

WOOD DENSITY AND KRAFT FIBRE AND PULP PROPERTIES OF FOUR *PINUS RADIATA* PROVENANCES

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ABSTRACT

Four native provenances of *Pinus radiata* D. Don were sampled in a common environment for studying wood density (as chip density), kraft pulp yield at Kappa number 302, 10 pulp fibre properties, and four handsheet properties. Each provenance sample comprised a nominal 30 unrelated trees. Separate wood specimens were taken to represent toplog and slabwood material respectively. Within each of the eight provenance/wood-zone subclasses the trees were allocated at random to give duplicate bulked chip samples. Use of four refining treatments gave further replication and allowed various handsheet properties to be evaluated in relation to density, tear index, and tensile index.

The various properties were similar for the four provenances (Año Nuevo, Monterey, Cambria, and Guadalupe), except in the Guadalupe toplog material. Chip densities for the Guadalupe toplog and slabwood samples were surprisingly similar, and Guadalupe toplog fibres were short, slender, of low coarseness, stiff (high collapse resistance), and thus present in large numbers compared with those of the other toplog pulps. Opportunities for tree breeding could, therefore, involve selecting Guadalupe trees with high density and large numbers of slender tracheids of low coarseness in the corewood. Such selection should substantially improve corewood properties for both solid-wood products and pulping. Verification of the distinctive tracheid properties found in Guadalupe material is now needed.

Keywords: wood properties; fibre properties; pulp properties; handsheet properties; provenance; *Pinus radiata*.

INTRODUCTION

Much heritable tree-to-tree variation is known to exist in numerous wood properties of cultivated stocks of *Pinus radiata* (Cown *et al.* 1992; Burdon 1992; Shelbourne 1997). This variation gives great scope to improve by selective breeding the value of the wood, in terms of its processing characteristics and end-product values. Less well-known, however, have been the patterns of variation in these properties among the species' five native populations (provenances), especially for traits that govern pulping characteristics. Even so, it was known that the exploitation of provenance variation in wood density could be crucial for rapid attainment of a target value for the trait (Burdon 1992). At the same time, it has become clear that wood properties other than the basic physical properties that have traditionally

been studied can be very important for pulping (Corson *et al.* 1989; Kibblewhite & Bawden 1992; Matheson *et al.* 1997).

With these considerations in mind, plus a need to fell material, a study was made of kraft fibre and handsheet properties in four of the native provenances of *P. radiata*. This involved the four provenances for which material was readily available, at the same time excluding the one of least commercial interest. The study is described and the results are reported in this paper.

MATERIALS AND METHODS

Wood Sample Origins and Chipping

Thirty trees from each of four *P. radiata* provenances were chosen and felled from a provenance-progeny trial (Burdon *et al.* 1992) located in Cpt 918, Kaingaroa Forest, in the central North Island of New Zealand. Provenances involved were Año Nuevo, Cambria, and Monterey from mainland California (all var. *radiata*), and Guadalupe (var. *binata*). The trees were aged 31–32 years from planting. The trial contained around 50 open-pollinated families from each of the natural populations, with effectively full randomisation at the level of the individual tree. The mainland material was stratified into five well-separated “subpopulations” per provenance.

The sampling scheme involved 30 trees, one from each of 30 randomly chosen families, from each provenance. Trees that were subdominant or suppressed were avoided, being replaced by the next trees prescribed in the sampling scheme. A few trees had to be discarded, leaving specimens from 109 of the prescribed 120 trees, and there were a few accidental cases of duplicate trees per family. Replication of provenance material was achieved, in the face of cost considerations, by splitting each provenance sample into two nominal 15-tree lots (sets), taking alternate trees from the progeny list, essentially equalising between duplicates the representation from each locality within a provenance.

One sample of wood chips was taken from each of two positions in each tree:

- Slabwood: metre-long knot-free roundwood billets from the top of the butt logs (≥ 5 m height): the slabwood chips of each tree comprising the wood from outside the fifteenth growth layer from the pith, minus that involved in taking a 20-mm-thick bark-pith-bark slab used for mechanical testing.
- Toplog: similar roundwood billets containing 13 ± 1 growth layers from the pith were split down the centre and one half of the billet was chipped.

