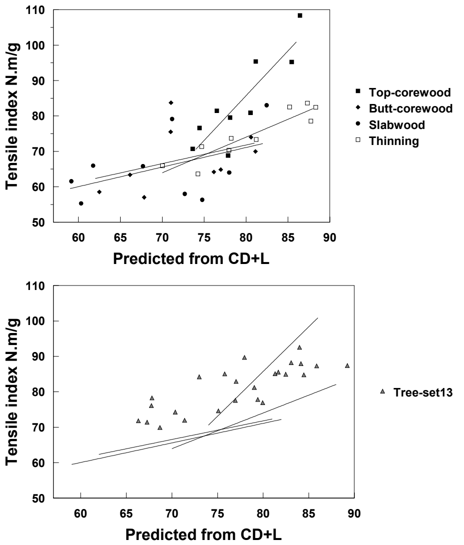

Figure 5: Actual versus predicted tensile index relationships for each of the four new-crop wood-types (top-corewood,butt-corewood, slabwood and thinnings regressions), and for Tree-set13 seedling trees (data points (7)). Model predictor variables are chip density and kraft fibre length only.

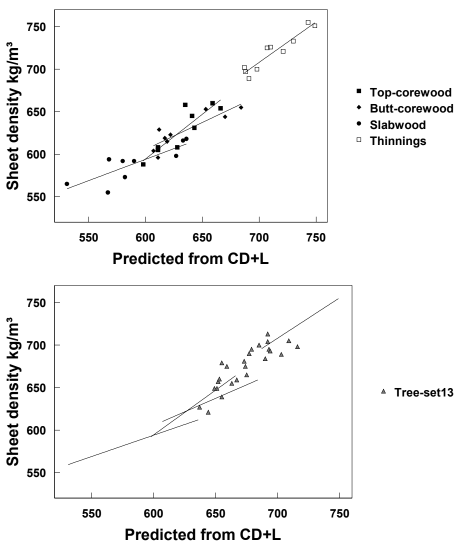

Figure 6: Actual versus predicted sheet density relationships for each of the four new-crop wood-types(top-corewood,butt-corewood, slabwood and thinnings regressions), and for Tree-set13 seedling trees (data points (7)). Model predictor variables are chip density and kraft fibre length only.

HANDSHEET PROPERTY PREDICTION USING CHIP DENSITY, SILVISCAN COARSENESS AND MFA, FIBRE LENGTH, GLUCOSE CONTENT AND PULP KAPPA NUMBER (7, 13)

The handsheet property prediction models considered here (density, log tear index, tensile index, stretch and T.E.A. index) are limited to those for which SilviScan properties are available: the cloned trees of Tree-set16 and Tree-set27 (slabwood and toplogs) (Table 1), and the seedling trees of Tree-set13 and Tree-set15 (7, 20). All handsheet property prediction models are at 500 PFI mill rev except for log tear index which is at 1000 PFI mill rev.

Chip density is used as a predictor variable instead of SilviScan density since overall it gives better sheet property predictions (Table 8), and the measurement of chip density is completely independent of the measurement of SilviScan coarseness (8, 18). Finally, pulp kappa number is included as predictor variable because of the acknowledged low values of the Tree-set15 pulps (7, 20). For the combined models only, the kappa number effect is significant for sheet density and log tear index but limited for the stress/strain properties of tensile index, stretch and T.E.A. index (Table 8). The effect is consistently non-significant for all individual models (Table 9), where acceptable pulp kappa numbers within a wood-type are 30+/-2, except for those of Tree-set15 where individual-tree pulp kappa numbers are lower by more than 2 units (20).

Table 8: Combined wood-type model for sheet density tensile index, stretch and T.E.A. index and log tear index. The combined models are based on the five wood-types of Table 9, three from cloned-trees and two from seedling-trees. Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

