

Kraft pulps from second-growth Douglas-fir: relationships between wood, fiber, pulp, and handsheet properties

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ABSTRACT Kraft pulps were produced from a broad range of juvenile and mature woods from 50-year-old second-growth Douglas-fir trees. Handsheets made from these pulps were tested for sheet density, tensile index, stretch, burst index, and tear index. These data were then statistically analyzed for the purpose of identifying and quantifying relationships between wood, fiber, pulp, and handsheet properties. Very strong correlations were found between handsheet properties and wood/chip density, fiber length, and fiber coarseness. Multiple linear regression analysis of the data yielded equations that predict pulp properties from wood and fiber properties.

Several options for using wood from managed second-growth Douglas-fir stands are presented. As rotation times are shortened, there is a marked increase in the proportion of juvenile wood. The industry can maximize the end-use potential of managed forests by chipping juvenile and mature wood separately and then combining the chips in different ratios to produce kraft pulps with a wide range of properties.

KEYWORDS

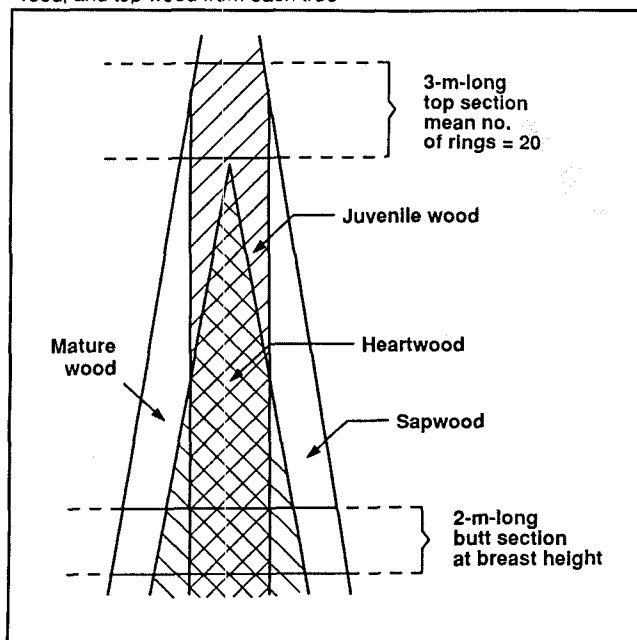
Density
End use
Fiber
 dimensions
Fiber length
Hand sheets
Juvenile wood
Kraft pulps
Mature wood
Pseudotsuga menziesii
Pulp properties
Rotation period
Secondary forest
Statistical
 analysis
Wood properties

The future of the Canadian forest industry will depend on the successful conversion of the second-growth resource into forest products. A managed second-growth resource will be characterized by faster growth rates, smaller log diameters, and shorter rotation times. The result will be a marked increase in the proportion of juvenile or core wood in Canada's forests. The physical and chemical

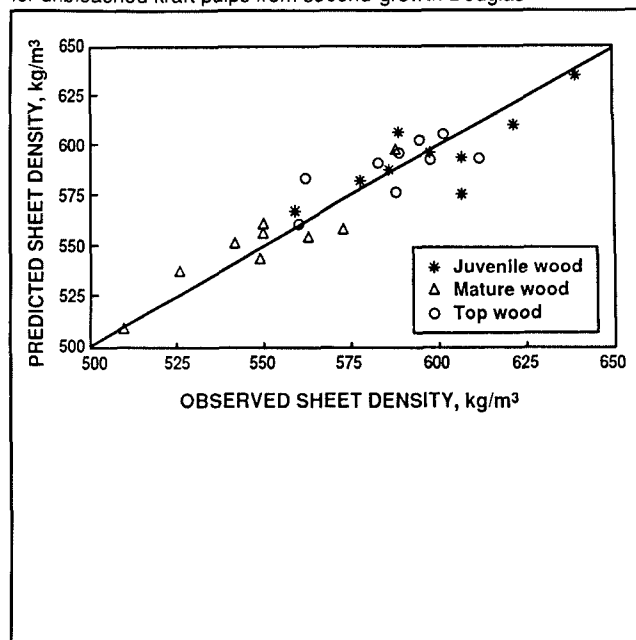
properties of juvenile wood differ in several respects from those of mature wood (1), and these differences must be quantified if the industry is to maximize the end-use potential of these second-growth stands. Information on the pulping and papermaking characteristics of juvenile and mature wood was recently obtained in earlier studies of second-growth Douglas-fir from Vancouver Island (1, 2).