Wood was processed in the PAPRO laboratory chipper with acceptable chips passing through the 32-mm holes and being retained by the 6-mm holes of a Williams laboratory round-hole screen. At this stage, the chips of each nominal 15-tree lot were bulked together on an equal-o.d.-mass basis. Thus, the volume ratio of each tree included in a bulk 15-tree sample was determined by the reciprocal of the tree bulk density determined from discs taken at the top of the each butt log, and so the chips from trees of highest density were of smallest volume in the bulked samples.

In total, 16 bulked “15-tree” samples were made up of 4 provenances \times 2 “replicates” (nested within provenances) \times 2 wood types (slabwood and toplog). These samples became the basic experimental units.

Chip 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 (Cown 1980).

Pulping

Kraft pulps to kappa 30 ± 2 were produced for each of the 16 chip lots by varying the H-factor at constant alkali charge. The pulping conditions were:

- 16% effective alkali as sodium oxide
- 32% sulphidity
- 4:1 liquor-to-wood ratio
- 87 to 96 minutes to maximum temperature
- 170°C maximum temperature

Pulps were prepared in 2.0-litre 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. After dewatering and fluffing, kappa number, percentage rejects, and total yield were determined.

Handsheet Preparation and Evaluation

Handsheets were prepared and pulp physical evaluation was done 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 for 500, 1000, 2000, and 4000 rev. Handsheet physical evaluation data are reported on o.d. bases.

Fibre Dimension Measurement

Cross-section kraft-fibre dimensions of thickness (T), width (W), wall area, and wall thickness were measured using image-processing procedures (Kibblewhite & Bailey 1988) (Fig. 1). Measurements were made on dried fibres rewetted from handsheets. The product fibre-width \times fibre-thickness ($W \times T$) represents the minimum rectangle area and is an indicator of fibre cross-section size. The minimum area rectangle perimeter ($2 \times (W + T)$) is an indicator of fibre perimeter. The ratio width/thickness (W / T) is an indicator of the collapse resistance of the fibres. The greater the width and the lower the thickness of a fibre cross-section, the greater is the extent of fibre collapse. Relative number of fibres was calculated as the reciprocal of the product of fibre length and wall area. Length-weighted fibre length and fibre coarseness were determined with a Kajaani FS 200 instrument using Tappi T271 pm-91.

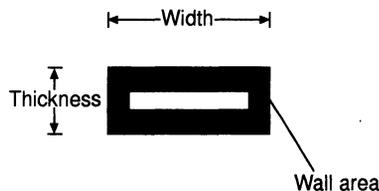


FIG. 1—Cross-section diagram of a fibre dried and rewetted from a handsheet

Statistical Analysis

Data were analysed using SAS Proc GLM (SAS 1989).

Initially, analyses of variance (ANOVAs) were performed for selected individual variables. Provenance and wood type and the provenance \times wood type interaction were treated as fixed effects, and the sets within provenance as a random effect. In the presence of provenance \times wood type interaction the differences among provenances were analysed separately for each wood type, using one-way ANOVA models.

Bivariate analyses were also carried out, mainly in the form of analyses of covariance (ANCOVA), reflecting the importance of combinations of properties in papermaking.

In addition to the basic classification of 4 provenances \times 2 replicate samples (i.e., sets) \times 2 wood types, the four refining treatments (500, 1000, 2000, and 4000 revolutions) for each pulp prepared provided a further element of replication by introducing apparent density, tear index, and tensile index as covariates in relation to other handsheet variables. Thus, provenance differences in one variable were tested after adjusting for the pooled within-subclass covariance (or regression) on another, independent variable. Where different refining levels introduced another level of replication, tests could be made of additional random effects, sets within provenances \times wood type if both wood types were considered, or sets within provenances if only one wood type was considered.

Where random effects were clearly negligible, the analyses were repeated with those effects omitted.

Pairwise differences between provenances were tested using the Ryan-Einot-Gabriel-Welsch multiple range test, which seems especially appropriate for the particular group of provenances (cf. SAS 1989, p. 942).

