Testing pulp quality—an alternative to conventional laboratory evaluation

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ABSTRACT: An alternative method of measuring pulp quality is presented. The method is rapid, reproducible, and shows a high degree of correlation with tensile strength as measured conventionally in mill laboratories. The method gives pulp mills the option of increasing the frequency of testing, resulting in better quality management.

KEYWORDS: Evaluation, fiber analysis, fiber length, freeness, measurement, mechanical properties, PFI mills, pulp mills, pulps, quality, strength tests, tensile tests.

The pulp industry monitors product quality by periodically testing pulp samples in the laboratory. The high cost and elaborate nature of standard laboratory evaluation discourages its more extensive use, despite the heightened focus on quality brought about by such well-publicized activities as ISO 9000 accreditation and the Baldrige awards for quality. The Pulmac PQ System *(1)* is a reliable, rapid, and economic method of measuring pulp quality in the mill laboratory. The method measures pulp quality in terms of an FS (fiber strength) number and an L (fiber length) number *(2, 3)*. This article presents the results of a laboratory study comparing PQ System data and the conventional laboratory data that now serve as the accepted pulp-quality standard for the industry.

Test program

Samples of 24 bleached kraft softwood pulps (dry-lap form) were obtained from six market-pulp mills in North America. Multiple pulps were obtained from five of the mills, with pulps from the same mill representing production at different times. All pulps were tested (a) by a cooperating pulp-mill laboratory using a PFI mill and standard operating procedures and (b) by Pulmac using standard PQ System procedures.

Results

Results from the conventional PFI-mill handsheet testing data were expressed as

- Tensile strength at constant freeness (400 mL CSF), km breaking length
- Tear index at constant tensile strength (7.0 km), mN·m²/g.

PQ System results were expressed as

- FS number—wet zero-span strength corrected to 60-g/m² basis weight, N/cm
- L number—ratio of wet short-span (0.4 mm) strength to wet zero-span strength.

Data for the 24 pulps are presented in **Table I**.

The variability in pulp quality exhibited by these samples is summarized in **Table II**. The precision of the test data is estimated in terms of the expected coefficient of variation (COV) for multiple tests on the same sample. For the Pulmac data, this is an unambiguous number directly calculated from the 48 repetitive measurements used to generate each average value. The PFI-mill procedure produces the reported parameters as averaged results from interpolation within two sets of data,

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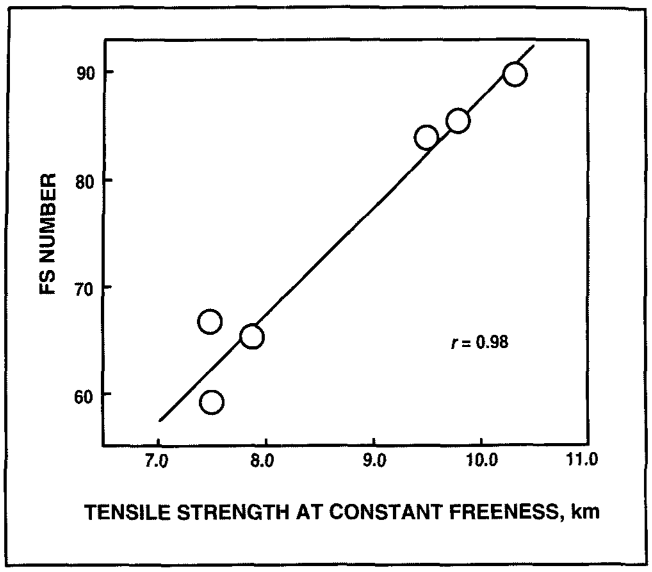
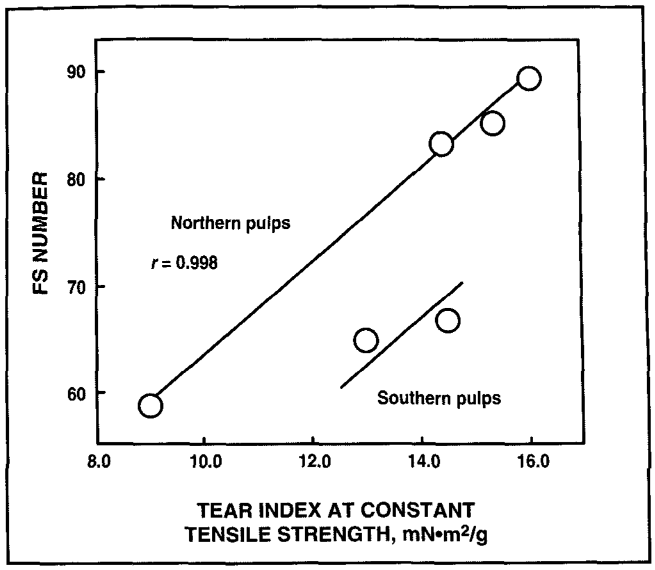
1. FS number as a function of handsheet tensile strength at constant freeness (400 mL CSF) for pulp from six mills (average data from each mill)



