Explaining handsheet tensile and tear in terms of fiber-quality numbers

Wavell F. Cowan

ABSTRACT: Mills conventionally evaluate pulp response to refining by measuring changes in handsheet tensile and tear strength. This traditional approach remains an art form, subject to misinterpretation. An alternative method is available. Pulp quality can be reliably evaluated by directly measuring relevant fiber properties (fiber strength, fiber length, and fiber bonding). This article shows that direct measurement of fiber properties offers useful insights into the response of handsheet tensile and tear to changes in laboratory refining. The results suggest that the alternative method provides fundamental information about pulp quality.

KEYWORDS: Beating, fibers, hand sheets, PFI mills, physical properties, quality, tensile strength, tear strength.

Mills typically evaluate pulp quality by forming handsheets and testing their physical properties (e.g., tensile strength, tear index). The observed changes in physical properties after various degrees of beating in a PFI mill are used to interpret the character of the fibers.

Fiber properties can be measured directly using an alternative method—Pulmac fiber-quality testing. Direct measurement of fiber properties provides information that helps explain the response of handsheet tensile and tear to various levels of refining. The explanatory power of this approach provides evidence that the fiber-quality testing is a reliable method of evaluating pulp quality.

Fiber response to treatment in a PFI mill

A cooperating industrial lab provided handsheets for three different pulps that had been conventionally tested for tensile strength and tear index after various degrees of beating in a PFI mill. These handsheets were further tested at Pulmac for their fiber-quality numbers using the Pulmac Fiber Quality Tester *(1, 2)*. The basic data provided by the cooperating lab and the fiber-quality numbers determined in our lab are presented in Table I. The conventional handsheet freeness, tensile, and tear data are plotted against revolutions in a PFI mill in Fig. 1. The Pulmac fiber-quality numbers—FS (fiber strength), L (fiber length), and B (fiber bonding)—are comparably presented in Fig. 2.

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

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

The 15–20% increase in the FS number indicates 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 cell wall induced by fiber swell-

Cowan is research director and CEO of Pulmac Instruments International, Box 50, HCR 34, Moretown, VT 05602.

Reprinted from **Tappi Journal**, Vol. 78, No. 1, January 1995.