RESULTS AND DISCUSSION

Individual Variables

Values for individual determinations, involving only 500 revolutions for handsheet properties, are listed in Table 1. Among the variables ANOVA was used for handsheet apparent density @ 500 rev. PFI, chip density, Kajaani FS200 length-weighted fibre length, Kajaani FS200 coarseness, mean fibre perimeter, mean fibre wall area, mean fibre width/thickness ratio, and relative number of fibres.

The sets-within-provenance effect was statistically significant for coarseness ($p = 0.008$) and nearly so for chip density ($p = 0.07$). These differences are seen as a consequence of low-probability sampling differences between duplicate sets in wood density (in effect, as Type 1 errors), primarily for the Cambria provenance. This interpretation was well confirmed by cross-checking against independent wood-density determinations on discs from the top of each butt log (Table 2). Notwithstanding the statistically significant sets-within-provenances differences, it was deemed appropriate to pool this effect with the residual for the final univariate analyses. Results on this basis are summarised in Table 1.

Provenance differences overall were significant ($p < 0.05$) for all variables except chip density ($p = 0.07$) and apparent density and Kajaani fibre length ($p > 0.4$).

Wood types differed strongly for all variables tested statistically. In addition, the remaining handsheet properties showed the expected strong differences between wood types

TABLE 1—Chip density and kraft fibre and pulp data for replicate provenance samples

Wood zone	Prov.	Handsheet properties @ 500 PFI mill rev.				Chip density (kg/m ³)	Kappa No.	Pulp yield (%)	Kraft pulp fibre properties									
		Apparent sheet density (kg/m ³)	Tear index (mN.m ² /g)	Tensile index (N.m/g)	Stretch (%)				Length weighted average (mm)	Coarseness (mg/m)	Width (µm)	Thickness (µm)	Perimeter (µm)	Width × thickness (µm ²)	Wall area (µm ²)	Wall thickness (µm)	Width / thickness	Rel. No. fibres
Top	Año	661	12.8	80	2.38	394	29.9	47.7	2.72	0.236	34.5	12.4	93.8	431	263	3.85	2.97	81
		649	13.2	83	2.44	382	31.2	48.7	2.80	0.228	34.4	12.3	93.5	421	247	3.49	3.01	84
	Cam.	654	12.8	83	2.24	392	30.8	47.9	2.75	0.234	33.1	12.4	90.9	412	243	3.59	2.80	87
		670	11.4	93	2.37	357	31.5	48.6	2.76	0.221	35.0	12.3	94.7	432	248	3.48	3.04	85
	Mon.	656	12.1	82	2.32	386	31.6	47.4	2.72	0.235	34.8	13.3	96.4	463	275	4.00	2.78	78
		656	11.7	81	2.43	380	30.4	46.1	2.71	0.226	33.6	13.1	93.5	442	270	4.09	2.70	79
	Gua.	662	11.6	78	2.38	420	31.3	48.2	2.51	0.207	30.5	12.5	86.0	384	231	3.77	2.56	100
		665	12.0	79	2.42	428	31.9	47.4	2.51	0.204	31.5	12.5	87.9	395	233	3.63	2.66	99
Slab	Año	620	17.4	69	2.07	430	31.4	48.9	3.12	0.259	33.5	14.4	95.9	485	297	4.38	2.45	63
		625	19.0	69	2.12	426	29.1	47.1	3.08	0.253	34.5	13.5	96.1	465	279	4.09	2.72	67
	Cam.	584	26.3	62	1.76	467	28.4	48.6	3.21	0.263	32.2	14.2	92.7	459	285	4.48	2.38	63
		611	19.6	71	2.00	429	30.5	49.4	3.08	0.254	32.5	13.4	91.8	434	261	4.05	2.57	72
	Mon.	591	23.1	62	1.94	443	29.6	48.5	3.23	0.279	32.9	14.3	94.4	470	290	4.43	2.43	62
		612	19.4	69	1.97	424	30.2	49.5	3.08	0.270	33.7	14.4	96.2	490	298	4.36	2.49	63
	Gua.	592	22.5	63	1.75	464	29.1	48.9	3.11	0.267	31.5	13.4	89.8	424	265	4.30	2.46	70
		608	21.2	67	1.79	441	28.8	[52.4]	3.33	0.270	31.8	14.2	92.0	454	286	4.45	2.35	61
Differences (p)																		
Provenance		0.6	-	-	-	0.07	-	-	0.4	0.03	-	-	0.001	-	0.02	-	0.04	0.007
Wood type		<0.001	-	-	-	<0.001	-	-	<0.001	<0.001	-	-	0.07	-	<0.001	-	<0.001	<0.001
Interaction		0.2				0.3			0.04	0.006			0.2	0.5		0.4	0.02	

TABLE 2—Mean disc wood basic densities of replicate 15-tree bulk samples.

