"Explaining" PFI handsheet tensile and tear in terms of fiber quality numbers

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PFI handsheet tensile and tear data are conventionally used to assess pulp quality. Measurement of Pulmac fiber quality numbers provides useful insights into why tensile and tear respond in the way they do, and underscores the more fundamental character of fiber quality testing.

Conventional pulp evaluation, as currently conducted, examines the changes in the physical properties (e.g. tensile, tear) of laboratory handsheets when produced from pulps beaten for different periods of time in a PFI mill. These changes are then used to interpret the character of the fibers that will produce these responses. Pulmac fiber quality testing provides the means to directly measure fiber properties. The extent to which such direct measurements can be used to explain the tensile and tear response of PFI handsheets provides useful evidence for the pulp evaluation credentials of fiber quality testing.

An overview of how fibers respond to PFI mill treatment

A cooperating industrial lab provided PFI mill handsheets for three different pulps which had been tested for TAPPI tensile (breaking length,Km) and TAPPI tear (milliNewtons*sq. meters per gram) in the conventional manner. These handsheets were tested at Pulmac for their fiber quality numbers[1] using the Pulmac Fiber Quality Tester *(1,2)*. The basic data provided by the cooperating lab together with the fiber quality numbers determined in our lab are presented in the appendix in Table 3. The conventional handsheet freeness, tensile and tear data are plotted against PFI mill revs in Figure 1. The Pulmac fiber quality numbers are comparably presented in Fig 2.

The curves in Figure 1 will be instantly recognized as the characteristic profiles illustrating how handsheet tensile, tear, and freeness respond to laboratory beating. Our work indicates that the curves in Figure 2 are equally characteristic of the manner in which the FS, L, and B numbers of chemical pulps respond to laboratory beating; FS and L numbers rise quite dramatically and quickly to a stable plateau level, while B numbers increase continuously and linearly with beating.

The Pulmac L number is sensitive to both changes in geometric length and curl or kinkyness. The 5 to 15%increase in L number illustrated in Figure 2 is interpreted as a measure of the extent to which fiber swelling in the early stages of beating causes the fibers, which in the unbeaten state are typically quite kinked and curled, to straighten out. This general phenomenon has been well described by Page et al *(3)*.

The 15 to 20% increase in the FS number evidences an improvement in the load bearing capability of the fibers in response to the beating action. In effect, the fibers are getting stronger. This is interpreted to be a consequence of structural changes in the