	Sheet density (kg/m³)		**Log tear index (mN.m²/g)**		**Tensile index (N.m/g)**		**Stretch %**		**T.E.A. index (J/kg)**	
Wood-type	**	**	**	**	**	**	**		*	
Chip density kg/m³	-0.586 **		0.00189 **		-0.166 **		-0.0025**		-3.91 **	
SilviScan density kg/m³		-0.372 **		0.00116 **		-0.103 **		-0.00165**		-2.40 **
Fibre coarseness μg/m	-0.076 *	-0.088 *	-0.00002	0.00003	-0.059 **	-0.063 **	-0.00229**	-0.00232**	-1.95 **	-2.05 **
MFA °	2.13 **	1.48	0.00021	0.00213	-0.295	-0.467 *	0.0307 **	0.0276 **	15.4 *	11.4
Fibre length mm	-43.2 **	-45.0 **	0.139 **	0.143 **	0.413	0.063	-0.050	-0.060	-71.2	-78.9
Glucose %	-4.36 **	-5.31 **	0.0093 **	0.0128 **	-0.553	-0.857 *	-0.0387 **	-0.0421 **	-30.1 *	-37.4 **
Kappa number	-2.30 *	-2.30 *	0.00833 **	0.00809*	-0.593 *	-0.575	0.0013	0.0010	-7.00	-6.50
R^2	0.94	0.92	0.95	0.91	0.92	0.88	0.90	0.90	0.91	0.90
RMSE	12.0	14.0	0.0293	0.0391	3.17	3.88	0.139	0.142	112	124

Table 9: Clone- and seedling-tree, wood-type prediction models for sheet density, tensile index and log Tear index, with chip density, SilviScan coarseness and MFA, fibre length, glucose content and kappa number as predictor variables. Note: * indicates that an effect is significant at the 0.05 level, and ** indicates that an effect is significant at the 0.01 level.

	Tree-set27 Slabwood	Toplogs	Tree-set16 Whole-tree	Tree-set13	Tree-set15
Sheet density at 500 PFI mill rev (kg/m³)					
Intercept	1391	1215	814	1291	1426
Chip density kg/m³	-0.562 **	-0.671 **	-0.420 **	-0.562 **	-0.532 **
Coarseness µg/m	-0.081	-0.074	0.184 **	-0.085	-0.051
MFA °	2.05	-1.00	5.35 **	2.80 *	1.71
Fibre length mm	-12.7	-104.1 **	-77.1 **	-33.8	-12.9
Glucose %	-8.90	1.40	1.12	-7.06 **	-8.62
Kappa number	-3.79	-1.32	-0.56	-1.65	-5.55
R^2	0.88	0.92	0.94	0.89	0.66
Root MSE	13.72	11.18	6.71	9.49	14.07
Log tear index at 1000 PFI mill rev (mN.m²/g)					
Intercept	-0.652	-0.456	0.209	-0.494	-1.244
Chip density kg/m³	0.00216 **	0.00188 **	0.00147 **	0.00177 **	0.00217 **
Coarseness µg/m	0.00027	-0.00026	-0.000523 *	-0.00028 *	-0.00005
MFA °	0.00110	0.000283	-0.00533	0.00336	0.00175
Fibre length mm	0.039	0.217 *	0.211 **	0.142 **	0.113
Glucose %	0.0103	0.0017	0.00051	0.0138 **	0.0207
Kappa number	0.00898	0.01032	0.00338	0.00093	0.01284
R^2	0.92	0.86	0.913	0.93	0.72
Root MSE	0.031	0.033	0.021	0.018	0.036
Tensile index at 500 PFI mill rev					
Intercept	202.0	193.8	197.1	218.3	281.8
Chip density kg/m³	-0.161 **	-0.186 **	-0.177 **	-0.163 **	-0.158 **
Coarseness µg/m	-0.044 **	-0.063	-0.037	-0.049 *	-0.077 *
MFA °	0.213	-0.586	-0.138	-0.429	-0.801
Fibre length mm	-2.31	-0.22	-6.64	2.48	5.46
Glucose %	-0.323	-0.145	0.280	-0.976	-1.956
Kappa number	-0.928	0.264	-0.802	-0.432	-0.939
R^2	0.93	0.81	0.77	0.80	0.71
Root MSE	2.58	3.85	3.33	3.35	3.75
Stretch at 500 PFI mill rev((%)					
Intercept	7.87	5.82	2.29	7.94	5.37
Chip density kg/m³	-0.00320	0.00058	-0.00222 *	-0.00259 **	-0.00135
Coarseness µg/g	-0.00095	-0.00206	0.00097	-0.00371 **	-0.00422 **
MFA °	0.0290	-0.0065	0.0466 *	0.0378 **	0.0203
Fibre length mm	-0.258	-0.965 **	-0.712 *	0.463 *	0.160
Glucose %	-0.068	-0.027	0.042	-0.103 **	-0.037
Kappa number	-0.0271	0.0301	-0.0076	-0.0071	0.0201
R^2	0.83	0.78	0.77	0.90	0.66
Root MSE	0.134	0.135	0.107	0.099	0.142
T.E.A. index at 500 PFI mill rev (J/kg)					
Intercept	5042	5488	3556	6825	6433
Chip density kg/m³	-3.27 *	-2.32	-4.37 **	-4.31 **	-3.62 *
Coarseness µg/m	-0.91	-2.09 *	0.07	-2.94 **	-3.41 **
MFA °	18.4	-11.2	26.6 *	18.7	2.96
Fibre length mm	-145	-644 *	-650 **	295	141
Glucose %	-31.7	-25.5	27.6	-78.3 **	-56.9
Kappa number	-26.3	20.0	-18.2	-8.47	-2.61
R^2	0.87	0.85	0.90	0.90	0.68
Root MSE	90.9	111.7	71.3	89.6	130.8

