

# Dimensional relationships among radiata pine wood tracheid, and chemical and TMP pulp fibres

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Softwood tracheid and pulp fibre dimensions can be indicators of the quality of a pulp and its suitability for use in the manufacture of specific paper products. There is a need to be able to use wood tracheid and/or pulp fibre dimensional data in the assessment of pulp qualities and processing effects, and ultimately in the production of designer fibres for specific product types and end uses.

In this paper softwood fibre cross-section dimensions are shown to be strongly influenced by the pulping process used, chemical and structural organisations within fibre walls, and the procedures used to prepare pulps for fibre measurement. Furthermore, latewood (but not earlywood) kraft fibre wall areas and wall thicknesses (but not perimeters) show high levels of variation when compared to those of corresponding wood tracheid, and TMP fibre properties, indicating different chemical and/or structural wall organisations for some fibres in latewood fibre populations.

## Keywords

Kraft, NS-AQ, soda-AQ, bisulfite, perimeter, wall area, wall thickness, coarseness

Relationships among wood tracheid/fibre, mechanical pulp fibre (TMP), and chemical pulp fibre properties are species, wood type, process and sample preparation dependent (1,2). Hence, fibre level comparisons are difficult and often misleading or confusing. For example, individual-tree radiata pine wood tracheid and kraft fibre properties of perimeter, but not wall thickness or wall area, have been shown to be strongly correlated one to another (3,4). Confusion centres about the poor wall thickness and wall area correlations. Hatvani et al. in a series of three papers indicates that the problem is related to the response of fibres to kraft

pulping and/or pulp sample preparation processes (5,6,7).

In this paper the wood tracheid, and kraft and TMP fibre, dimensions of the same 25 radiata pine trees (4,8) are compared, with the (SilviScan) wood tracheid (8) dimensions used as base. These results are interpreted in relation to published earlywood and latewood tracheid and kraft fibre dimensions (7) as well as a range of kraft and other chemical pulp fibre dimensional data (2). The primary objective of the research was to assess deviations from wood tracheid values to identify levels of fibre change and/or damage brought about by kraft, other chemical pulping processes, and TMP pulping.

## Fibre dimension measurement

Transverse tracheid dimensions are determined on SilviScan using image analysis and X-ray densitometry (9,10). The method uses a thin strip (2 mm wide x 7 mm high x core length) cut from a dried increment core or disc. Wood density, and tracheid radial and tangential diameters, are measured at 50  $\mu\text{m}$  intervals along the strip. Tracheid coarseness, outer perimeter (from radial and tangential diameters) and average wall thickness are generated from these primary measures.

Cross-sectional pulp fibre dimensions of thickness and width of the minimum-

bounding rectangle, wall area and wall thickness are measured using image processing procedures described previously (Fig. 1) (11). The ratio, width/thickness, is an indicator of the level of collapse of a dried and rewetted fibre. Measurements were made on dried and rewetted fibres reconstituted from TMP and kraft hand-sheets (4,8) or never-dried kraft, soda-anthraquinone (Soda-AQ) and neutral sulfite anthraquinone (NS-AQ) pulps stored at about 20% solids and 4°C (2,12). For the 25 individual-tree TMP pulps, freeness ranged from 79 to 114 CSF with two outliers at 122 and 146.

## RESULTS AND DISCUSSION

### Kraft and TMP pulp fibre dimension relationships

The fibre dimensions of perimeter, wall area and wall thickness are poorly or moderately correlated one with another (Fig. 2) for paired kraft and TMP pulps made from 25 individual-tree chip lots (4,8). Of the three fibre dimensions, perimeter is the most highly correlated property, as expected (3,4), although to a moderate level only ( $r^2 = 0.54$ ).

A poor level of correlation is also obtained for fibre collapse (width/thickness) when mean kraft and TMP pulps are compared (Fig. 3). Levels of correlation increase markedly when the basis of