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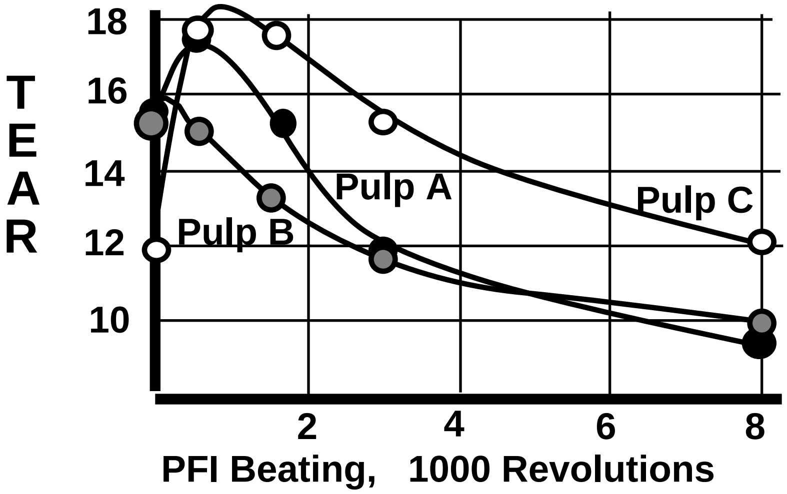
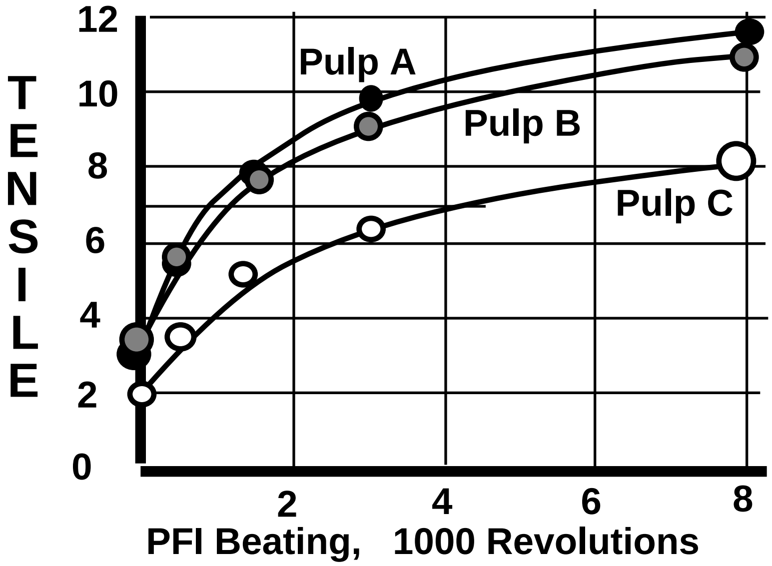
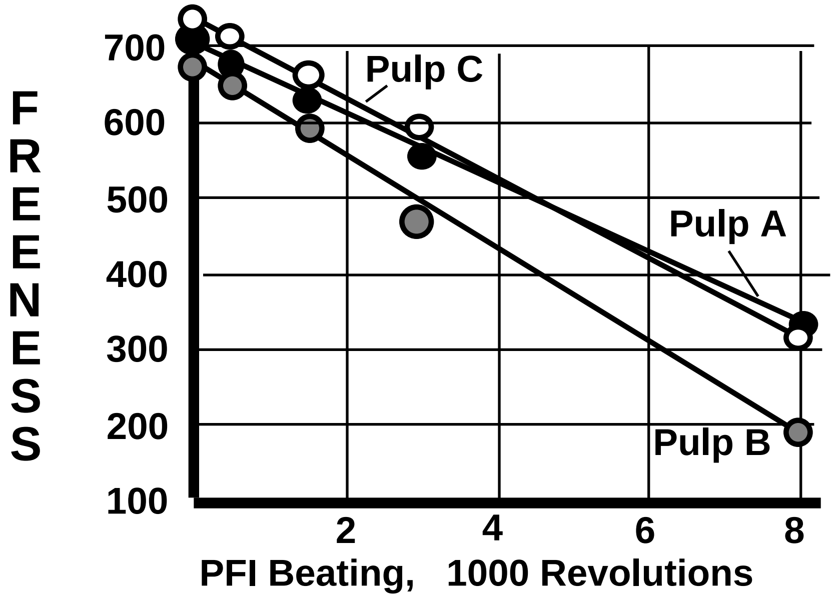
[1] *FS number (wet zero span value at 60 gsm); L number (ratio of wet 0.4 mm span value to wet zero span value); B number (ratio of dry to wet 0.4 mm span values)*