Table 10: Comparison of wood-type means from ANCOVA with chip density, SilviScan coarseness and MFA, fibre length, glucose content and kappa number as predictor variables. Comparisons are made among three wood-types from clones, and among these clones and two wood-types from seedling-trees (Table 9). Note: Wood-type least square mean values with the same letter following are not significantly different one from another (0.05 level).

	Sheet density (kg/m³)	**Log tear index (log(mNm²/g)**	**Tensile index (Nm/g)**	**Stretch (%)**	**TEA Index (J/kg)**
Tree-set13	649	1.11 c	75.8 a	2.42 ab	1279 a
Slabwood	665 a	1.11 bc	74.7 a	2.29 a	1273 a
Toplogs	666 a	1.06 a	82.0 b	2.36 a	1333 ab
Tree-set15	673 a	1.13 c	74.1 a	2.51 b	1303 a
Tree-set16	674 a	1.08 ab	81.5 b	2.51 b	1417 b

Sheet density and log tear index

Chip density is a highly significant predictor variable for the sheet density and log tear index models of all five wood-types (Table 9). The remaining predictor variables are significant or highly significant in the whole-tree pulp-sets of tree-set16 (coarseness, MFA and length) and Tree-set13 (MFA and glucose content) sheet density models. Furthermore, the sheet density models are similar one to another except for that of Tree-set15 with its relatively small range of density and other sheet property values (7), low coefficient of determination and high RMSE values (Tables 9, 10). Hence, the high levels of predictor-variable-significance in the combined sheet density model is justified (Table 8). Similar trends occur with the log tear index models, although the combinations of significant predictor variables can be different; coarseness and length for Tree-set16, and coarseness, length and glucose content for Tree-set13.

The significant and highly significant contributions of all five wood and fibre predictor variables in the combined sheet density and log tear index models (Table 8) is noteworthy. The combined model is based on a wide range of tree ages, seedling and clone origins, and selection criteria represented by the five radiata pine wood-types of Table 9; 13-year-old individual seedling-trees selected to cover the available range of tracheid perimeter and wall thickness combinations (or indirectly the range of wood density) (Tree-set13), 15 year-old individual seedling trees (Tree-set15), 16-year-old individual cloned-trees selected to cover the available range of density and fibre length combinations (Tree-set16), through mature slabwood and toplog wood-types from 27-year-old cloned-trees (Tree-set27). The 25 individual seedling-trees of Tree-set13 can be expected to contain the highest proportion of juvenile wood, with its shorter than normal fibres, small perimeter, thin walls, low coarseness and high MFA (2, 23, 24), compared to the other four wood-types (Table 9). The same cannot necessarily be said for the 22 individual cloned-trees of tree-set16 (11 clones x 2 ramets (3)), although the highly significant MFA effect might indicate a juvenile wood influence (Table 9).

Chip density is a highly significant effect in the five wood-types (Table 9), as well as the combined (Table 8), sheet density and log tear index models. In contrast, the remaining four wood-fibre predictor variables are significant or highly significant effects for some wood-types and not others (Table 9), but significant or highly significant in the combined sheet density model (Table 8). The following comments are made about each predictor variable based on the sign and magnitude of the coefficients in the sheet density and log tear index separate and combined regression models.