I. Properties of three softwood pulps at five levels of refining

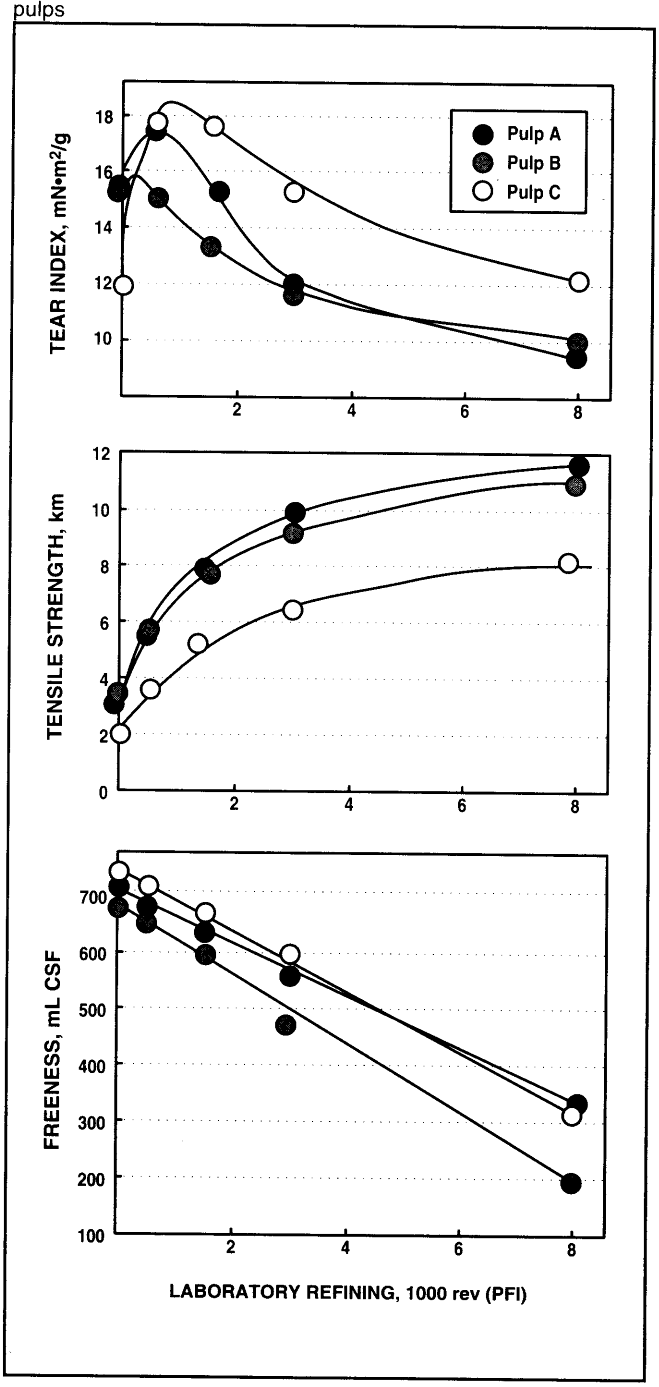
	PFI-mill treatment				
Item	*Zero beating*	*500 revs*	*1500 revs*	*3000 revs*	*8000 revs*
Pulp A (northern species)					
Freeness, mL CSF	707	677	635	562	334
Coarseness (Kajaani), µg/m	17.9	...	...	...	...
Tensile strength, km	2.9	5.5	7.7	9.7	11.5
Tear index, mN·m²/g	15.5	17.4	15.2	11.8	9.3
FS number, N/cm	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 (northern species)					
Freeness, mL CSF	672	646	590	467	190
Coarseness (Kajaani), µg/m	18.8	...	...	...	...
Tensile strength, km	3.3	5.6	7.6	9.1	10.8
Tear index, mN·m²/g	15.1	15.0	13.3	11.7	9.9
FS number, N/cm	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 (southern species)					
Freeness, mL CSF	732	709	667	595	304
Coarseness (Kajaani), µg/m	28.2	...	...	...	...
Tensile strength, km	1.9	3.5	5.0	6.3	8.1
Tear index, mN·m²/g	11.7	17.7	17.6	15.2	12.1
FS number, N/cm	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

ing. Dislocations and constrictions, which in the unbeaten state act to create load concentrations, are smoothed out by the swelling action induced by beating. This improves 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 testimony of these important events.

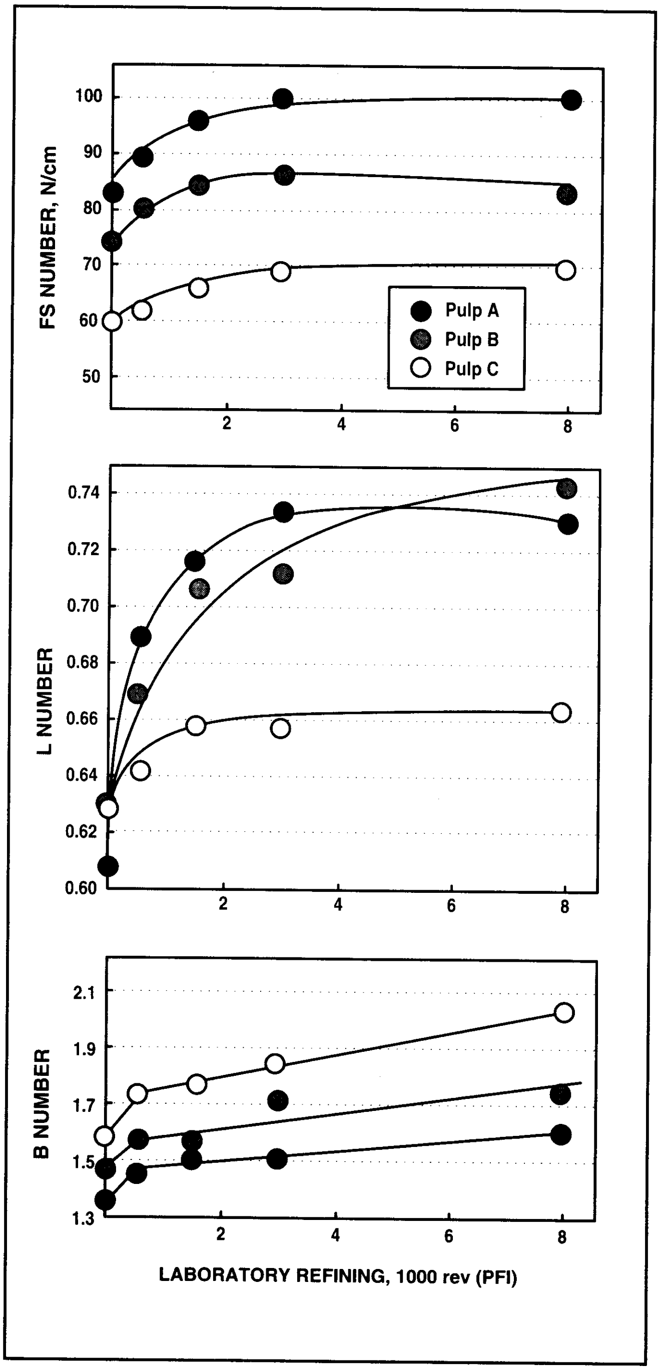
Explaining tensile strength of handsheets