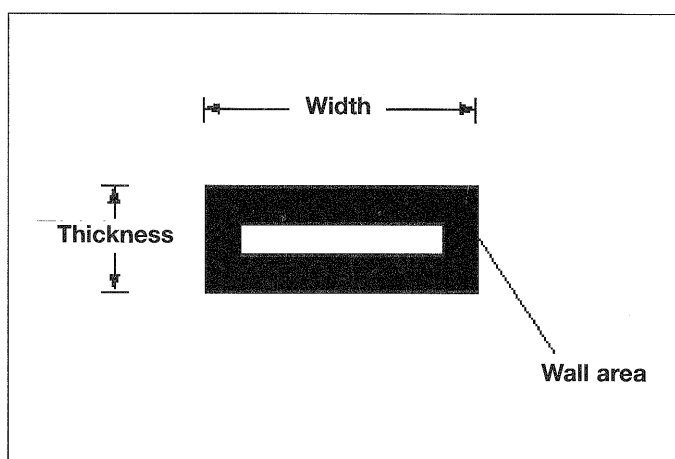
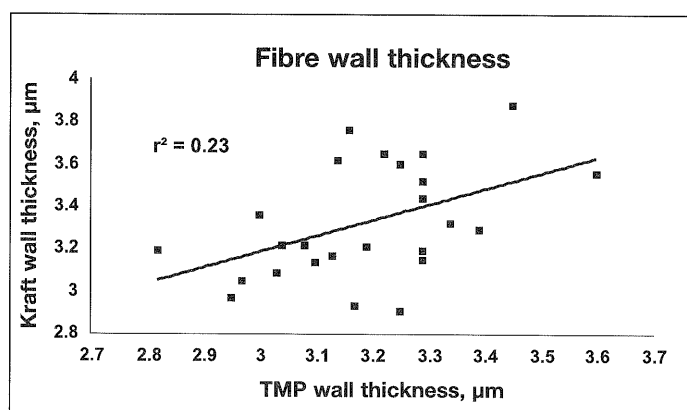
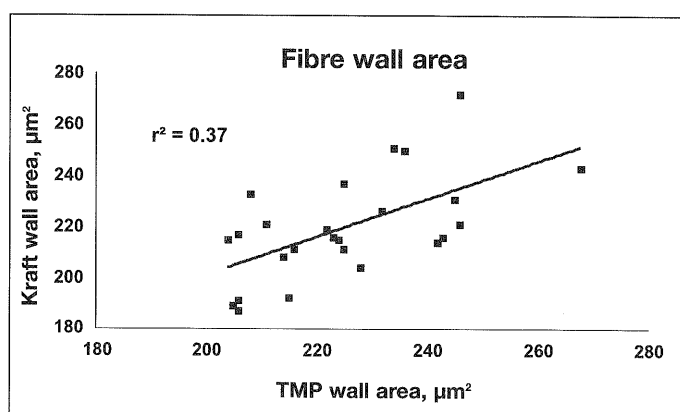
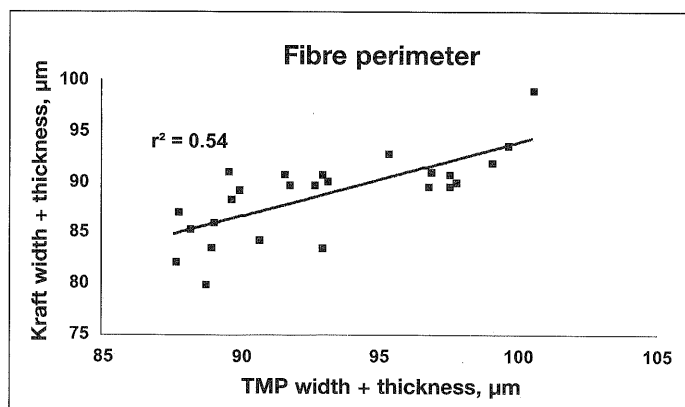


Fig. 1 Cross-section diagram of a fibre dried and rewetted from a handsheet.

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**Fig. 2** Interrelationships among individual-tree TMP and kraft pulp fibre perimeter, wall area and wall thickness. Fibres dried and rewetted from handsheets.

comparison is chip density (Fig. 4). Fibre collapse and chip density are compound kraft fibre and wood properties, which have been consistently shown to be strongly correlated one to another (13,14). The low coefficient of determination obtained for the TMP pulps ( $r^2 = 0.38$ ) reflects the small variation in TMP fibre collapse rather than high variation in regression residuals. In fact, the TMP correlation with chip density is clearly stronger than that of the kraft pulp (Fig.

4). It is suggested, therefore, that the poor wall area and wall thickness correlation between the paired TMP and kraft pulps could indicate different and non-predictable responses of all or some of the fibres in each individual-tree chip sample to either the kraft and/or TMP pulping process. For example, with TMP pulping different individual-tree chip lots could show different levels of selective earlywood or latewood damage. Alternatively, levels of fibre shrinkage with kraft

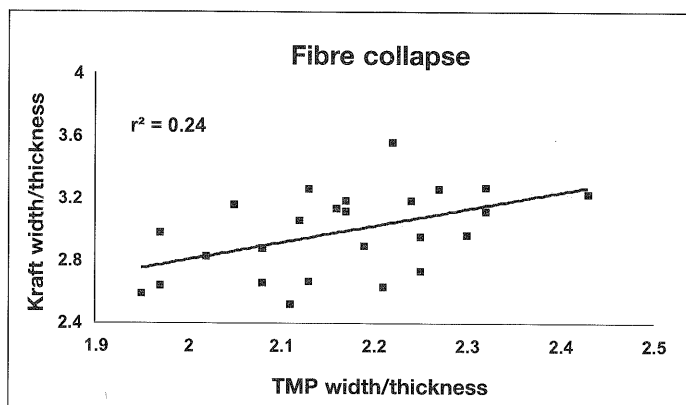
pulping could be different for earlywood and latewood fibres and/or for the fibres in different individual-tree chip lots.

### Wood tracheid, and kraft and TMP pulp fibre dimension relationships

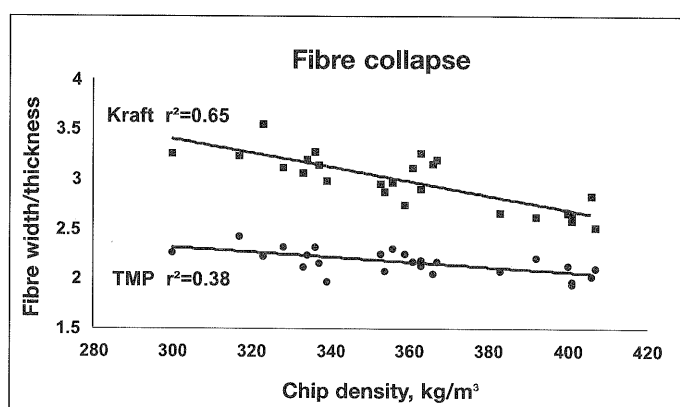
Kraft and TMP fibre properties are compared with corresponding wood tracheid properties as base (Fig. 5). Hence, any changes in mean individual-tree fibre properties brought about by pulping should be indicated through comparison with the mean individual-tree tracheid properties representing unprocessed trees.