Provenance	Mean wood basic density (kg/m ³)	
	Bulk sample 1	Bulk sample 2
Año Nuevo	404	398
Cambria	424	396
Monterey	395	387
Guadalupe	429	426

(Kibblewhite & Bawden 1992), with toplogs giving high apparent density and tensile strength and low tear strength compared with slabwood.

Provenance \times wood type interaction was significant ($p < 0.05$) for coarseness, fibre length, and relative number of fibres. This interaction was manifested in the Guadalupe provenance having a smaller difference between toplog and slabwood wood types for chip density, and a larger difference between wood types for fibre length, coarseness, and relative number of fibres, compared with the other three provenances (Table 1).

Using one-way ANOVA involving only one wood type at a time:

- For the slabwood samples, provenance was a significant effect ($p < 0.05$) for the variable fibre perimeter. Provenance was not significant for any other variable tested. The mean fibre perimeter for the Guadalupe provenance was significantly lower than the Año Nuevo and Monterey means.
- For the toplog samples provenance was a significant effect ($p < 0.05$) for the variables fibre length, coarseness, perimeter, and wall area, and relative number of fibres. The mean fibre length for the Guadalupe provenance was significantly lower, and relative number of fibres significantly higher than for the other three provenances. Also, the Guadalupe coarseness, fibre perimeter, and wall area were significantly lower than the Año Nuevo and Monterey means. Furthermore, the Cambria wall area was significantly lower and the relative number of fibres significantly higher than for the Monterey provenance.

Toplog chip density and kraft fibre number, length, perimeter, and coarseness values were thus remarkably different for Guadalupe compared with the other three provenances. In contrast, corresponding slabwood wood and fibre properties are generally similar for all four provenances (Table 1). Thus, Guadalupe toplog pulps contain large numbers of fibres which are short, stiff (low width/thickness), slender, and of low coarseness compared with toplog pulps from the other provenances. It is noteworthy that the largest fibres (highest perimeters and width \times thickness products) generally came from the Año Nuevo and Monterey pulps for both toplogs and slabwood wood types. These provenances actually had the highest mean stem diameters in a study of discs taken next to the bolts used for pulping.

Bivariate Relationships

Properties with chip basic density as the covariate

Sheet density at 500 rev. PFI showed a strong negative association with chip density within provenance/wood-type subclasses overall ($R^2 = 0.68$) (Fig. 2). The salient difference about the general pattern was the much higher sheet density of Guadalupe toplog material in relation to chip density. This was reflected in significant ($p = 0.03$) provenance \times wood

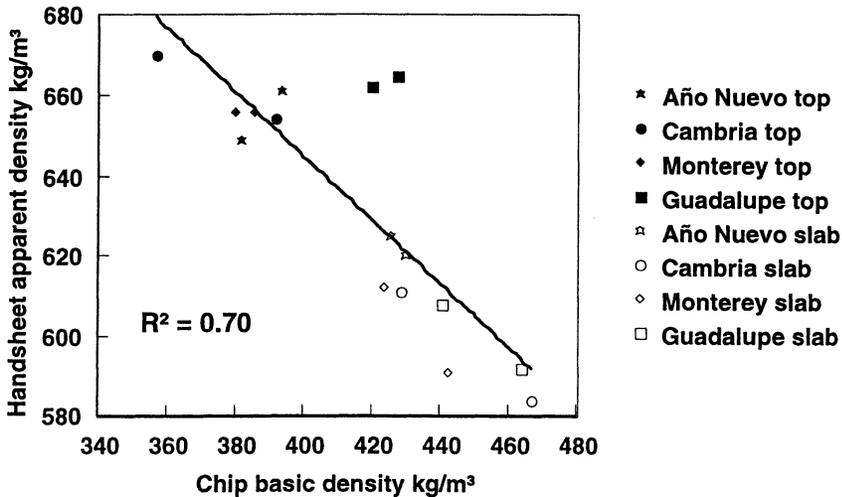


FIG. 2—Handsheets apparent density (@ 500 revolutions beating) v. chip basic density for toplog and slabwood pulps from all provenances. The R^2 value is the overall R^2 for straight-line regression using all of the data points plotted.