2. FS number as a function of handsheet tear index at constant tensile strength (7 km) for pulp from six mills (average data from each mill)



but without replication. The expected COV is thus experimental, rather than specific to these data. TAPPI test methods *(4)* provide repeatability data in terms that correspond to a COV of 7.2% for tear index and 3.6% for tensile strength. Anecdotal information suggests that these values may be somewhat high.

The typical *within*-mill quality variation exhibited by these particular samples, while statistically distinguishable by fiber-quality testing, may well not be distinguishable by PFI-handsheet testing. *Between*-mill variation in pulp quality is sufficiently great, however, to be reliably distinguished by both systems of measurement.

Since only the between-mill quality variation is sufficient to be unambiguously distinguished by the PFI-handsheet data, the within-mill data for the six mills were averaged to provide a basis for comparing PFI-handsheet data with the fiber-quality numbers, i.e., FS number and L number. As seen in **Fig. 1**, there is a strong correlation between FS number and tensile strength (measured at constant freeness of 400 mL CSF) for pulps from all six mills. **Figure 2** shows a similarly strong correlation between FS number and tear index (measured at constant tensile strength of 7 km) for the four mills producing pulps from northern species. However, the data for the two mills producing pulps from southern species fall on a line substantially displaced from that for the northern pulps.

The within-mill data provide similar results for the correlation of FS number with tensile strength and tear index, as seen in **Figs. 3 and 4**, respectively. However, the use of the within-mill data reduces the precision, as evidenced by the decline in correlation coefficient, r, for the linear relationships.

Discussion

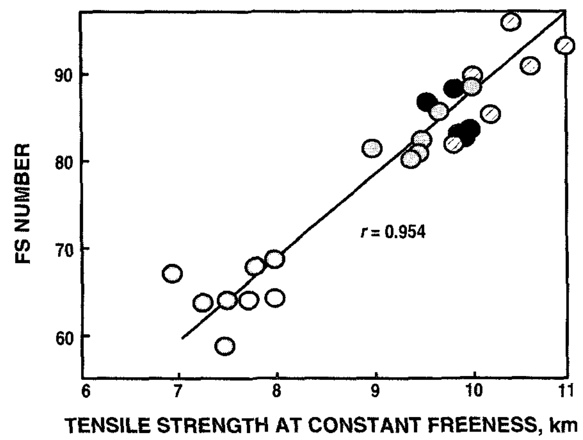
Tensile-strength parameter

The upper limit of tensile strength attainable by any handsheet is established by the average number of fibers at any cross-section of the sheet, multiplied by their average strength. The FS number (wet zero-span strength) provides a sensitive indicator of this potential.

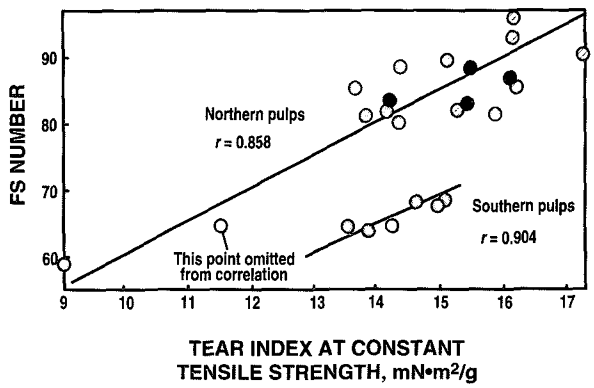
The sheet tensile strength depends on how uniformly the tensile load can be transmitted through the fiber network. That is, tensile strength increases as the fibers at any cross-section are more uniformly loaded, with the ideal and maximum attainable load occurring when all fibers share equally in load transfer across the cross-section. Uniformity of load transfer depends on the ease with which the load can transfer back and forth between fibers. Shorter fibers and less bonding in the paper network reduce opportunities for this back-and-forth transfer of load, thus increasing the nonuniformity of load transfer and reducing available tensile strength. Thus tensile strength is very dependent upon both fiber length and the degree of interfiber bonding.