In planning a new forest, or in preparing to use second-growth stands, it is important to understand the effects of wood density and fiber properties on pulp properties. We need to know whether an increase in wood density merely gives more woody material per cubic meter or, more importantly, whether there are useful relationships between wood, fiber, and handsheet properties. Such

2. Sampling scheme for removing butt juvenile wood, butt mature wood, and top wood from each tree



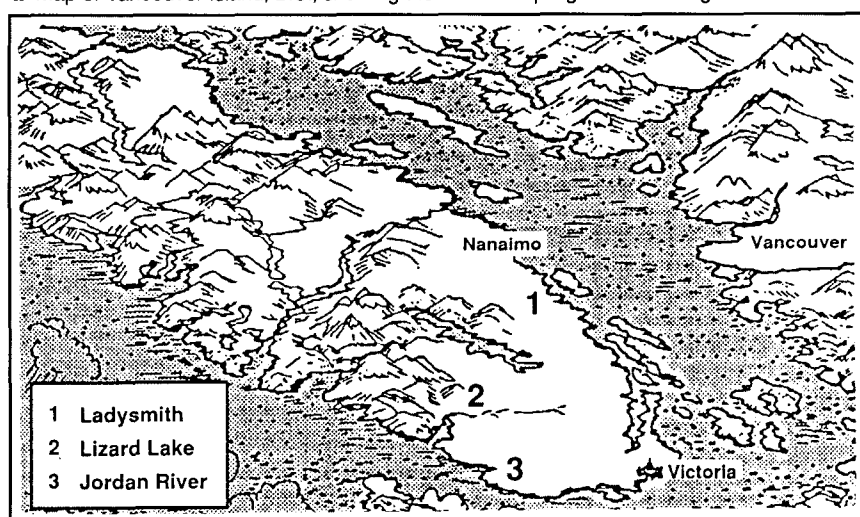
3. Predicted (CDEN, FC, FL) vs. observed values of sheet density for unbleached kraft pulps from second-growth Douglas-fir



relationships would be useful in (a) assessing the effects of stand management practices on the properties and quality of end products made from this resource and (b) predicting the pulp properties of improved planting stock.

Early work by Kellogg *et al.* (3-5) on western hemlock and by Matolcsy (6) on balsam fir are notable Canadian efforts to relate wood and fiber morphological properties to handsheet properties, particularly for softwood kraft pulps. The equations derived were quite successful in predicting the effects of changes in wood quality on pulp strength (5), although it was found that the physical properties of pulp handsheets could not be accurately predicted from fiber-dimension ratios (6). In much of this early pioneering work, fiber dimensions such as length, diameter, cell-wall thickness, and fibril angle could only be determined by tedious and often expensive methods in which accuracy was often at a premium. Rapid techniques for measuring fiber length (7), fiber coarseness (7), and fibril angle (8) have been developed recently. These techniques offer new approaches to, and increased incentive for, studies of relationships between wood, fiber, and handsheet properties. There is increasing evidence that for some species, particularly *Pinus*, kraft pulp

1. Map of Vancouver Island, B.C., showing the three sampling sites for Douglas-fir



handsheet properties are well correlated with wood density (or, correspondingly, chip density), alone or in combination with easily measured fiber properties such as length and coarseness. This is nicely illustrated by Semke's review (9) of the effects of juvenile fibers from loblolly and slash pine on kraft paper properties. Increasing juvenile wood density led to reduced bursting strength, breaking length, and handsheet density, while tearing resistance increased. These trends are qualitatively in agreement with those recently derived for second-growth Douglas-fir kraft

pulps from juvenile and mature wood (2).

During the past decade, detailed studies of Kibblewhite and co-workers (10-15) on *P. radiata* from New Zealand confirm these earlier studies and support even more strongly the high degree of correlation between chip density and various properties of kraft pulp handsheets made from trees ranging in age from 12 years to 52 years. This report presents relationships that were developed between wood, fiber, pulp, and handsheet properties of second-growth Douglas-fir kraft pulps. These rela-