type interaction after adjustments were made in ANCOVA for within-subclass covariance on chip density. Significant differences in both the provenance and wood type main effects after the adjustment were interpreted as being mainly incidental to this fixed-effect interaction, although there was a significant ($p = 0.03$) provenance effect for the slabwood wood type. The high handsheet density of the Guadalupe toplog pulps was explained by a higher packing density being obtained with larger numbers of shorter, more slender, and low-coarseness fibres (Table 1) (cf. Kibblewhite & Shelbourne 1997).

Relative number of fibres showed a similar pattern (details not shown), the higher value in Guadalupe toplogs standing out strongly in relation to both a general negative association with chip density and a positive association with sheet density (although in neither case was the actual within-subclass regression statistically significant).

Width/thickness ratio also showed a strong negative relationship overall with chip density (Fig. 3). Although the pooled R^2 within provenance/wood-type subclasses (0.28) was much lower than either the overall R^2 of 0.76 (Fig. 3) or the corresponding within-subclass R^2 of 0.68 for sheet density on chip density, there was no significant residual effect of provenance, wood type, or interaction in ANCOVA adjusting for within-subclass covariance on chip density.

Handsheets property inter-relationships

The handsheet properties were evaluated at the four different PFI mill refining levels in order to compare the provenances and wood types for combinations of sheet properties. The covariance adjustment in each ANCOVA was made on the basis of the pooled regression within provenance/wood-type/set subclasses. Handsheet property data are available from the authors on request.

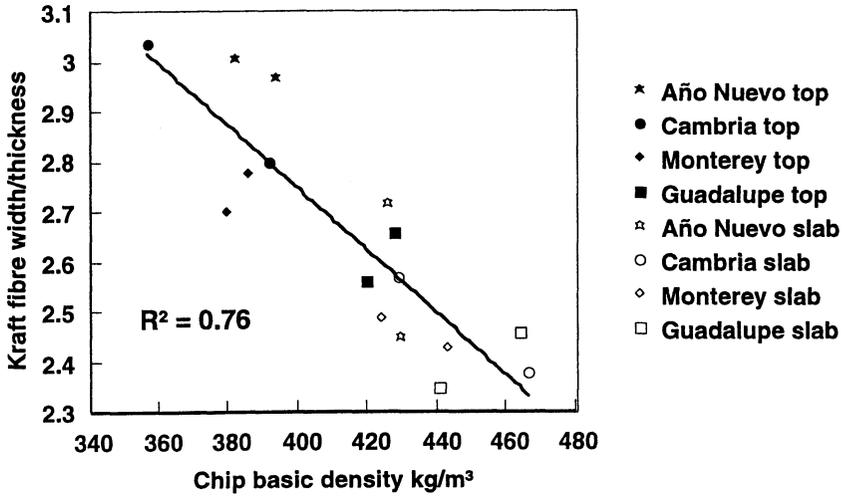


FIG. 3—Kraft fibre width/thickness v. chip basic density for toplog and slabwood pulps from all provenances. The R² value is the overall R² for straight-line regression using all of the data points plotted.

Tensile index was addressed as a dependent variable and with independent variables provenance, sets-within-provenance, wood type, and provenance × wood type, and with the covariate sheet density (Fig. 4). Given that certain sampling differences between sets within provenances were accommodated with the covariate, it was deemed appropriate to test provenances against sets-within-provenances. For this full model the provenance × wood type interaction was significant ($p = 0.0001$) and the sets-within-provenance random effect