In this study, softwood pulps of similar fiber lengths were compared at the same level of bonding (assuming that equal freeness means equal interfiber bonding). Reducing the variability introduced by differences in fiber length and bonding served to amplify the relationship between the observed tensile-strength data and the maximum potential tensile strength. Thus it was expected that differences in handsheet tensile

3. FS number as a function of handsheet tensile strength at constant freeness (400 mL CSF) for pulp from six mills (data for individual pulp samples)



4. FS number as a function of handsheet tear index at constant tensile strength (7 km) for pulp from six mills (data for individual pulp samples)



I. Pulp quality as measured in the mill laboratory and using the PQ System

	Mill laboratory data		PQ System data	
Sample code	Tensile strength (at constant freeness[a]), km	Tear index (at constant tensile strength[b]), mN·m²/g	FS number, N/cm	L number
		Northern species		
A-1	9.8	15.5	87.0	0.70
A-2	10.0	14.3	83.8	0.68
A-3	9.6	16.2	86.4	0.69
A-4	9.9	15.5	82.6	0.68
B-1	7.5	9.0	59.0	0.58
C-1	9.7	13.7	85.8	0.69
C-2	10.0	14.4	88.2	0.69
C-3	9.5	13.9	80.7	0.68
C-4	9.4	14.4	80.0	0.69
C-5	9.0	15.9	81.4	0.69
C-6	9.5	14.2	82.4	0.96
D-1	11.0	16.2	92.5	0.70
D-2	10.0	15.2	89.1	0.69
D-3	10.2	16.3	85.0	0.68
D-4	9.8	15.3	82.9	0.66
D-5	10.6	17.3	90.8	0.71
D-6	10.4	16.2	95.9	0.74
Southern species				
E-1	8.0	15.1	68.5	0.66
E-2	7.5	13.9	63.7	0.66
E-3	7.3	13.6	63.9	0.67
E-4	7.8	14.7	68.3	0.67
E-5	6.9	15.0	67.3	0.67
F-1	7.7	14.3	64.3	0.67
F-2	8.0	11.6	64.6	0.59

[a]400 mL CSF
[b]7-km breaking length

strength at constant freeness would strongly relate to the FS numbers for the various pulps. Figures 1 and 3 verify this connection. However, the fact that the pulps were all softwoods is no guarantee of constant fiber length, nor does similar freeness guarantee equivalence in degree of bonding. Fluctuations in these parameters thus would be expected to produce discrepancies from the correlation. Despite these fluctuations, the data clearly indicate a strong dependence of handsheet tensile strength (at constant freeness) on the measured FS parameter for the fibers.

Tear-index parameter

Tear strength of paper is a consequence of a far more complex interplay of relationships than is tensile strength. Tear strength measures the energy exerted in propagating a line of failure across a predefined tear distance. The tear-failure line propagates as a series of events, with each event defining the interaction of the failure line with each successive fiber encountered as the failure line propagates. At each such encounter, the fiber will either break or one

II. Variability in pulp quality as measured in the mill laboratory and using the PQ System

Sample code	Number of pulps	Mill laboratory data: Tensile strength (at constant freeness[a]), km		Tear index (at constant tensile strength[b]), mN·m²/g		PQ System data: FS number, N/cm		L number	
		Avg.	COV, %	Avg.	COV, %	Avg.	COV, %	Avg.	COV, %
Test precision	...	...	2–4	...	5–7	...	0.6	...	1.2
All pulps	24	9.1	13.1	14.7	11.5	78.9	13.8	0.68	4.8
Northern pulps	17	9.8	7.7	14.9	12.2	84.3	9.3	0.69	4.5
Southern pulps	7	7.6	5.3	14.0	8.6	65.8	3.3	0.66	4.4
Mill A	4	9.8	1.7	15.4	5.1	85.0	2.5	0.69	1.5
Mill B	1	7.5	...	9.0	...	59.0	...	0.58	...
Mill C	6	9.5	3.5	14.4	5.4	83.1	3.9	0.69	0.8
Mill D	6	10.3	4.2	16.1	4.8	89.4	5.4	0.70	3.7
Mill E	5	7.5	5.7	14.5	4.7	66.3	3.6	0.67	0.8
Mill F	2	7.9	2.7	13.0	14.7	64.5	0.3	0.63	9.2

[a]400 mL CSF
[b]7-km breaking length

end will pull out from the bonded structure. The total energy required to propagate a tear failure line is thus the energy used to break a fiber, summed over all the ruptured fibers on the failure line, plus the stripping energy needed to pull a fiber out of the network, summed over all the unruptured fibers on the failure line.

This can be expressed as:

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

where

N_R = total number of fibers along the failure line that ruptured

E_R = average rupture energy

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

E_P = average stripping energy associated with fiber pullout.