Kraft and TMP pulp fibre dimensions of perimeter, wall area and wall thickness increase in accordance with corresponding wood tracheid values (Fig. 5, Table 1), as expected (3,4). The kraft pulp fibres are of smaller perimeter, but similar wall area, compared to those of the TMP fibres.

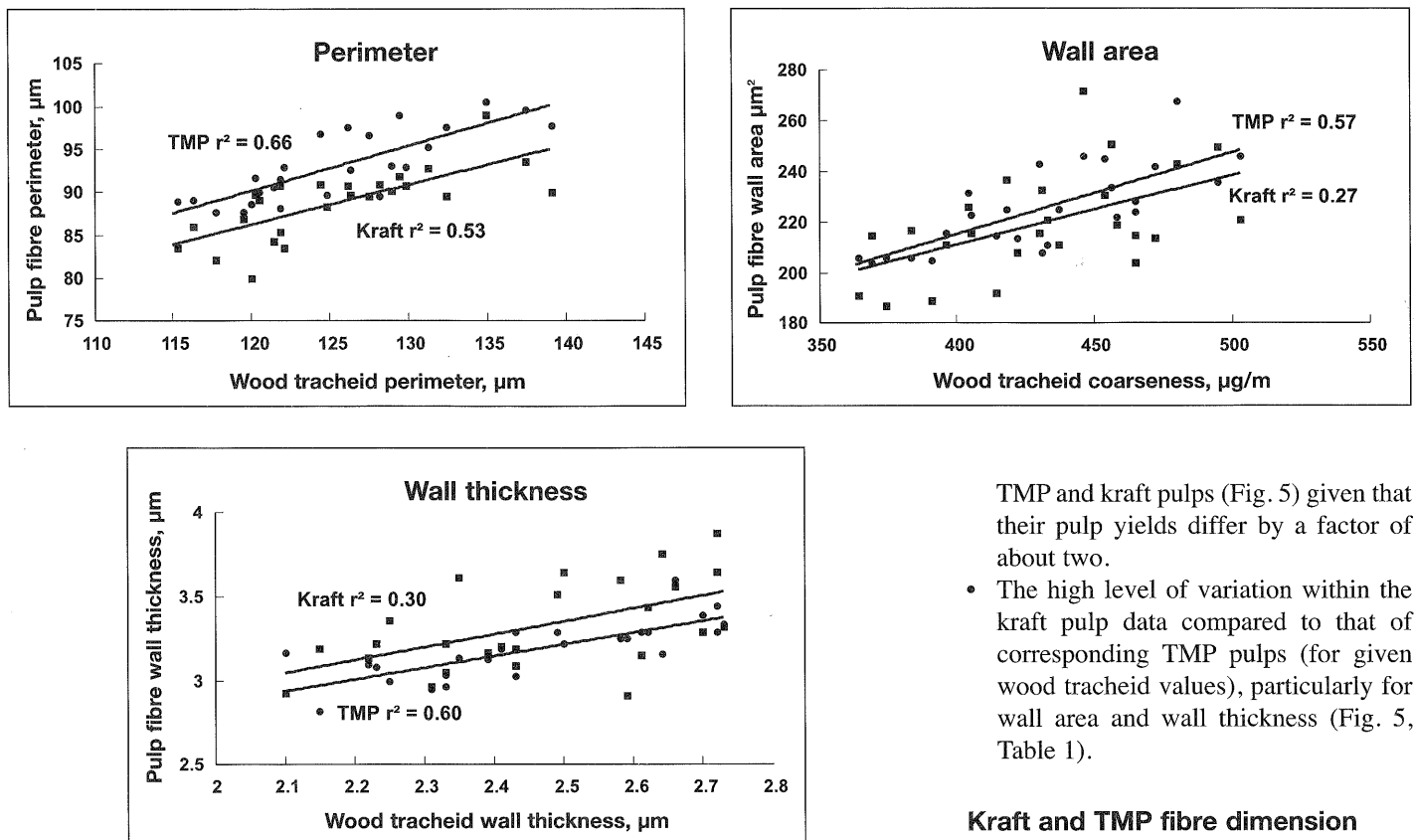
The wood tracheid dimensions of perimeter, wall area and wall thickness are good predictors ( $r^2 = 0.57$  to  $0.66$ ) of corresponding TMP pulp fibre dimensions (Fig. 5). In contrast, kraft fibre perimeter is the only cross-section dimension able



**Fig. 3** Fibre collapse relationships among 25 paired, individual-tree TMP and kraft pulps. Fibres dried and rewetted from handsheets.



**Fig. 4** Fibre collapse and chip density relationships among 25 paired, individual-tree TMP and kraft pulps. Fibres dried and rewetted from handsheets.