I. Correlation coefficients (*r*) for handsheet properties* and wood/fiber properties

	Handsheet properties (dependent variables)					Wood/fiber properties (independent variables)				
	Sheet density	Tensile index	Stretch	Burst index	Tear index	Disc density	Chip density	Fiber length	Fiber coarseness	R14 fiber fraction
Sheet density	1.00	0.75	0.86	0.74	-0.75	-0.70	-0.71	-0.65	-0.68	-0.21
Tensile index	0.75	1.00	0.66	0.99	-0.63	-0.79	-0.82	-0.33	-0.37	0.18
Stretch	0.86	0.66	1.00	0.67	-0.58	-0.49	-0.49	-0.63	-0.74	-0.08
Burst index	0.74	0.99	0.67	1.00	-0.63	-0.80	-0.82	-0.31	-0.39	0.22
Tear index	-0.75	-0.63	-0.58	-0.63	1.00	0.72	0.71	0.75	0.31	0.54
Disc density	-0.70	-0.79	-0.49	-0.80	0.72	1.00	0.99	0.25	0.17	-0.02
Chip density	-0.71	-0.82	-0.49	-0.82	0.71	0.99	1.00	0.26	0.20	-0.05
Fiber length	-0.65	-0.33	-0.63	-0.31	0.75	0.25	0.26	1.00	0.57	0.70
Fiber coarseness	-0.68	-0.37	-0.74	-0.39	0.31	0.17	0.20	0.57	1.00	0.03
R14 fiber fraction	-0.21	0.18	-0.08	0.22	0.54	-0.02	-0.05	0.70	0.03	1.00

* Handsheets prepared using unbleached kraft pulps made from second-growth Douglas-fir after 1000 rev in PFI mill.

tionships can be used to plan strategies for optimizing the use of second-growth Douglas-fir resources and to predict pulp properties from wood and fiber characteristics.

Materials and methods

Site, tree, and sample selection

Second-growth Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] was chosen from three sites on Vancouver Island, illustrated in Fig. 1. Three trees were selected from each site, one tree each of low, medium, and high density. Wood density was determined in the field using breast-height increment cores. A wide range of wood density was chosen because this would provide data with sufficient scope to derive meaningful relationships between wood density and other wood and pulp properties.

Three samples—juvenile wood and mature wood from the butt, and top wood—were taken from each tree using the sampling scheme depicted in Fig. 2. (Juvenile wood was defined as the innermost region of 20 annual rings, i.e., the inner cylinder of wood that surrounds the pith from the base to the top of the stemwood.) Two adjacent 1-m-long bolts were taken from the butt, and two adjacent 1.5-m-long bolts were removed near the 80% total-height position, where the number of annual rings varied from

17 to 23. These top-wood samples were mostly juvenile wood, contained heartwood in the first 8–10 annual rings, and served as an internal check on the juvenile wood from the breast-height bolts, which were all heartwood. Top-wood samples represent, but are not identical to, material typical of thinnings of a similar age. The bolts were transported to the Vancouver laboratory and stored frozen until processed.

Chip preparation

After thawing, the butt and top-wood bolts were debarked. The butt bolts were slabbed on a handsaw to produce sections of juvenile wood and mature wood. These sections of juvenile wood, mature wood, and top wood were chipped in a CAE six-knife disc chipper to provide chips for kraft pulping trials. Each of the 27 chip samples (3 sites × 3 trees × 3 components) was screened to remove over-size and fine material and was homogenized before representative samples were taken.

Kraft pulping

Four-kg quantities (o.d. wood basis) of each of the 27 chip samples were individually cooked in a 28-L Weverk laboratory digester to give bleachable-grade kraft pulps with a Klason lignin content of 5%. All pulps were

washed, screened, and processed as described in a previous work (2).

Fiber properties

Representative samples of more than 20,000 fibers from each of the 27 bleachable-grade kraft cooks were analyzed for fiber length and coarseness using a Kajaani FS-100 instrument.

Handsheet properties

Representative samples of each of the 27 bleachable-grade kraft pulps were beaten in a PFI mill across the range of 0–12,000 rev. Handsheets were made and tested for bulk and mechanical properties using TAPPI test methods.

Analytical methods

The effects of wood and fiber properties on the bulk and mechanical properties of handsheets were determined on kraft pulps that had been lightly beaten (refined for 1000 rev) in a PFI mill. This basis of comparison was considered to be the most meaningful because, as recommended by Kibblewhite (10), it allows all pulps to be subjected to a limited, but similar, amount of mechanical treatment before sheetmaking. In addition, light beating of Douglas-fir kraft pulps ensures that maximum values of tear index are obtained.