Although the force required to rupture a fiber is necessarily higher than that required to pull a fiber out of the network, the rupture force acts over a much shorter distance than the force of fiber pullout. Thus the energy absorbed by fiber rupture is substantially less than the energy absorbed by fiber pullout (stripping energy). Stripping energy increases with bonding level and fiber length, while rupture energy depends solely on the fiber's strength and modulus. Whether a fiber will rupture or pull out depends on how securely it is bonded into the network, relative to the strength of the fiber. That is, at a fixed level of bonding, more fibers will rupture as fiber strength declines.

The conventional view is that the tear-index value for a given pulp, commencing at a zero bonding level, will increase with bonding (because of the enhanced stripping energy) until the growth rate for E_P is offset by the rate of decline in N_P. That is, at some point, a marginal increase in bonding causes a sufficient increase in the number of fibers that rupture, N_R, to produce a net decline in overall energy absorption. Thereafter, the tear-index value continues to fall. This qualitative description implies that a given pulp must have a critical bonding level at which tear strength is at its maximum. This represents the point of optimum balance between bond enhancement of stripping energy and bond-induced reduction in the number of fibers that resist rupture.

The tear-index parameter of the standard laboratory handsheet is defined by the conditions of bonding that produce a particular tensile strength, in this case, a breaking length of 7 km. The corresponding tear-index value thus depends on two factors:

1. The maximum attainable tear-index value (dependent upon fiber strength and length)
2. The extent to which the bonding level at the target tensile strength differs from the critical bonding level needed to achieve maximum tear strength.

The tear-index data in Figs. 2 and 4 fall on two curves—one for northern pulps and one for southern pulps—illustrating a major discrepancy in the connection between the handsheet tear-index parameter and the FS number for the pulp fibers. To reasonably accommodate the tear-index data, it was clear that northern and southern pulps had to be considered separately. Such a distinction was not required to deal with the handsheet tensile-strength parameter, as seen in Figs. 1 and 3.

III. Effect of fiber coarseness on fiber strength

	Avg. FS number, N/cm	Relative coarse-ness	Relative fiber strength, S
Northern pulps	88	1.0	88
Southern pulps	65	1.0	65
		1.3	85
		1.5	98
		1.7	111

The thick-walled fibers from southern species have a bleached coarseness (weight per unit length) that typically exceeds that of thin-walled northern fibers by more than 50%. As stated previously, the FS number is a measure of the load-bearing capability of the wet fibers clamped in a 60-g/m^2 test sheet. That is, FS number is proportional to N x S, where N is the number of clamped fibers and S is the average strength of individual fibers. When comparing pulps of vastly different coarseness, the number of fibers, N, at any cross section of a 60-g/m^2 test sheet will be very different. This alters the relationship between FS and S. For instance, for two pulps of identical fiber strength, S, whose coarseness differs by 50%, the FS number for the higher-coarseness pulp would be 50% lower because of the 50% reduction in N. The significance of coarseness on fiber strength is illustrated in **Table III**, where the average FS numbers for northern and southern pulps are based on the data in Table I.

The potential tensile strength of a 60-g/m^2 test sheet depends on the strength of the total cellulose cross section, i.e., N x S. The FS number correctly reflects this value, independent of coarseness. That is, it doesn't matter whether N changes or S changes, the FS number will correctly reflect the impact upon the potential handsheet tensile strength. Tear strength is quite another matter.

From Table III, it is apparent that the fiber strength, S, of the southern fibers is likely to be 10–25% *higher* than for the northern fibers, even though the FS number is 25% lower. The impact of this coarseness effect on tear index is two-fold. The increased fiber strength means that the critical bonding level will be higher, increasing the stripping energy associated with fiber pullout. On the other hand, the total number of fibers, N, across the tear failure line will be significantly reduced. It is likely that the increase in stripping energy outweighs the reduction in the number of available fibers, so that the maximum tear-index value will be enhanced, and the handsheet tear-index parameter would be expected to rise. It is thus likely that coarseness accounts for the difference in handsheet tear-index response between the northern and southern pulps identified in Figs. 2 and 4.

Conclusion

Mills conventionally monitor the quality of bleached kraft softwood market pulps in the laboratory by beating the pulps in a PFI mill, preparing handsheets, and testing the handsheets for physical properties. Tensile strength of handsheets from 24 commercial pulps showed a strong correlation with FS number (wet zero-span strength), as measured using the Pulmac PQ System. The rapidity, precision, and low cost of Pulmac data acquisition recommend the method as a reliable and economical means of monitoring pulp quality at the frequency required to accommodate modern trends in quality management.

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