**Fig. 5** Interrelationships among the TMP and kraft pulp, and wood tracheid cross-section dimensions of perimeter, wall area and wall thickness. Fibres dried and rewetted from handsheets.

to be predicted to a moderate degree ( $r^2 = 0.53$ ) by a corresponding wood tracheid property. Kraft wall area and wall thickness variances of regression residuals (variation in kraft wall area and wall thickness not explained by the regression on wood tracheid dimensions) are significantly higher (F test at 5% level) than those for the TMP pulps (Table 1, Fig. 5). For fibre perimeter, on the other hand, variances of regression residuals are not

significantly different for the TMP and kraft pulps.

Coefficients of determination ( $r^2$ ) are similarly lower for the kraft than the TMP pulps for the ratio perimeter/wall thickness (Fig. 6). Such property ratios are highly relevant since they are indicators of fibre collapse (13,14).

Two noteworthy features are identified:

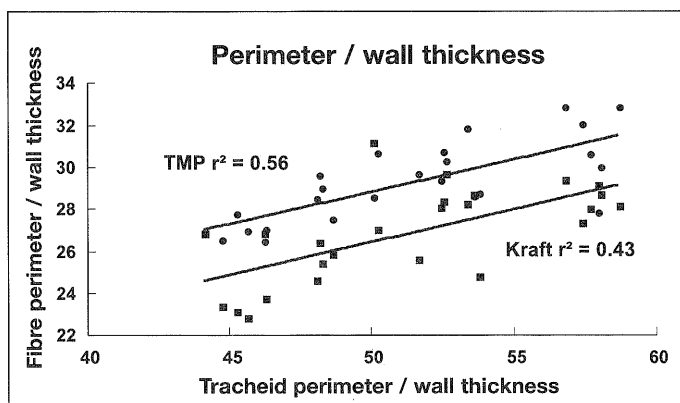
- The similar wall area and wall thickness values/regressions of the paired

TMP and kraft pulps (Fig. 5) given that their pulp yields differ by a factor of about two.

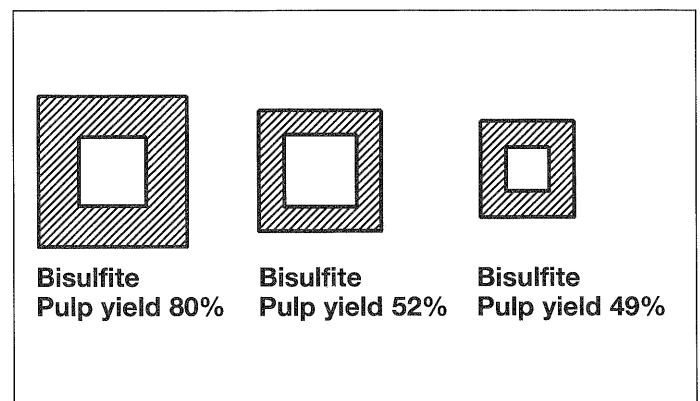
- The high level of variation within the kraft pulp data compared to that of corresponding TMP pulps (for given wood tracheid values), particularly for wall area and wall thickness (Fig. 5, Table 1).

#### Kraft and TMP fibre dimension differences

Based purely on pulp yield considerations, kraft fibre wall areas should be about half those of TMP fibres made from the same chip supply. This is certainly not the case since wall areas are roughly the same for the 25 TMP and kraft pulps (Fig. 5, Table 1). Two interactive factors are proposed to explain the large difference in kraft and TMP pulp yields and the small experimentally measured differences between the kraft and TMP fibre wall area values. Kraft and TMP wall thickness values are unable to be compared in this way because of the possibility that wall thickness might increase as fibre perimeter and pulp yield decrease during kraft



**Fig. 6** Interrelationships among the TMP and kraft pulp, and wood tracheid perimeter/wall thickness ratio. Fibres dried and rewetted from handsheets.



**Fig. 7** Fibre dimension changes with pulping for kraft and sodium bisulfite pulps. Fibres from never dried pulps stored at about 20% solids and 4°C (15).