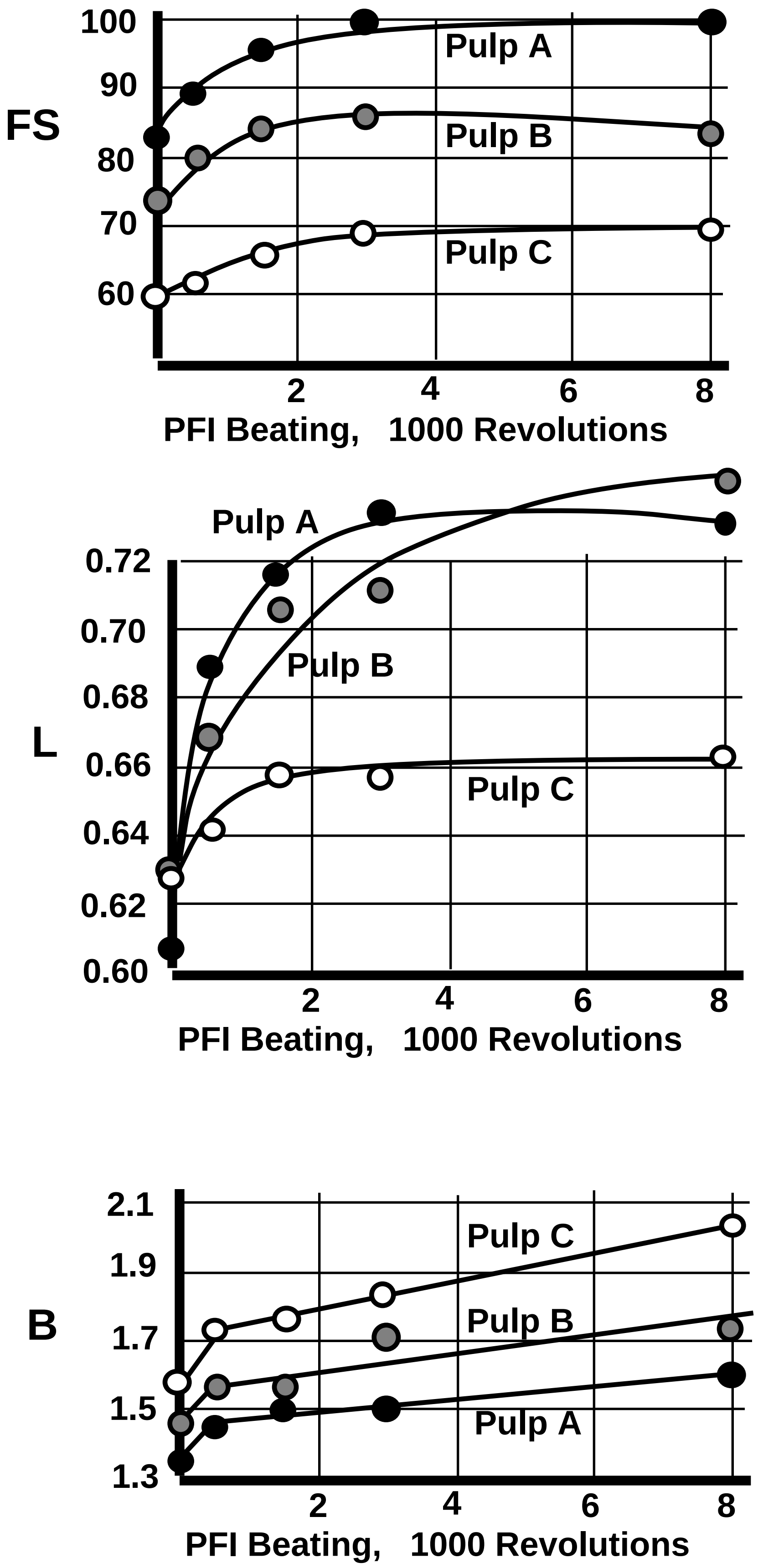
1. Conventional PFI-handsheet data







2. Fiber quality data for PFI handsheets



cell wall induced by fiber swelling. Dislocations and constrictions, which in the unbeaten state act to create load concentrations, are smoothed out by the swelling action induced by beating, thereby improving the uniformity of load transfer, which in turn increases the load that can be transferred prior to failure. The increase in the FS number is witness to these important events.

Explaining tensile strength of PFI-handsheets.

It is immediately apparent from an examination of Figures 1 and 2 that the shape of the tensile curve has a great deal more in common with the shape of the FS and L curves than with the B number curve. This implies an amplification of Page's statement *(3)* that, "More than half the strength improvement upon beating comes from the straightening out, during beating, of the fibers that have been curled and kinked during pulping and bleaching". The concomitant increase in the FS number, which Page did not measure, might well play as important a role as that which he attributes to decurling.

Theoretical considerations:

The actual tensile failure load at any given level of beating will depend upon three factors. First is the average load bearing capability of individual fibers, that is, average fiber strength, *†*.

Second is the number of fibers, *N*, available for load transfer at any given cross-section. For a standard 60 gsm test strip, this will be inversely dependent upon fiber coarseness, *wpl*, (i.e. weight per unit length).

Third is the uniformity of load transfer allowed by the network structure. That is, at any cross-section the available fibers can transfer a maximum load only if the load entering the cross-section is uniformly distributed so that excessive load is not fed into particular fibers. The fundamental character of the paper network, however, guarantees that non-uniformity of load transfer is the norm. The extent of non-uniformity of load transfer will be fundamentally dependent upon fiber length and the degree of interfiber bonding, being reduced when fiber length and degree of bonding are increased. This basic non-uniformity will be increased to the extent that avoidable structural non-uniformities are introduced by the process of sheet formation and drying. The degree of non-uniformity characteristic of any particular fiber network can be characterized by a uniformity coefficient, U_{coeff}.