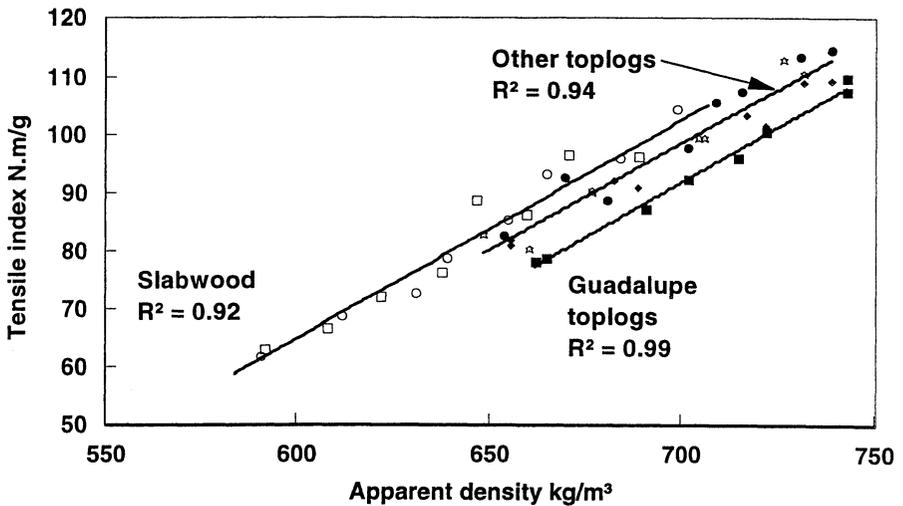


FIG. 4—Handsheet tensile index and apparent density relationships. Individual plottings are for provenance/wood-type/beating-treatment combinations. Filled symbols refer to toplog, and unfilled symbols refer to corresponding slabwood material. Symbol assignments for provenances are as indicated in Fig. 2 and 3. The R² values are overall R² for straight-line regression for each of the three categories labelled on the plot.

was nearly significant ($p = 0.08$). The provenance main effect was not significant, but the wood type main effect was significant. Each wood type was also analysed separately with tensile index as the dependent variable and with independent variables provenance, sets-within-provenance, and sheet density as the covariate. For slabwood the provenance effect was not significant. The slabwood sets-within-provenance random effect was significant ($p = 0.007$). For the toplogs analysis, sets-within-provenance differences were not significant, and the provenance effect was significant ($p = 0.006$), with the Guadalupe provenance having a significantly lower tensile index at a given sheet density. The displacement to higher apparent density values of the Guadalupe toplog regression compared to the regression for the other toplog pulps (Fig. 4) is accounted for by different fibre packing arrangements in the Guadalupe toplog handsheets. This occurs because the Guadalupe toplog fibres are long, slender, coarse (high wall area), resistant to collapse, and present in large numbers compared to those other toplog pulps (Table 1) (cf. Kibblewhite & Shelbourne 1997). The possibility of other factors being involved, such as fibre chemistry and fibre microfibril angle, is unlikely since the toplog pulps are of a similar kappa number (30 ± 2) and have similar handsheet tensile index and stretch relationships (Kibblewhite 1999).

Relationships between tear and tensile indices were quite different between the wood types (Fig. 5). In toplogs, tear index in relation to tensile index did not differ much among provenances, but the differences were statistically significant ($p = 0.02$) despite being of little practical significance, Año Nuevo showing the highest adjusted value and Guadalupe the lowest. It is suggested that the selection of Guadalupe corewood with long tracheids will give improved kraft handsheet tear indices (Kibblewhite & Shelbourne 1997). In slabwood the comparisons among provenances were complicated by significant curvilinearity, and apparently some residual heterogeneity of regressions and some sets-within-provenance