**Table 1**  
Wood tracheid, and kraft and TMP fibre dimensions for 25 radiata pine trees (4).

Chip basic density kg/m <sup>3</sup>	Perimeter $\mu\text{m}$	Wood tracheid coarseness $\mu\text{g/m}$	Wall thickness $\mu\text{m}$	Perimeter $\mu\text{m}$	Kraft fibre wall area $\mu\text{m}^2$	Wall thickness $\mu\text{m}$	Perimeter $\mu\text{m}$	TMP fibre wall area $\mu\text{m}^2$	Wall thickness $\mu\text{m}$
300	128.9	405	2.22	90.2	216	3.14	93.1	223	3.10
317	124.4	404	2.33	91.0	226	3.22	96.9	232	3.04
323	132.4	437	2.33	89.6	211	3.05	97.6	225	2.97
328	134.9	446	2.35	99.0	272	3.62	100.6	246	3.14
333	126.3	383	2.15	89.8	217	3.19	92.7	206	2.82
334	121.4	391	2.31	84.4	189	2.97	90.7	205	2.95
336	139.1	472	2.41	90.0	214	3.21	97.8	242	3.19
337	127.5	430	2.43	89.6	216	3.19	96.8	243	3.29
339	121.8	364	2.10	85.4	191	2.93	88.2	206	3.17
353	126.2	454	2.62	90.8	231	3.44	97.6	245	3.29
354	116.3	369	2.25	86.0	215	3.36	89.1	204	3.00
356	122.1	414	2.43	83.6	192	3.09	93.0	215	3.03
359	131.3	495	2.72	92.8	250	3.65	95.4	236	3.29
361	128.2	433	2.39	91.0	221	3.17	89.6	211	3.13
363	120.0	374	2.23	80.0	187	3.22	88.7	206	3.08
363	129.8	465	2.59	90.8	204	2.91	93.0	228	3.25
366	129.4	480	2.66	92.0	243	3.56	99.1	268	3.60
367	137.4	503	2.61	93.6	221	3.15	99.7	246	3.29
383	120.2	418	2.50	89.8	237	3.65	91.8	225	3.22
392	119.5	431	2.64	87.0	233	3.76	87.7	208	3.16
400	117.7	422	2.58	82.2	208	3.60	87.7	214	3.25
401	121.8	456	2.72	90.8	251	3.88	91.6	234	3.45
401	124.8	465	2.70	88.4	215	3.29	89.7	224	3.39
406	120.5	458	2.73	89.2	219	3.32	90.0	222	3.34
407	115.3	396	2.49	83.6	211	3.52	89.0	216	3.29
				2.86*	17.8**	0.229**	2.47*	11.3*	0.111*

\* Root MSE of residuals from regressions on corresponding wood tracheid properties.

\*\* Significantly different level of variation among pulps compared to TMP pulps at the 5% level of significance. Note: the root MSE values for replicate kraft pulp wall area and wall thickness measurements on the same chip sample are 8.4  $\mu\text{m}^2$  and 0.13  $\mu\text{m}$  (16).

pulping (Fig. 7). It is proposed; therefore, that the similar kraft and TMP fibre wall area values are the result of experimentally induced artefacts brought about by the procedures used to prepare pulps for fibre dimension measurement (11) as follows:

- Levels of swelling during pulp rewetting can be expected to be significantly different for the dried lignin-rich TMP fibres compared to those of dried kraft fibres of low lignin content. Fibres are rewetted from handsheets by soaking in water overnight before subsequent dehydration and resin embedment. The requirement that fibre dimensions be determined for dried and rewetted pulps ensures that wall densities are comparable for the fibres within a pulp and among pulps prepared by the same process. Such an assumption is, however, considered to be invalid for fibres prepared by different chemical and/or mechanical processes as indicated by Figures 7, 8 (2).
- Levels of fibre shrinkage during the solvent exchange dehydration process are also expected to be significantly

different for lignin-rich TMP fibres compared to those of kraft fibres. Kraft pulps are strongly influenced by the level of polarity of the solvents used in the solvent exchange dehydration process (2).

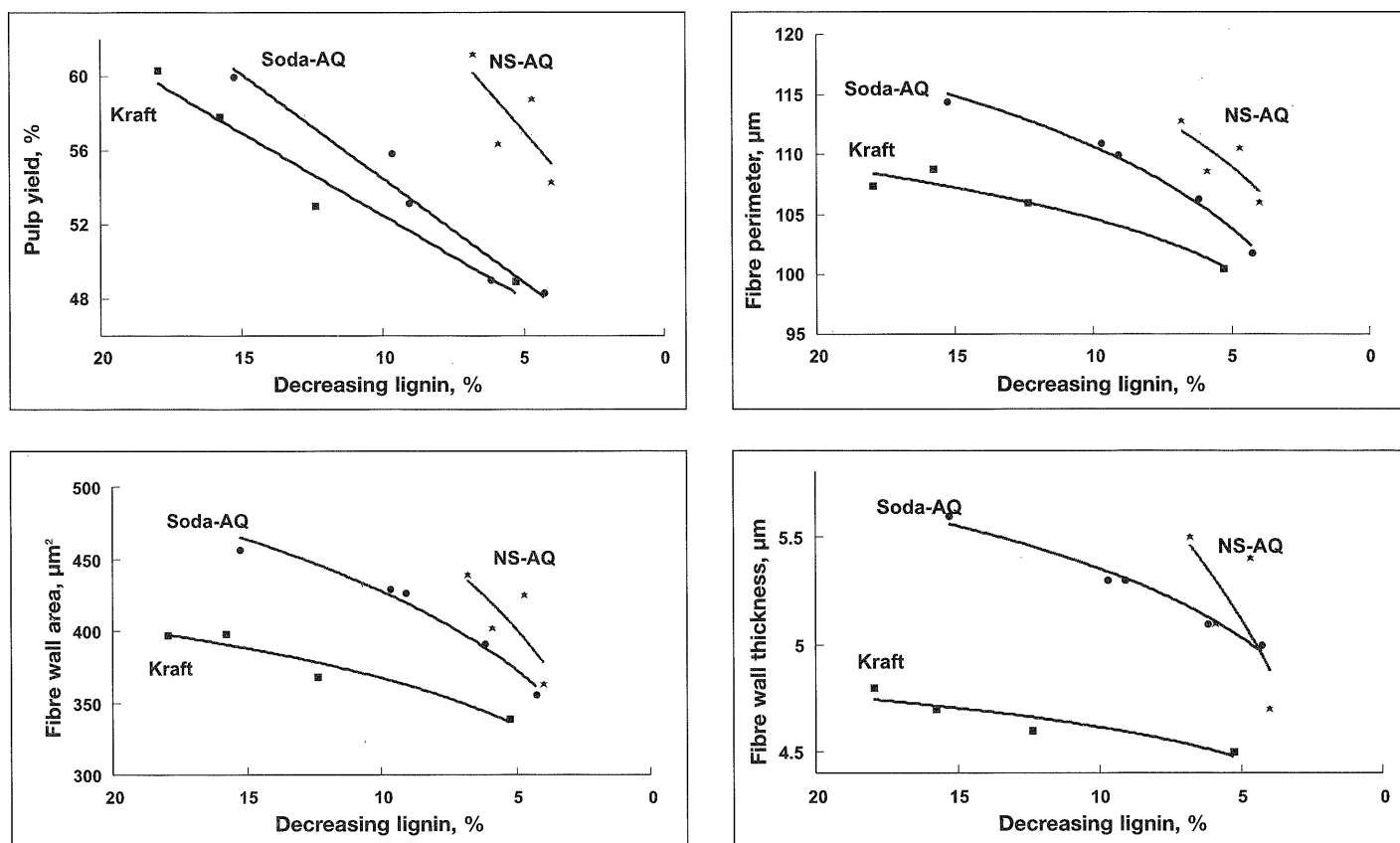
#### Kraft pulp fibre property variation