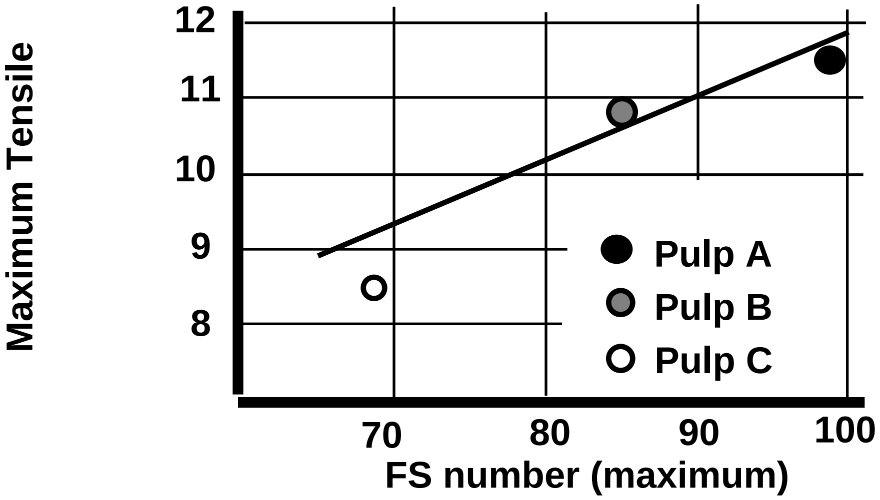
Combining these three factors defines the tensile failure load, *T*, as proportional to (U_{coeff} . 1/wpl . †). The Pulmac FS number measures the load bearing capability of the fibers clamped by the zero span jaws. This will be proportional to N x †, which thereby defines the connection between handsheet tensile strength and the FS number as:

$$T \qquad U_{coeff} . FS$$

Maximum tensile strength as a pulp quality criterion.

The characteristic PFI-handsheet tensile curve approaches a maximum value asymtotically with beating. Since FS and L have also stabilized at their maximum values, well beaten pulps will tend to produce handsheets with the highest possible U_{coeff}. This implies that comparing the maximum PFI tensile values of different pulps will provide the closest possible correlation with the FS number. This is illustrated in Figure 3, where the pulp's maximum handsheet tensile is compared to its maximum FS number. The straight line is an arbitrary suggestion of what a perfect correlation, indicative of a

3. Maximum tensile in relation to maximum FS number.



constant between-pulps U_{coeff}, might look like. Pulp C, being a southern species, in distinction to pulps A and B which are both northern species, is conceived to have the greatest displacement from such a perfect correlation.

Broadly speaking, however, it can be seen that judging a pulp's quality on the basis of its maximum PFI tensile strength is tantamount to accepting the FS number as the quality criterion that is being assessed.

Multiple Correlation:

The data listed in the appendix include 5 tensile values for each of three pulps representing beating levels varying from unbeaten to 8000 PFI mill revs, as well as the corresponding FS, L and B numbers. These data were evaluated by logarithmic multiple correlation analysis. The result showed the data to correlate with an R-squared of 0.99 yielding the regression equation:

$$T = \frac{FS^{2.63}.L^{1.85}.B^{3.40}}{41523}$$

with predicted tensile values, compared to actual values, listed in Table I. The implication is that the interplay of the changes in the FS, L and B numbers during beating can account for the characteristic PFI-tensile curve with substantial fidelity.

Explaining tear strength of PFI-handsheets.

Tear strength is a measure of a substantially more complex form of stress transmission than is tensile strength. It is a measure of the energy required to propagate an out of plane tear failure line over a predetermined distance in a sheet of paper. The characteristic PFI-tear curve shown in Figure 1 illustrates that the maximum tear strength attainable occurs at low levels of beating, and thereafter the tear strength declines continuously. The theoretical explanation generally advanced to explain this behaviour was reviewed in an earlier paper *(4)* which summarized the result as:

$$\text{Tear} = (N_R \times E_R) + (N_P \times E_P)$$

1. Correlation of Tensile with FS, L, and B numbers

	Actual Tensile	Predicted Tensile
Pulp A		
Unbeaten	2.9	2.9
500 PFI revs	5.5	5.7
1500 PFI revs	7.7	8.2
3000 PFI revs	9.7	9.6
8000 PFI revs	11.5	12.0
Pulp B		
Unbeaten	3.3	3.1
500 PFI revs	5.6	5.5
1500 PFI revs	7.6	6.8
3000 PFI revs	9.1	9.5
8000 PFI revs	10.8	10.4
Pulp C		
Unbeaten	1.9	2.1
500 PFI revs	3.5	3.5
1500 PFI revs	5.0	4.8
3000 PFI revs	6.3	6.1
8000 PFI revs	8.1	8.4