Examination of Figs. 1 and 2 reveals 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 curves for B number. The similarity between the L and tensile curves lends support to Page's assertion *(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

1. Tear index, tensile strength, and pulp freeness as functions of laboratory refining for handsheets produced from three softwood pulps



2. FS, L, and B numbers as functions of laboratory refining for handsheets produced from three softwood pulps



well play as important a role as that which he attributes to decurling.

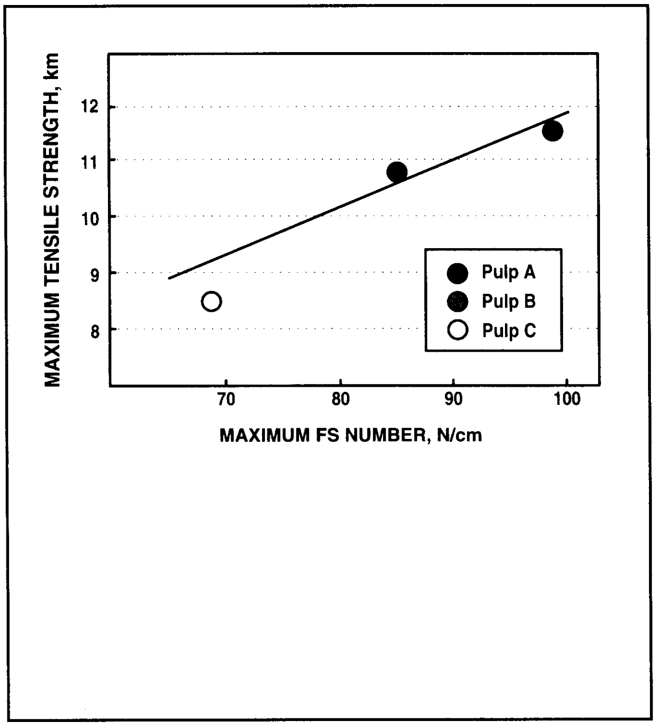
Theoretical considerations

The tensile failure load at any given level of beating depends on three factors.

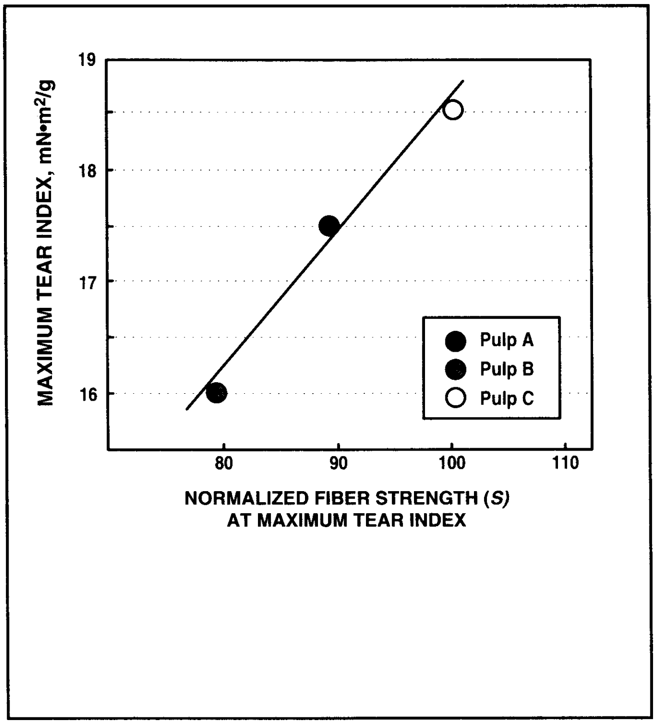
1. The average load-bearing capability of individual fibers, i.e., average fiber strength, *S*.
2. The number of fibers, *N*, available for load transfer at any given cross-section. For a standard 60-g/m² test strip, this is inversely dependent on fiber coarseness, WPL, which represents weight per unit length.
3. The uniformity of load transfer allowed by the network structure.