It is suggested that much of the measured high level of variation in kraft fibre

dimensions, compared to that in corresponding TMP pulps (Fig. 5, Table 1), could be the result of disproportionate shrinkage, during pulping, of earlywood and/or latewood kraft fibres. Such a hypothesis is supported by the very different fibre cross-section dimensions in pulps made by different chemical processes (Fig. 7 (15), Fig. 8 (2,12)). Fibre

**Table 2**  
Lignin and carbohydrate compositions based on yield for kraft, soda-anthraquinone (Soda-AQ) and neutral sulfite-anthraquinone (NS-AQ) pulps (12).

Process	Pulp yield %	Per cent composition based on pulp yield			
		Lignin	Glucose	Xylose	Mannose
Kraft	60.4	18	36.4	3.5	2.5
	57.9	15.8	36.7	3.2	2.2
	53.1	12.4	33.9	3.8	3.0
	49	5.3	37.9	3.2	2.6
Soda-AQ	60	15.3	36.5	3.9	4.3
	55.9	9.7	38.3	3.6	4.3
	53.2	9.1	36.7	3.1	4.3
	49.1	6.2	36.2	3.0	3.7
NS-AQ	48.4	4.3	37.4	3.2	3.5
	61.2	6.8	42.2	4.7	7.5
	58.8	4.7	42.8	5.0	6.3
	56.4	5.9	40.2	4.0	6.2
	54.3	4	40.5	4.5	5.3



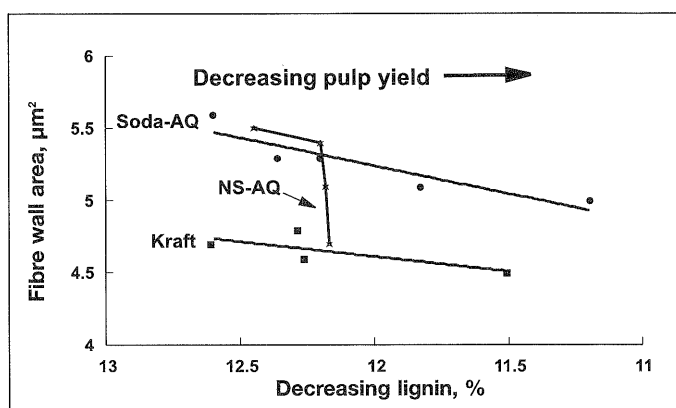
**Fig. 8** Pulp yield, lignin content and some fibre dimension interrelationships for kraft, soda-anthraquinone (Soda-AQ) and neutral sulfite anthraquinone (NS-AQ) pulps. Fibres from never-dried pulps stored at about 20% solids and 4°C (2,12).

perimeter, wall area and wall thickness decrease with decreasing kraft pulp yield and lignin content, with the major decreases occurring early in the pulping process when compared to some other chemical pulping processes (Fig. 8). Furthermore, lumen perimeter decreases with kraft pulping, but not with bisulfite or neutral sulfite-anthraquinone pulping (Fig. 7, 9). Kraft pulp hemicelluloses are also removed early during kraft pulping, with pulp hemicellulose contents lower than those made by some other chemical processes for a lignin content range 18 to 5.3% (Table 2) (12).

Hatvani et al. recently compared the tracheid and kraft fibre dimensions of extreme earlywood and latewood material using a range of measurement procedures (7). Data listed in Table 3 are taken from the Hatvani paper since tracheid and kraft fibre dimensions were determined with the same equipment and procedures as used to measure the TMP and kraft pulps of Fig. 2-6 (11). These earlywood/latewood data show extreme ranges in softwood tracheid and kraft fibre dimensions, particularly when compared to those of 25 individual-tree kraft pulps of normal earlywood/latewood proportions (Fig. 10).