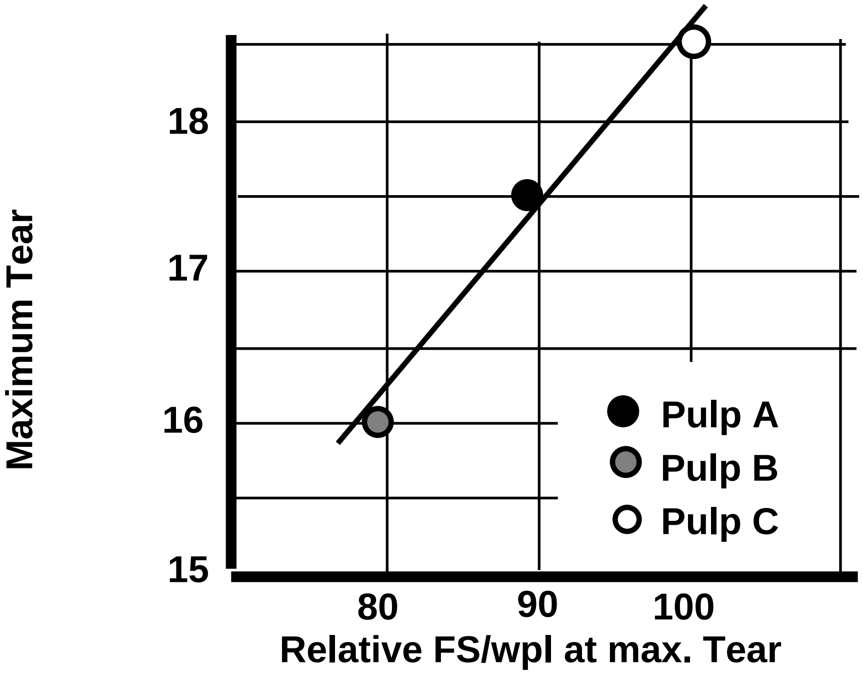
where the tear value is seen as the sum of the average energy required to rupture a fiber, E_R, multiplied by the number of fibers along the tear failure line that ruptured, N_R, plus the average energy (stripping energy) required to pull a fiber out of the network, E_P, multiplied by the number of fibers along the tear failure line that pulled out, N_P. The distance over which the stripping force acts in order to pull a fiber out of the network is very much greater than the distance over which the rupture force need act to break a fiber, so that $E_P >> E_R$. The tear value is therefore very dependent on the details of how and how many fibers are pulled out of the network during propagation of the tear failure line. The maximum tear will occur when $N_P \times E_P$ is a maximum, and it is clear from the empirical evidence that this occurs very early in the beating sequence.

How can fiber quality numbers contribute to an understanding of this complex phenomenon? Clearly the strength of individual fibers cannot be overemphasized. The stronger the fiber the less likely it is to break. Increased fiber strength, other things being equal, will inevitably cause an increase in tear value. It is important, however, to recognize that it is the fiber strength, †, and not the FS number that is being referred to. The relative value of † for the three pulps examined by this study can be calculated by normalizing all FS numbers to reflect a common coarseness; i.e.

$$\dagger = FS \times \frac{wpl}{18}$$

where *wpl* is the Kajaani coarseness of the pulp given in the appendix, and 18 is an arbitrary normalization constant. The maximum tear value, interpolated from Figure 1, is compared to the normalized † (calculated from the above equation using the FS value corresponding to the maximum tear) in Figure 4. This correspondence reinforces the importance of true fiber strength (note that the FS number will reflect this at constant coarseness) upon the maximum tear value.

4. Maximum tear in relation to corresponding fiber strength, †



The effect on the tear value of decurling, which is the predominant effect characterized by the L number changes reported in Figure 2, is unclear, being masked by the greater significance of the increase in the FS (†) value. Page *(3)* cites evidence that increased curl increases tear, which would imply that tear is adversely effected during beating by the removal of curl.

The decline in the tear value during the later stages of beating, when FS and L values have reached their plateau level, can only be accounted for by the increase in bonding reflected by the B number. This is in accord with the expectation that as bonding increases fibers will be more securely held in the network resulting in more fiber breakage and fewer fiber pull-outs as the tear failure line propagates.