Multiple linear regression analysis was carried out using handsheet properties of sheet density, tensile index, stretch, burst index, and tear index as dependent variables. The independent variables were the wood and fiber properties of disc density (1), chip density (1), weight-weighted fiber length (2), and fiber coarseness (2). A fifth variable, R14 fraction (2), was included in this group even though it was highly correlated with fiber length ($r = 0.70$), as seen in the correlation matrix depicted in Table I. (Klason lignin in wood was also investigated as a sixth independent variable and was found to be significant in the regression equations for predicting stretch and tear index.) Multiple linear regression analysis was carried out with the objective of developing equations for predicting the bulk and mechanical properties of kraft pulp handsheets from measured fiber characteristics produced from wood of a given density.

Values of sheet density, tensile index, stretch, burst index, and tear index for the 27 bleachable-grade kraft pulps beaten to 1000 rev in a PFI mill are shown in Table II. The means, standard deviations, minima, and maxima of the 27 values for each of these dependent variables were computed. These summary statistics are presented in Table III. Note that the regression equations developed using these data are not valid for values below the minimum or beyond the maximum for each independent variable.

A correlation coefficient was computed for each pair of variables (Table I), and tests for significant linear correlation were performed. Such tests are useful for pairs of dependent variables (handsheet properties) because a significant linear correlation ($r > 0.99$) between any pair indicates that one variable can be determined from the other. In the case of independent variables (wood or chip density and fiber properties), significant linear correlation between two variables suggests that only one need be included in a regression equation, since inclusion of both variables would not improve the predictive power of the equation.

Linear regression equations for each of the five dependent variables (sheet density, tensile index, stretch, burst index, and tear index) were

II. Handsheet properties for pulps prepared from wood obtained at three sampling sites^a

Tree no.	Wood sample ^b	Sheet density, kg/m ³	Tensile index, N·m/g	Stretch, %	Burst index, kPa·m ² /g	Tear index, mN·m ² /g
<u>Ladysmith</u>						
7	JW	559	78	2.66	5.8	26.4
	MW	510	65	2.46	4.5	39.5
	TW	595	84	2.97	6.5	19.7
2	JW	589	84	3.10	6.6	24.6
	MW	550	74	2.85	5.3	30.7
	TW	583	82	2.91	6.5	20.5
9	JW	640	97	3.13	7.3	17.6
	MW	588	77	2.70	5.8	26.6
	TW	602	85	2.95	6.5	18.9
<u>Lizard Lake</u>						
9	JW	578	65	2.90	4.6	19.4
	MW	526	58	2.60	4.1	27.1
	TW	562	68	2.68	4.9	18.9
7	JW	586	72	2.73	5.2	21.9
	MW	542	68	2.54	5.1	31.3
	TW	598	90	2.85	6.7	16.6
5	JW	607	77	2.98	5.8	19.0
	MW	550	64	2.55	4.8	25.9
	TW	589	85	2.68	6.3	14.3
<u>Jordan River</u>						
6	JW	598	70	2.98	5.1	22.5
	MW	563	64	2.72	4.6	29.5
	TW	560	81	2.69	6.1	19.9
2	JW	607	73	2.94	5.4	20.7
	MW	549	65	2.73	4.7	31.2
	TW	588	82	2.89	6.3	18.7
8	JW	622	82	3.03	6.1	20.1
	MW	573	73	2.74	5.3	30.5
	TW	612	89	3.02	6.8	18.9

^a Handsheets prepared using unbleached kraft pulps made from second-growth Douglas-fir after 1000 rev in PFI mill.

^b JW = juvenile wood; MW = mature wood; TW = top wood.

III. Summary statistics for data used to develop the prediction equations for Douglas-fir kraft pulps

Variable	Sample size	Mean	Standard deviation	Minimum	Maximum
Sheet density (SHEET), kg/m ³	27	579.0	30.0	510.0	640.0
Tensile index (TENS), N·m/g	27	76.0	9.6	58.0	97.0
Stretch (STRCH), %	27	2.82	0.18	2.46	3.13
Burst index (BURST), kPa·m ² /g	27	5.7	0.8	4.1	7.3
Tear index (TEAR), mN·m ² /g	27	23.4	5.9	14.3	39.5
Disc density (DDEN), kg/m ³	27	426.0	57.0	319.0	558.0
Chip density (CDEN), kg/m ³	27	420.0	51.0	325.0	534.0
Weight-weighted fiber length (FL), mm	27	2.94	0.27	2.39	3.48
Fiber coarseness (FC), μg/m	27	218.0	25.0	170.0	269.0
R-14 fraction (R14), %	27	58.5	10.4	31.0	73.5

IV. Development of one-, two-, and three-variable models for predicting handsheet properties from density and fiber properties