Two features of interest are:

- The similar levels of kraft fibre perimeter variation at given wood tracheid values for the composite earlywood/latewood individual-tree, and earlywood and latewood pulps (Fig. 10). Kraft fibre perimeter variances of regression residuals are not significantly different (F test at 5% level) for either the individual-tree or earlywood and latewood pulps (Tables 1, 3).
- The low levels of earlywood kraft fibre wall area and wall thickness variation at given wood tracheid values, and the corresponding high levels of variation for the individual-tree and latewood pulps (Fig. 10). Kraft individual-tree and latewood fibre wall area and wall thickness variances of regression residuals are significantly higher (F test at 5% level) than those for the earlywood pulps (Tables 1, 3).



**Fig. 9** Fibre wall thickness and lumen radius relationships for kraft, soda-anthraquinone (Soda-AQ) and neutral sulfite anthraquinone (NS-AQ) pulps. Fibres from never dried pulps stored at about 20% solids and 4°C.

Table 3

Wood tracheid and kraft fibre dimensions for selected early and latewood from radiata pine and loblolly pine wood (7), and for 25 radiata pine trees (4).

Air-dried Density	Perimeter $\mu\text{m}$	Wood tracheid coarseness $\mu\text{g/m}$	Wall thickness $\mu\text{m}$	Perimeter $\mu\text{m}$	Kraft fibre wall area $\mu\text{m}^2$	Wall thickness $\mu\text{m}$
<b>Latewood</b>						
1037	112.2	803	6.15	70.58	223.3	5.28
1060	108.1	764	6.09	71.96	224.7	5.23
1057	106.0	730	5.92	70.16	201.3	4.70
1017	108.4	735	5.74	66.10	180.7	4.30
805	119.5	706	4.68	75.87	216.8	4.18
1017	97.5	586	5.06	63.37	162.4	4.12
921	105.8	637	4.95	65.98	168.5	4.05
774	112.2	588	4.10	67.77	155.8	3.30
				2.52*	14.2**	0.265**
<b>Earlywood</b>						
327#	138.1	385	1.97	78.57	131.7	2.06
340#	136.9	396	2.05	79.40	130.1	2.03
349	138.9	415	2.12	82.68	136.3	2.03
340#	133.2	376	1.99	76.75	124.1	1.98
313#	134.3	350	1.84	82.25	129.3	1.89
339	133.2	372	1.97	77.41	117.7	1.86
310#	137.9	365	1.87	79.68	119.6	1.81
293	131.6	312	1.67	81.79	121.4	1.76
				2.38*	5.6*	0.068*

# Of *P. radiata* origin: all other samples of *P. taeda* origin.

\* Root MSE of residuals from regressions on corresponding wood tracheid properties.

\*\* Significantly different level of variation among pulps compared to earlywood pulps at the 5% level of significance. Note: the root MSE values for replicate kraft pulp wall area and wall thickness measurements on the same chip sample are  $8.4 \mu\text{m}^2$  and  $0.13 \mu\text{m}$  (16).

### Fibres from never dried pulps stored at about 20% solids and 4°C (15).

Thus, it is suggested that the wall areas and wall thicknesses, but not perimeters of some fibres (within a given population of softwood latewood fibres) can be changed disproportionately to others during kraft pulping and/or subsequent pulp dehydration and embedment processes. Perhaps it is chemical and/or microstructural influences which catalyse these changes in some latewood kraft fibre wall area and wall thickness dimensions (e.g. microfibril angle, and the chemical and microstructural properties of compression wood) (14,17,18)? Such a hypothesis is supported by the consistently high levels of prediction of kraft fibre perimeter from wood tracheid perimeter, and the consistently poor levels of prediction of kraft fibre wall area and wall thickness from corresponding wood tracheid dimensions (3,4).

The shrinkage with decreasing kraft pulp yield of fibre perimeters, lumens, wall areas and wall thickness (Fig. 7, 8) has been explained elsewhere in terms of