On the basis of this general analysis it would be an expectation that the portion of the tear curve which describes its decline would be influenced by (1) changes in the relative fiber strength, †, calculated in accordance with the equation presented on the previous page; (2) changes in the relative curl, which can be calculated as:

$$C \;=\; \text{Relative Curl} \;=\; 1 - \frac{(L_R - L_0)}{L_0}$$

where L_R is the L number at any given PFI revs, and L_0 is the L number of the unbeaten pulp, giving a relative curl value of 1.0 for pulps in the unbeaten stage, and exhibiting lower values as beating progresses; and (3) changes in the relative amount of bonding that has been developed, calculated according to:

$$B \;=\; \text{Relative Bonding} \;=\; \frac{(B_R - B_0)}{B_0}$$

where B_R is the B number at any given PFI revs, and B_0 is the B number of the unbeaten pulp, giving a relative bonding value of 0.0 for pulps in the unbeaten stage, and exhibiting higher values as beating progresses.

2. Correlation of Tear with †, Curl, and Relative Bonding

	Actual Tear	Predicted Tear
Pulp A		
1500 PFI revs	15.2	12.9
3000 PFI revs	11.8	12.7
8000 PFI revs	9.3	10.3
Pulp B		
500 PFI revs	15.0	15.3
1500 PFI revs	13.3	14.5
3000 PFI revs	11.7	11.4
8000 PFI revs	9.9	9.6
Pulp C		
1500 PFI revs	17.6	16.6
3000 PFI revs	15.2	16.0
8000 PFI revs	12.1	12.0

Using multiple regression to relate the declining tear values of all three pulps to relative fiber strength, curl, and bonding yields the following regression equation with an R-squared of 0.834. The actual and predicted tear values are given in Table II.

$$\text{Tear} = -20.7 + 0.19\dagger + 23.6\,C - 31.9\,B$$

The implication of this statistically significant relationship implies that the tear value of PFI-handsheets for nominally equal fiber length bleached kraft softwood pulps will depend as beating progresses, upon a complex interplay of the increasing fiber strength which enhances the tear value competing with the decurling and bonding increases which act to diminish tear.

Conclusion.

The Pulmac fiber quality numbers provide measurements which characterize basic changes in three important fiber properties, their average ability to transmit a tensile load, their average effective length, and the average extent by which bonding connects these fibers into a network. This paper has provided evidence that all three of these parameters are significantly altered by laboratory beating, and that the handsheet tensile and tear responses can be explained by these changes. In the absence of precise knowledge of the manner in which these three fiber properties are changing, the interpretation of pulp quality by observing tensile and tear data from laboratory handsheet studies must remain an art form with considerable opportunity for misinterpretation.

Literature cited

1. Wavell F. Cowan, Pulp & Paper 60(13): 108 (Dec.1986)
2. Wavell F. Cowan, Pulp & Paper 60(5): 84 (May, 1986)
3. D.H. Page, R.S. Seth, B.D. Jordan, M.C. Barbe, JPPS 10:J74 (May, 1984)
4. Wavell F. Cowan, Tappi (first article in this series)

Appendix

3. Basic Data

Item	Zero Beating	500 Revs	1500 Revs	3000 Revs	8000 Revs
	PFI Mill Treatment				
Pulp A					
Canadian Std Freeness	707	677	635	562	334
Kajaani Coarseness	17.9	--	--	--	--
Tensile	2.9	5.5	7.7	9.7	11.5
Tear	15.5	17.4	15.2	11.8	9.3
FS Number	82.8	88.9	95.6	98.9	99.1
L number	0.61	0.69	0.72	0.73	0.73
B Number	1.33	1.44	1.48	1.50	1.60
Pulp B					
Canadian Std Freeness	672	646	590	467	190
Kajaani Coarseness	18.8	--	--	--	--
Tensile	3.3	5.6	7.6	9.1	10.8
Tear	15.1	15.0	13.3	11.7	9.9
FS Number	73.5	80.6	84.2	84.9	83.9
L number	0.63	0.67	0.71	0.71	0.74
B Number	1.47	1.56	1.56	1.71	1.73
Pulp C					
Canadian Std Freeness	732	709	667	595	304
Kajaani Coarseness	28.2	--	--	--	--
Tensile	1.9	3.5	5.0	6.3	8.1
Tear	11.7	17.7	17.6	15.2	12.1
FS Number	58.8	61.2	65.7	68.6	68.4
L number	0.63	0.64	0.66	0.66	0.66
B Number	1.55	1.74	1.77	1.84	2.03