Dependent variable	Number of independent variables in model	Disc density	r^2	Chip density	r^2
Sheet density	1	DDEN	0.50	CDEN	0.50
	2	DDEN, FC	0.82	CDEN, FC	0.80
	3	DDEN, FC, FL	0.86	CDEN, FC, FL	0.85
Tensile index	1	DDEN	0.63	CDEN	0.67
	2	DDEN, FC	0.69	CDEN, FC	0.71
	3	DDEN, FL, R14	0.79	CDEN, FL, R14	0.80
Stretch	1	FC	0.55	FC	0.55
	2	DDEN, FC	0.69	CDEN, FC	0.67
	3	DDEN, FC, FL	0.72	CDEN, FC, FL	0.71
Burst index	1	DDEN	0.63	CDEN	0.67
	2	DDEN, FC	0.70	CDEN, FC	0.72
	3	DDEN, FL, R14	0.82	CDEN, FL, R14	0.83
Tear index	1	FL	0.56	FL	0.56
	2	DDEN, FL	0.85	CDEN, FL	0.84
	3	DDEN, FL, R14	0.89	CDEN, FL, R14	0.88

V. Three-variable equations for predicting kraft pulp handsheet properties using disc density as an independent variable

Dependent variable	Independent-variable coefficients ^a					r^2	95% prediction interval ^b
	Intercept	DDEN	FC	FL	R14		
Sheet density	902.8	-0.297	-0.520	-28.694	...	0.861	579.0±25.0
Tensile index	149.5	-0.110	...	-19.285	0.512	0.789	76.0±10.1
Stretch	4.58	-0.001	-0.004	-0.142	...	0.723	2.87±0.21
Burst index	12.1	-0.010	...	-1.794	0.050	0.824	5.5±0.8
Tear index	-38.5	0.065	...	8.605	0.153	0.889	23.4±4.5

^aValid for values within the range of minimum-maximum values for each independent variable (see Table III).

^bComputed at the mean value of each independent variable (see Table III).

VI. Three-variable equations for predicting kraft pulp handsheet properties using chip density as an independent variable

Dependent variable	Independent-variable coefficients ^a					r^2	95% prediction interval ^b
	Intercept	CDEN	FC	FL	R14		
Sheet density	910.1	-0.325	-0.492	-29.915	...	0.847	579.0±27.0
Tensile index	153.6	-0.125	...	-17.801	0.469	0.795	76.0±9.9
Stretch	4.59	-0.001	-0.004	-0.149	...	0.707	2.86±0.22
Burst index	12.4	-0.011	...	-1.666	0.047	0.829	5.6±0.8
Tear index	-40.6	0.073	...	7.917	0.175	0.882	23.6±4.6

^aValid for values within the range of minimum-maximum values for each independent variable (see Table III).

^bComputed at the mean value of each independent variable (see Table III).

developed using the chosen wood and fiber properties (disc or chip density, fiber length, fiber coarseness, and R14 fiber fraction) as independent variables. Models for each dependent variable were computed from the data obtained in this study using one, two, or three independent variables. In each case, the "best" model was defined as the one providing the highest r^2 for a given combination of independent variables. An F -test was performed whenever a new variable was added to the equation to determine whether it significantly increased the equation's predictive power (16). Finally, the predicted values vs. observed values for the chosen models were plotted for each dependent variable, and 95% confidence intervals for each dependent variable were computed at the mean value for each independent variable. The plots and confidence intervals provide measures of the predictive ability of the developed equations.