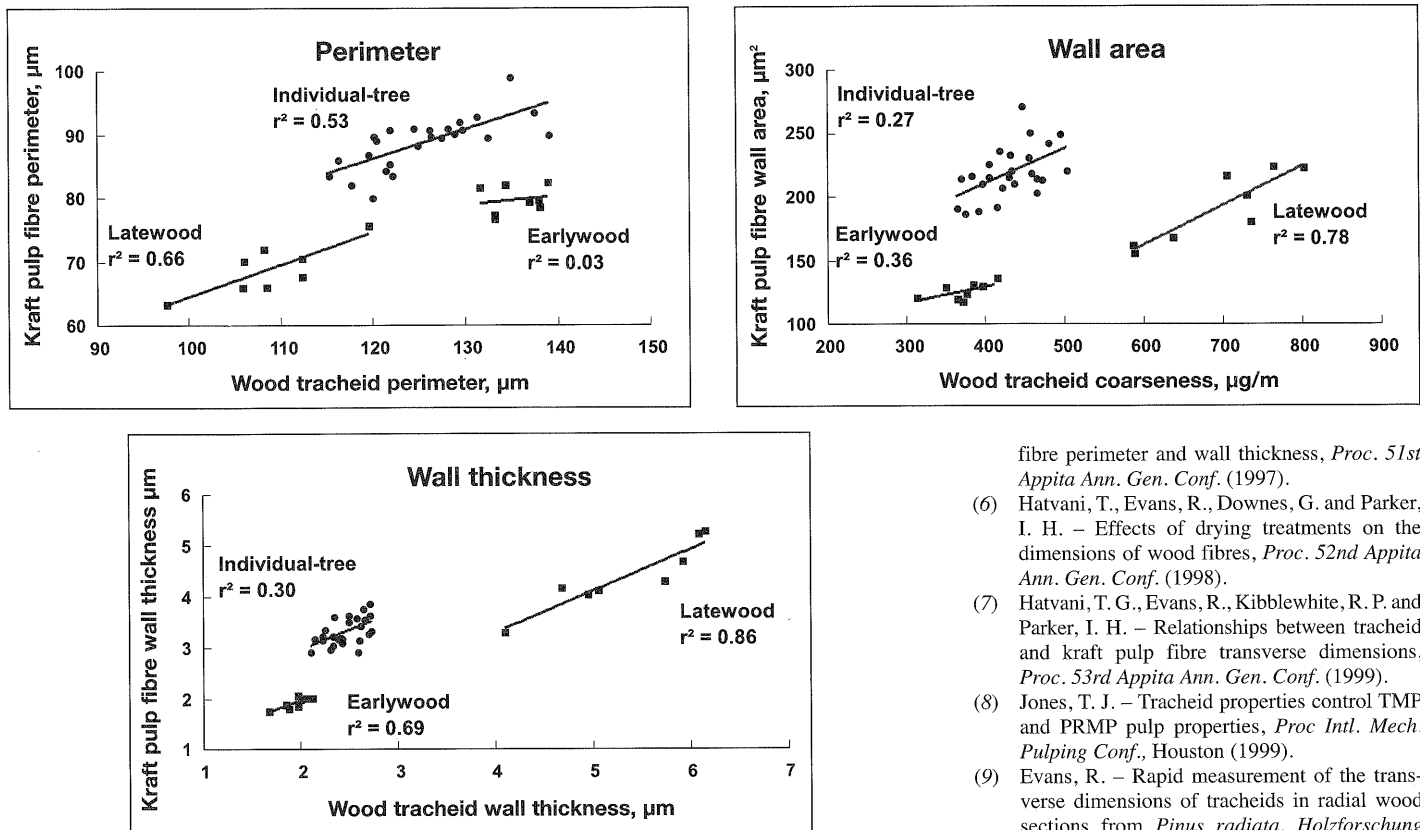
fibre wall structural and chemical organisations (2). This mechanism of shrinkage can account for fibres of high or low microfibril angles and/or of different chemical composition.

The displacement of the individual-tree kraft fibre data (4) above those of the earlywood and latewood kraft fibre data (7) is surprising (Fig. 10). Comparison with another set of paired kraft fibre and wood tracheid properties (3) shows superposition over the individual-tree data of Figure 10. For this reason it is suggested that the apparent low values obtained with the earlywood and latewood pulps are related to the use of large liquor-to-wood ratios during pulping, extremely low pulp lignin contents, and the non-standard sheet making and drying procedures (7). The practice of using *Pinus radiata* and *P. taeda* samples to obtain an extreme range of fibre dimensions is probably valid since levels of variation among the eight earlywood samples (3 x *P. taeda* and 5 x *P. radiata*) are minimal (Fig. 10, Table 3).

### CONCLUSIONS

Softwood kraft fibre cross-section dimensions can be strongly influenced by the pulping process, chemical and structural organisations within fibre walls, and sample preparation processes:

- Kraft fibre perimeters, lumens, wall areas and wall thicknesses, and hemicellulose contents, are greatly reduced early in the pulping process.
- Latewood (but not earlywood) kraft fibre wall areas and wall thicknesses (but not perimeters) show high levels of variation when the comparison bases are the corresponding wood tracheid properties, indicating different chemical and/or structural wall organisations for some fibres in latewood fibre populations.
- Levels of fibre swelling (during the rewetting of handsheets by soaking in water) and subsequent fibre shrinkage (during solvent exchange dehydration), account for the unexpectedly similar fibre wall area and wall thickness values of paired TMP and kraft pulps (of yield roughly 100 and 50% respectively).



**Fig. 10** Some individual-tree and earlywood and latewood kraft fibre and wood tracheid dimension inter-relationships. Fibres dried and rewetted from handsheets.

Softwood TMP fibre cross-section dimensions are relatively strongly correlated with corresponding wood tracheid properties. Furthermore, levels of TMP fibre property variation for given wood tracheid values are low compared to those of corresponding kraft pulps. Thus, the population distributions of individual TMP fibre properties should be able to be compared directly with those of corresponding wood tracheid properties. Such analyses should allow identification of the levels of damage, brought about by TMP processing, to different fibre types such as earlywood and latewood. Similar comparisons of fibre property population distributions for TMP and kraft pulps should be confined to the assessment of fibre perimeter. Any assessment of the wall area and wall thickness populations for kraft fibres must necessarily take account of the selective changes to some latewood fibre brought about by kraft pulping and/or sample preparation procedures. This could well be sufficient to identify some levels of TMP fibre damage since mean kraft pulp perimeters are normally different for earlywood and latewood pulps.

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