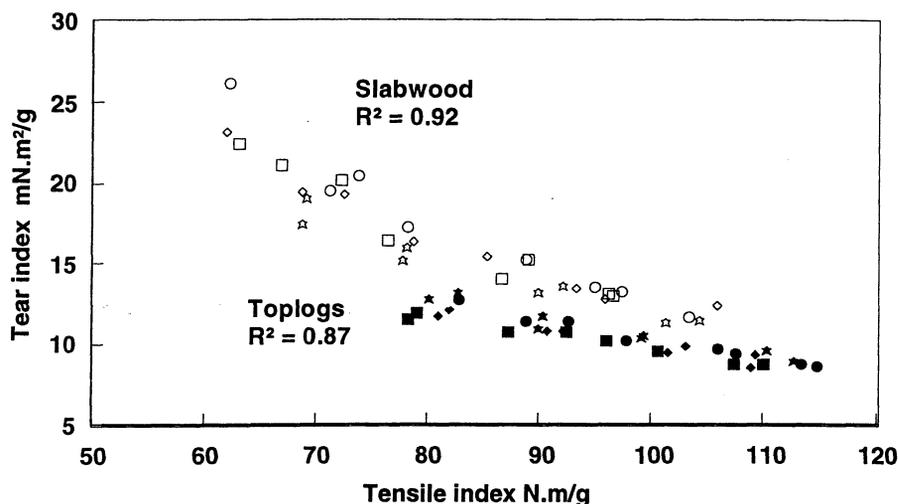


FIG. 5—Handsheets tear index and tensile index relationships showing what are relatively small/unimportant differences among provenances. Filled symbols refer to toplog, and unfilled symbols refer to corresponding slabwood material. Plottings and other symbol assignments are as indicated in Fig. 2 and 3. The R^2 values are overall R^2 for a quadratic regression using all slabwood data points, and a straight-line regression using all toplog data points.

differences. Hence, no real provenance differences could be inferred. Of note, however, was a high tear index at the 500 revolutions refining level for one of the Cambria sets (Fig. 5).

Tear-strength in relation to apparent density showed a similar pattern (Fig. 6), except that there were no significant differences among either provenances or sets within provenances after adjusting for covariance on apparent density.

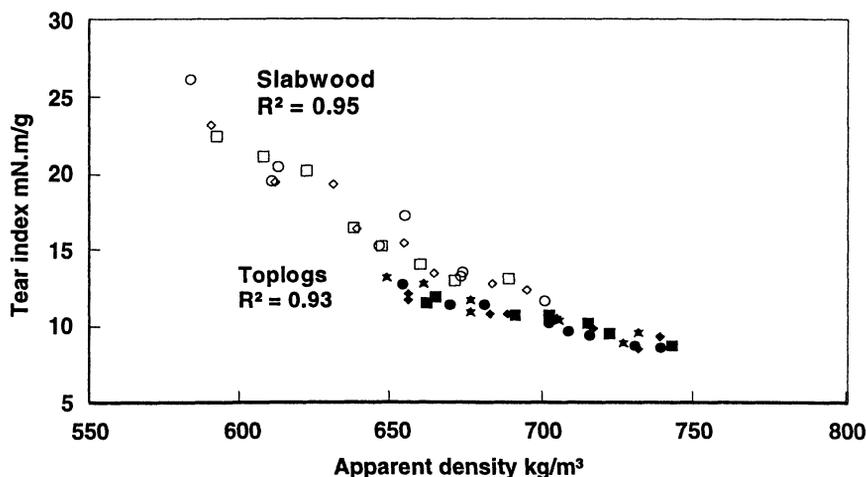


FIG. 6—Handsheet tear index and apparent density relationships. Filled symbols refer to toplog, and unfilled symbols refer to corresponding slabwood material. Plottings and other symbol assignments are as indicated in Fig. 2 and 3. The R^2 values are overall R^2 for a quadratic regression using all slabwood data points, and a straight-line regression using all toplog data points.

CONCLUSIONS

Chip density and kraft fibre and pulp properties of the slabwood were similar for the four provenances. In contrast, corresponding toplog chip density and kraft-fibre properties for the Guadalupe material were very different from those of the other three provenances. Guadalupe toplog chip density was high and tracheids were short, slender, of low coarseness, stiff (low width/thickness), and present in large numbers. A noteworthy concomitant feature was the minimal difference between Guadalupe toplog and slabwood chip-density values.

For tree breeding, there is the prospect of selecting Guadalupe trees with high density and high numbers of slender tracheids of low coarseness in the corewood compared to “ordinary” *P. radiata* trees. This should much improve the corewood properties, with some reduction in the pith-to-bark basic-density gradient, and thus enhance some solid-wood properties. For the kraft pulp end use, selective improvements in handsheet tear index could be expected through the selection of Guadalupe corewood with long tracheids.

The necessary first step of any further research, however, is verification of the distinctive Guadalupe wood and fibre properties by studying corewood from the tops of the butt logs (i.e., corewood from the billet where the slabwood was taken). Associated with this is a need to clarify the influence of tree vigour on the fibre properties.

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