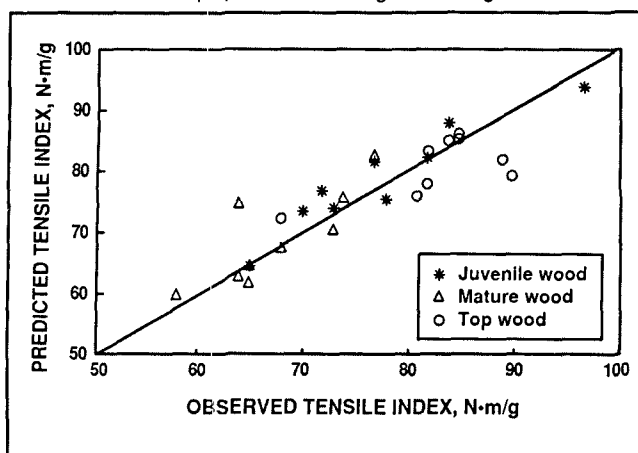
Results and discussion

Development of regression equations

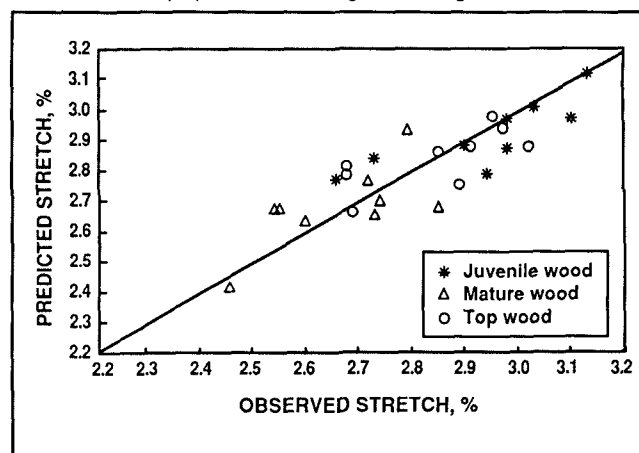
The summary statistics from the data used to develop the regression equations are shown in Table III. The broad ranges observed for each variable suggest that the predictive regression equations involving these variables should be widely applicable to the future Douglas-fir resource.

The correlation matrix in Table I shows that the most highly correlated pair of dependent values was tensile index and burst index ($r = 0.99$), as expected. Stretch was strongly correlated with sheet density ($r = 0.86$), while other pairs were moderately (yet significantly) linearly related. Among independent variables, disc density and chip density were highly correlated ($r = 0.99$), as shown previously (1). Disc density and chip density thus were not combined within any of the regression equations. Instead, one set of regression equations was developed using chip density as an independent variable, and another set was developed using disc density as an independent variable. The equations developed using chip density will be appropriate for quality control purposes during the pulping process. The equations using disc density will be more appropriate for

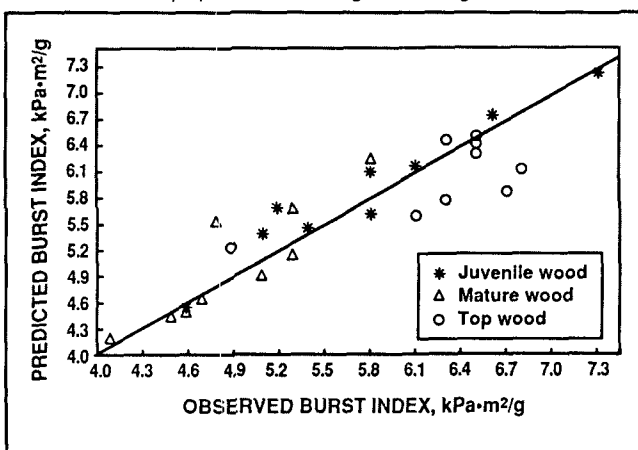
4. Predicted (CDEN, FL, R14) vs. observed values of tensile index for unbleached kraft pulps from second-growth Douglas-fir



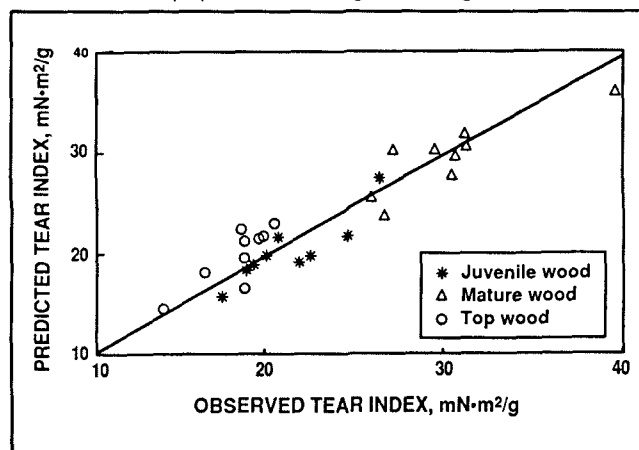
5. Predicted (CDEN, FC, FL) vs. observed values of stretch for unbleached kraft pulps from second-growth Douglas-fir



6. Predicted (CDEN, FL, R14) vs. observed values of burst index for unbleached kraft pulps from second-growth Douglas-fir



7. Predicted (CDEN, FL, R14) vs. observed values of tear index for unbleached kraft pulps from second-growth Douglas-fir



use in predicting handsheet properties for kraft pulps from trees with known disc densities.