For the sheet density models:

- Chip density is consistent for all five data sets (varies from -0.420 to -0.671).
- Coarseness is consistent for 4 of the 5 datasets (varies from -0.051 to -0.081), and possibly anomalous for Tree-set16 (0.184).
- MFA is similar for 3 out of 5 data sets (1.71 to 2.80), high for Tree-set16 (5.35) and small and opposite sign for Toplogs data set.
- Fibre length is consistent in sign for all data sets, but highly variable in magnitude, and small for the Toplogs and Tree-set15 datasets.
- Glucose is similar for 3 out of 5 data sets (-7.06 to -8.90), and small for the Toplogs and Tree-set15 datasets.

For the log tear index models:

- Chip density is consistent for all five data sets (varies from 0.00147 to 0.00217).
- Coarseness is variable in sign and small in magnitude.
- MFA is variable in sign and small in magnitude.
- Fibre length is similar in sign and magnitude for 4 out of 5 data sets with a small coefficient for the Slabwood dataset.
- Glucose is similar 3 out of 5 datasets, and same in sign but small in magnitude for Toplogs and Tree-set16.

For the greater radiata pine sheet density and log tear index models:

- Chip density (or the wall thickness/perimeter ratio (7, 21)) accounts for the major proportion of the variation among trees and wood-types.
- Although the effects of MFA and glucose content can be highly significant, their influence on the proportions of unexplained variation can be small compared to that of Chip density and fibre length alone (Tables 4, 7, 8).
- Fibre coarseness, which is and indicator of fibre number(7), is the least important of the five wood/fibre variables in the prediction of sheet density and log tear index.

Tensile index, Stretch and T.E.A. index

The influence of each of the five wood/fibre predictor variables in the tensile index, stretch and T.E.A. index models is very different among the five wood-type models (Table 9), which are in turn very different from those in the corresponding combined models (Table 8). The five individual wood-type models are, however, statistically generally similar one to another for each of the three sheet properties, with the tree-set16 models consistently closest to being outliers (Table 10). Grouping of the five wood-types is therefore justified, with their wide range of wood/fibre properties giving clear indications as to their relevance in the combined tensile index, stretch and T.E.A. index prediction models (Table 8). Thus, the chip density and wood-fibre coarseness effects are highly significant, the MFA and glucose content effects considered significant or highly significant, while the fibre length effect is non-significant. It is noteworthy that the four wood/fibre property effects of chip density, coarseness, MFA, and glucose content are all highly significant in the stretch model, significant or highly significant in the T.E.A. index model, and non-significant through highly significant in the tensile index model. While the MFA and glucose content effects are non-significant in the tensile index model, their coefficients are of negative sign as expected, and they are significant in the tensile index models when chip density is replaced by SilviScan density (a poorer predictor variable). Note that SilviScan density has little to do with SilviScan, as the density of each radial strip is directly measured independently from its mass and volume. SilviScan is only used to generate a profile that can be weighted according to contribution to discs or trees. Chip density has the advantage that much larger sample sizes are involved, and the chips are representative of the raw material pulped.

Influences of juvenile wood on kraft pulp tensile index are clearly shown by the combined historical data of Table 7 and Figure 5 when compared to Table 8 and Figure 4. The lowered slope of the Tree-set13, butt-corewood and thinnings wood-types (Figure 5) is explained by their high proportions of juvenile wood with fibres of high MFA, low coarseness, thin walls, small perimeter and short length (2, 23, 24). Effects of using different combinations of predictor variables in the prediction of tensile index are indicated by the Tree-set13 data set as follows: chip density and fibre length alone (Figure 5); chip density, fibre length, glucose content and kappa number (Figure 4); and chip density, fibre length, glucose content, kappa number, and SilviScan coarseness and MFA (Figure 7).