The issue of load transfer merits further discussion. The available fibers at any cross-section can transfer a maximum load only if the load entering the cross-section is uni-

3. Maximum tensile strength and corresponding maximum FS number for handsheets produced from three softwood pulps



4. Maximum tear index and corresponding fiber strength, *S*, for handsheets produced from three softwood pulps



formly distributed. If this is the case, excessive load will not be fed into particular fibers. However, the fundamental character of the paper network guarantees that nonuniformity of load transfer is the norm. The extent of nonuniformity of load transfer is fundamentally dependent on fiber length and the degree of interfiber bonding, with nonuniformity decreasing with increasing fiber length and degree of bonding. The inherent nonun-iformity of the fiber network will increase if avoidable structural nonuniformities are introduced by the process of sheet formation and drying. The degree of nonuniformity characteristic of any particular fiber network can be characterized by a uniformity coefficient, U_{coeff}.

Combining these three factors—fiber strength, fiber coarseness, and network uniformity—the tensile failure load, *T*, can be defined as

$$T \propto U_{coeff} \times 1/WPL \times S \qquad (1)$$

The FS number measures the load-bearing capability of the fibers clamped by the zero-span jaws, which means that the FS number is proportional to $N \times S$. Thus the connection between handsheet tensile strength, *T*, and FS number can be defined as

$$T \propto U_{coeff}\,FS \qquad (2)$$

Maximum tensile strength as a pulp-quality criterion

The characteristic handsheet tensile curve approaches a maximum value asymptotically with beating. Since FS andL have also stabilized at their maximum values, well-beaten pulps tend to produce handsheets with the highest possible U_{coeff}. This implies that the maximum tensile value for a given pulp will provide the closest possible correlation with its FS number.

Figure 3 plots the maximum handsheet tensile vs. maximum FS number for the three pulps. The straight line is an arbitrary suggestion of what a perfect correlation might look like. (A perfect correlation would be indicative of a constant between-pulp U_{coeff}.) Pulp C is a southern species, while Pulps A and B are both northern species. Thus Pulp C is conceived to have the greatest displacement from such a perfect correlation.

Broadly speaking, it is apparent that judging a pulp's quality on the basis of its maximum tensile strength is tantamount to accepting the FS number as the relevant quality criterion.

Multiple correlation

The data listed in Table I include five tensile values for each of three pulps representing beating levels varying from unbeaten to 8000 revs in a PFI mill, 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 r^2=0.99, yielding the following regression equation.

$$T = (FS^{2.63}\ L^{1.85}\ B^{3.4})/41{,}523 \qquad (3)$$

II. Actual and predicted* tensile strength for three softwood pulps at five levels of refining

	Tensile strength, km	
	Actual	*Predicted*
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

* Predicted values (r^2=0.99) obtained by inserting values for FS, L, and B (Table I) into Eq. 3

III. Actual and predicted* tear index for three softwood pulps at five levels of refining

	Tear index, mN·m²/g	
	Actual	*Predicted*
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

* Predicted values (r^2=0.834) obtained by inserting values for *S* (Eq. 5), *C* (Eq. 6), and B (Eq. 7) into Eq. 8

Table II shows the actual values for tensile strength and the predicted values from Eq. 3. It is clear that the interplay of changes in the FS, L, and B numbers during beating can account for the characteristic tensile-refining curve with substantial fidelity.