Table IV shows the one-, two-, and three-variable models for predicting handsheet properties (sheet density, tear index, stretch, burst index, and tear index) from density (disc or chip) and fiber properties (coarseness, length, or R14 fraction). Values of r^2 show that for sheet density, tensile index, and burst index, the single most important variable was disc density (DDEN) or chip density (CDEN). The addition of fiber coarseness (FC) and weight-weighted fiber length (FL) produced significant increases in r^2 values. Although DDEN and CDEN were important single variables for the property of tear index, the best fit for a one-variable model was obtained with FL. The two-variable equations with FL and DDEN or CDEN gave signifi-

cantly larger r^2 values of 0.85 and 0.84, respectively. Fiber coarseness was the single most important variable for the property of stretch, with $r^2 = 0.55$. For stretch, the three-variable models were not significantly better than the two-variable models.

The three-variable predictive regression equations developed using disc density are shown in Table V. The corresponding equations for chip density are presented in Table VI. Figures 3-7 show the predicted vs. observed values of the five dependent variables based on the CDEN models in Table VI. As these figures show, the properties of kraft pulp handsheets—made from three different components within nine second-growth Douglas-fir trees of widely differing wood density—can be predicted and explained on a basis of wood or chip density, fiber length, and fiber coarseness.

This finding is important, not only because these three parameters can be relatively easily measured, but because with more research into the ways trees grow, we anticipate having a reasonable degree of control over these and other parameters in the future.

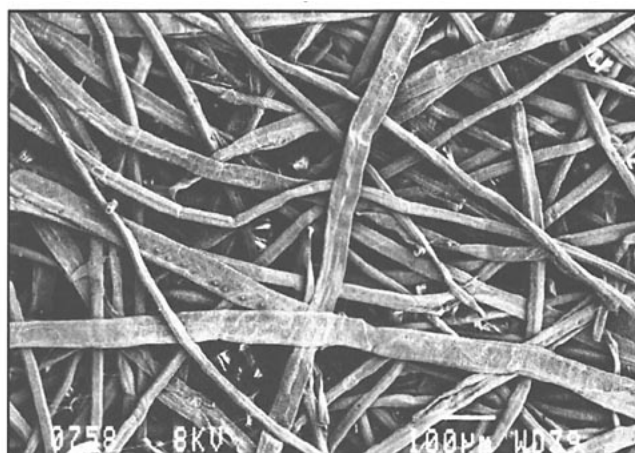
Options for utilization of shorter-rotation Douglas-fir

Future forest crops under some degree of management will be harvested in rotations shorter than those presently used. This change will bring about an increase in the ratio of juvenile to mature wood in a tree, depending on the relative growth rates of each wood type and the age of the tree at harvest. In the present study, the amount of juvenile wood in a stem, i.e., from the butt to the unmerchantable top, was determined to be 49% for Douglas-fir trees with a mean age of 50 years.

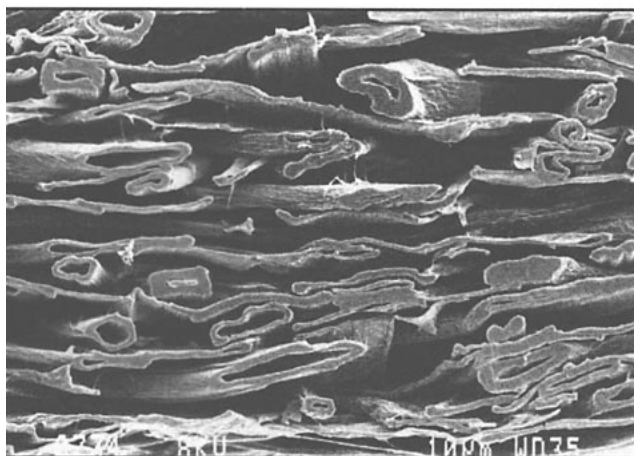
8. Surface of an unbleached kraft pulp handsheet made from juvenile wood (fiber coarseness = 170 $\mu\text{g}/\text{m}$; marker represents 100 μm)