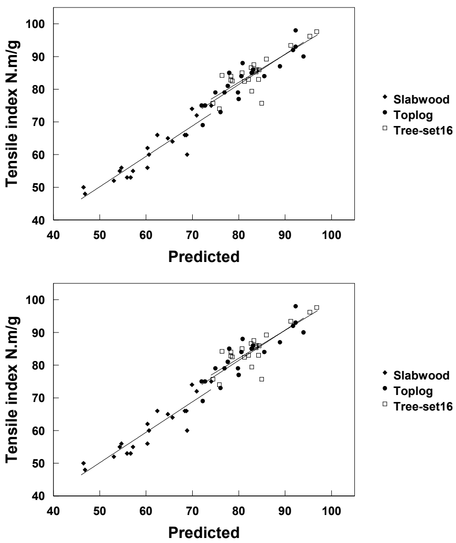

Figure 7: Actual versus predicted tensile index relationships for each of the three-clone (Tree-set16 and Tree-set27 (slabwood and toplogs)) and two seedling-tree (Tree-set13 and Tree-set15) wood-types (Table 9). Model predictor variables are chip density and kraft fibre length glucose content, SilviScan coarseness and MFA, and kappa number.

Some comments follow concerning wood/fibre property influences on the greater radiata pine tensile index, stretch and T.E.A. index prediction models (Table 8). For the purpose of this discussion the important wood/fibre predictor variables of density, coarseness, glucose content and MFA are described as follows:

- Density is a measure of the wood-fibre wall thickness/perimeter ratio, and in combination with glucose content and MFA is an indicator of fibre collapse resistance in pulp. Wood density, however, gives no indication as to the relative number of fibres in either wood or pulp.
- Coarseness is a measure of fibre mass per unit length, and, in combination with fibre length, is an indicator of the relative number of fibres in wood.
- Glucose content is an indicator of pulp yield, and in combination with wood-fibre coarseness and fibre length is an indicator of the relative number of fibres in pulp. It also is an additional influence on the pulp fibre wall thickness / perimeter ratio through its influence on the loss of material from the anisotropic fibre wall on pulping.
- MFA is a measure of the average angle of the microfibrils in a fibre wall relative to its axis. Pulp fibre extensibility increases and fibre collapse can be expected to decrease with increasing MFA.

An interpretation of these four wood/fibre property influences on the greater radiata pine tensile index, stretch and T.E.A. index prediction models (Table 8) is therefore:

- Tensile index increases as chip densities decrease (pulp-fibre collapse and sheet bonded areas increase), as wood-fibre coarseness and glucose content decrease (pulp-fibre numbers and specific surfaces, and sheet bonded areas increase), and as MFA decreases (although non-significant in this study).
- Stretch increases as chip densities decrease (pulp-fibre collapse and sheet bonded areas increase), as wood-fibre coarseness and glucose content decrease (pulp-fibre numbers and specific surfaces, and sheet bonded areas increase), and as MFA increases (pulp-fibre extensibilities increase).
- T.E.A. index increases as chip densities decrease (pulp-fibre collapse and sheet bonded areas increase), as wood-fibre coarseness and glucose content decrease (pulp-fibre numbers and specific surfaces, and sheet bonded areas increase), and as MFA increases (pulp-fibre extensibilities increase).

CONCLUSIONS

Handsheet property predictions for density, tensile index, stretch and T.E.A. index at 500 PFI mill rev, and log tear index at 1000 PFI mill rev, are strong ($R^2 > 0.90$) for a greater radiata pine data-set made up of a wide range of wood-types (whole-tree, toplogs and slabwood), tree-ages (13-28 years), and from cloned- and seedling-tree origins. The wood-type handsheet property models of Table 9 are generally similar for the two sets of radiata pine clones and two sets of seedling trees (respectively of 21 clones, 64 trees and ages 16 and 27 years, and 50 seedling trees, from 25 families, aged 13 and 15 years). Despite the diversity of wood types and sites of origin, combining the data has generally resulted in similar model root mean square error values for the combined (Table 8) and individual wood-type models (Table 9).

Sheet density and log tear index predictions are strong ($R^2 > 0.94$) with chip density, fibre length, and glucose as predictor variables. The sheet density model is modified when SilviScan wood coarseness and MFA are included in the predictor variable mix with each becoming significant. Coefficients of determination are, however, increased minimally. SilviScan coarseness and MFA are not significant predictors for log tear index.

As a sheet property group, tensile index, stretch and T.E.A. index are strongly influenced by chip density (a strong influencer of the pulp fibre wall thickness/perimeter ratio and pulp-fibre collapse), and wood-fibre coarseness (an indicator of pulp fibre numbers), and glucose content (an influencer of both pulp-fibre numbers and the pulp fibre wall thickness/perimeter ratio), and MFA (an indicator of pulp fibre extensibility). The three sheet properties are, however, not influenced by fibre length.

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