Explaining tear strength of handsheets

Tear strength measures a substantially more complex form of stress transmission than tensile strength. Tear 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 tear-refining curve shown in Fig. 1 illustrates that the maximum attainable tear strength occurs at low levels of beating, and thereafter the tear strength declines continuously. The theoretical explanation generally advanced to explain this behavior was reviewed in Part 1 of this study *(4)*, which summarized the result as:

$$\text{Tear} = (N_R \times E_R) + (N_P \times E_P) \qquad (4)$$

where

N_R = number of ruptured fibers along the failure line

E_R = average energy required to rupture a fiber

N_P = number of fibers along the failure line that pulled out of the network

E_P = average stripping energy required to pull a fiber out of the network.

The distance over which the stripping force acts to pull a fiber out of the network is very much greater than the distance over which the rupture force acts 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 occurs when N_P x 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, inevitably causes an increase in tear value. It is important, however, to recognize that it is the fiber strength, *S*, and not the FS number that is being referred to. The relative value of *S* for the three pulps examined by this study can be calculated by normalizing all FS numbers to reflect a common coarseness, i.e.,

$$S = \text{FS} \times \text{WPL}/18 \qquad (5)$$

where WPL is the Kajaani coarseness of the pulp given in Table I, and 18 is an arbitrary normalization constant.

The maximum tear value, interpolated from Fig. 1, is compared with the normalized *S* (calculated from Eq. 5 using the FS value corresponding to maximum tear) in Fig. 4. The linear relationship highlights the importance of true fiber strength on the maximum tear value. (Note that the FS number reflects true fiber strength at constant coarseness.)

The effect on the tear value of decurling, which is the predominant effect characterized by changes in the L numbers reported in Fig. 2, is unclear because it is masked by the greater significance of the increase in the FS (*S*) value. Page *(3)* cites evidence that increased curl increases tear, which would imply that tear is adversely affected during beating by the removal of curl.

The decline in the tear index during the later stages of beating, when FS and L values have reached their plateau levels, 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.

Based on this general analysis, the declining portion of the tear curve would be expected to be influenced by three factors.

1. Changes in the relative fiber strength, S, calculated in accordance with Eq. 5
2. Changes in the relative curl, calculated as

$$C = 1 - [(L_R - L_0)/L_0] \quad (6)$$

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.

3. Changes in the relative amount of bonding that has been developed, calculated as

$$B = (B_R - B_0)/B_0 \quad (7)$$

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 zero for pulps in the unbeaten stage and exhibiting higher values as beating progresses.

Using multiple regression to relate the declining tear values of all three pulps to these three factors (relative fiber strength, curl, and bonding) yields the following regression equation with $r^2 = 0.834$.

$$\text{Tear} = -20.7 + 0.19S + 23.6C - 31.9B \quad (8)$$

This statistically significant relationship implies that as beating progresses, the tear value of bleached-kraft softwood pulps (at nominally equal fiber length) will depend on a complex interplay of increasing fiber strength (enhanced tear) competing with increases in decurling and bonding (diminished tear). The actual and predicted tear values are given in Table III.

Conclusion

The Pulmac fiber-quality numbers provide measurements that characterize basic changes in three important fiber properties.

1. The average ability to transmit a tensile load (FS number)
2. The average effective length (L number)
3. The average extent to which bonding connects these fibers into a network (B number).

The data presented in this article show that these three parameters are significantly altered by laboratory beating. More importantly, changes in these three parameters show a direct connection to changes in the tensile and tear responses of handsheets produced from pulps subjected to varying degrees of laboratory beating.

Measurement of these three fiber properties provides a reliable basis for evaluating pulp response to beating. The conventional approach—measurement of handsheet tensile and tear—remains an art form with considerable opportunity for misinterpretation. TJ

Literature cited

1. Cowan, W. F., *Pulp Paper* 60(13): 108(1986).
2. Cowan, W. F., *Pulp Paper* 60(5): 84(1986).
3. Page, D. H., Seth, R. S., Jordan, B. D., *et al.*, *J. Pulp Paper Sci.* 10(5): J74(1984).
4. Cowan, W. F., *Tappi J.* 77(10): 77(1994).

Received for review Aug. 3, 1993.

Accepted March 20, 1994.