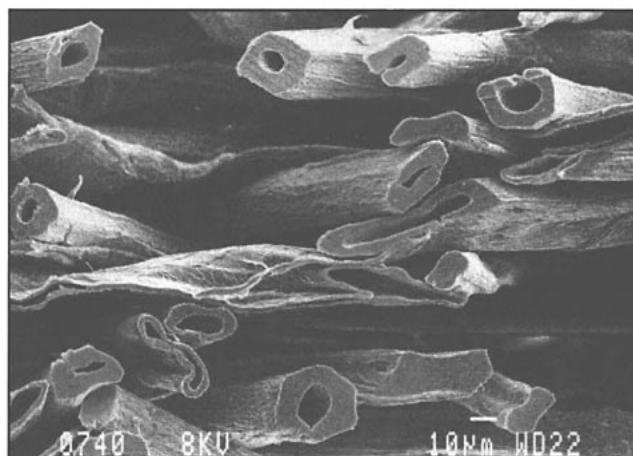
9. Surface of an unbleached kraft pulp handsheet made from mature wood (fiber coarseness = 269 $\mu\text{g}/\text{m}$; marker represents 100 μm)



10. Cross-sectional view of the thin-walled juvenile wood fibers in the handsheet of Fig. 8 (marker represents 10 μm)



11. Cross-sectional view of the thicker-walled mature wood fibers in the handsheet of Fig. 9 (marker represents 10 μm)



The following four options describe potential utilization of second-growth Douglas-fir for the production of kraft pulps if crop rotations are shortened and the proportion of juvenile wood increases.

Option A. Fifty-year-old trees are processed for solid products, and sawmill residual chips consisting of mature wood are processed into pulp. This would be equivalent to present practice, since the handsheet properties of kraft pulps from presently used mature wood (17–25) and those from mature wood of second-growth Douglas-fir trees are no different.

Option B. Fifty-year-old trees are sawn to segregate juvenile wood for use in pulping. Mature wood is converted to solid products with approximately 20% residual chips processed into pulp.

Option C. Fifty-year-old trees grown as pulpwood are sawn to segre-

gate juvenile and mature wood. Mature wood and juvenile wood chips could be processed for pulp either separately or together in prescribed ratios to produce pulps with specific qualities.

Option D. Managed Douglas-fir stands could be thinned at 20 years, for example. To a first approximation, the results for top-wood samples in the present study (1, 2) can be used to indicate the quality of kraft pulps from thinnings.

Table VII shows representative values of sheet density, tensile index, and tear index for juvenile wood, mature wood, and top wood, and the four utilization options. Clearly, increasing the quantity of juvenile wood (including thinnings) significantly reduces tear index, although it should be noted that tear index values of 20, while on the low side for Douglas-fir, are comparable with whole-stem

pulps from other Canadian softwoods. This tear reduction is offset to some extent by increased tensile index and sheet density. The ranges in values of sheet density, tensile index, and tear index suggest that this species offers a variety of utilization options whereby a range of kraft pulps with distinctive properties can be prepared.

The differences between juvenile and mature wood are illustrated clearly in Figs. 8 and 9, which are photomicrographs of the surfaces of handsheets made from juvenile wood (fiber coarseness = 170 $\mu\text{g}/\text{m}$) and mature wood (fiber coarseness = 269 $\mu\text{g}/\text{m}$), respectively. Figures 10 and 11 are photomicrographs of the corresponding cross sections of the same handsheets.

Summary and conclusion

The ability of the most basic wood property, density, and certain easily measured significant fiber properties to predict bulk and mechanical properties of handsheets was examined by multiple linear regression analysis. The kraft pulps used in this study were prepared from juvenile, mature, and top wood from nine trees of second-growth Douglas-fir ranging in density from 320 kg/m³ to 560 kg/m³.

Very strong relationships were found between major handsheet properties and wood or chip density, fiber length, and fiber coarseness. These findings are important because (a) the density and fiber properties can be measured with relative ease and (b) it is probable that wood and fiber properties can be controlled within a reasonable range as research continues to expand our insight into the ways in which trees grow.

There are several options for utilizing Douglas-fir on a shorter rotation. Consideration of these options

VII. Handsheet properties characteristic of selected utilization options for 50-year rotation Douglas-fir^a

Wood type and associated options ^b	Sheet density, kg/m ³	Tensile index, mN·m ² /g	Tear index, N·m ² /g
Mature wood	550	68	30
Option A	550	68	30
Option C (mature wood)	550	68	30
Juvenile wood	600	78	21
Option B	592	76	23
Option C (juvenile wood)	600	78	21
Top wood	590	83	19
Option D	590	83	19
Mixed wood			
Option C (mature + juvenile wood)	550-600	68-78	21-30

^aHandsheets prepared using unbleached kraft pulps from second-growth Douglas-fir after 1000 rev in PFI mill.

^bSee text for definition of Options A-D.

indicates that there is excellent potential for the production of kraft pulps with a wide range of properties suitable for many different end uses. □

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