Measurement of fiber length, coarseness, and shape with the fiber quality analyzer

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ABSTRACT

Fiber length, coarseness, and fiber curl index were measured for a variety of papermaking pulps using a new commercial instrument, the fiber quality analyzer (FQA). The results were compared with measurements obtained using other available methods. Fiber length measurements obtained with the FQA were similar to those reported by the Kajaani FS-200 fiber-length analyzer. Coarseness measurements obtained with the FQA were similar to results from both the FS-100 and the manual TAPPI method (TAPPI T 234 cm-84). Fiber curl index as measured by the FQA was approximately 20% lower than manual measurements obtained using image analysis. Repeatability and interlaboratory reproducibility data are reported for 3 samples at 11 laboratories. The FQA flow cell operated without plugging problems, suggesting that it is suitable for on-line measurements.

Application:

Evaluates the precision and accuracy of measurements of fiber length, coarseness, and curl as reported by the recently developed fiber quality analyzer.

THE FIBER QUALITY ANALYZER (FQA) is a new commercial apparatus that was adapted from a prototype imaging fiber analyzer (IFA). The prototype IFA was capable of rapidly and simultaneously measuring fiber curl, kink, and length distributions of papermaking fibers. Details of the prototype IFA—developed by Paprican and the University of British Columbia—have been reported previously *(1, 2)*. This report evaluates the accuracy and the precision of the commercial FQA, which was adapted from the prototype IFA by OpTest Equipment.

The FQA, like the IFA, comprises hydraulic, optical, and image-processing systems *(1, 2)*. A dilute suspension of pulp fibers is transported past the optical and imaging systems by a sheath flow cell that orients fibers hydrodynamically into a thin, nearly two-dimensional (2-D) plane. The sheath flow cell consists of a central fiber-bearing flow that passes through a tapered injector into a flow bounded by two convergent sheath flows. In the tapered region of the cell, preceding the imaging region, fibers are gradually oriented and positioned by the flow fields imposed by the cell taper. The image detection system consists of a 2-D 256 × 256 pixel CCD (charge-coupled device) camera. Its resolution and magnification correspond to a pixel size of about 35 μm at the fiber.

This report provides our validation of measurements of fiber length, coarseness, and curl with the FQA. The importance of these fiber characteristics on papermaking and product properties has been discussed previously *(3, 4)*.

MEASUREMENT OF FIBER LENGTH

The fiber length of papermaking pulps is generally expressed as an arithmetic mean, a length-weighted mean, or a weight-weighted mean, as defined by Eqs. 1–3, respectively *(5)*:

$$\ell_n = \frac{\Sigma_i n_i \ell_i}{\Sigma_i n_i} \tag{1}$$

$$\ell_{\ell w} = \frac{\Sigma_i n_i \ell_i^2}{\Sigma_i n_i \ell_i} \tag{2}$$

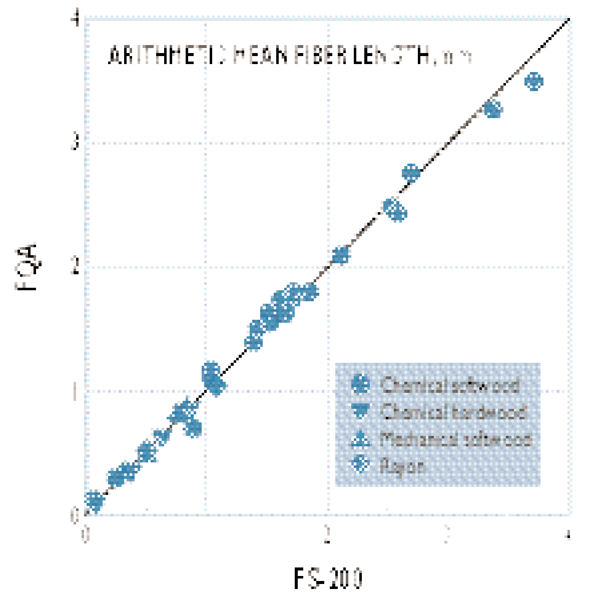
$$\ell_{ww} = \frac{\Sigma_i n_i \ell_i^3}{\Sigma_i n_i \ell_i^2} \tag{3}$$

Fibers are grouped into various length classes, and n_i is the number of fibers in the length class ℓ_i.

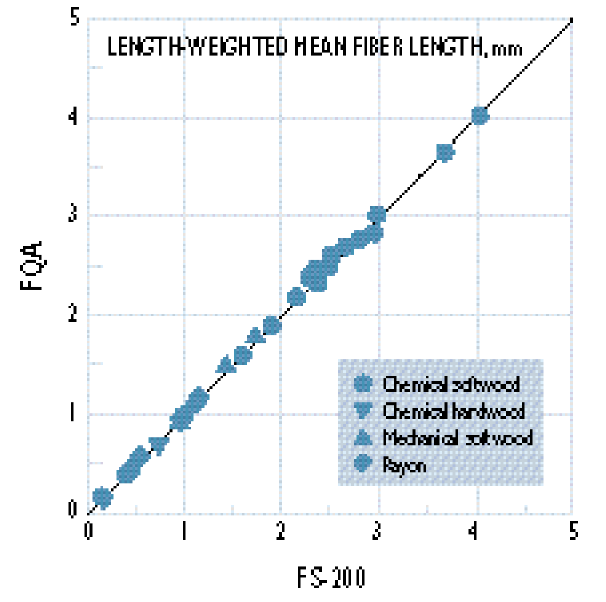
We measured fiber length with the FQA and compared the results with those obtained using a Kajaani FS-200 fiber-length analyzer. This is consistent with the approach used in our earlier validation of the IFA *(1)*. Both the FQA and the Kajaani FS-200 analyzer were calibrated and used according to the manufacturers' specifications *(6,7)*.

Several pulps were used in the validation study, including commercial and laboratory pulps, dried and never dried, chemical and mechanical, hardwoods and softwoods, and rayon fibers. Pulps were fractionated into different length fractions with a Bauer–McNett fiber classifier *(8)*, and these fines- and debris-free fractions were used for the comparison. Some whole pulps were also used.

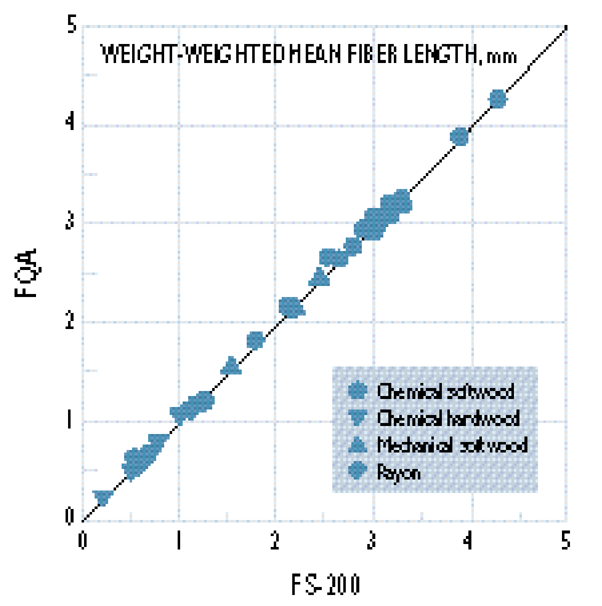
Figure 1 shows the arithmetic mean fiber length, ℓ_n, of various Bauer–McNett fractions as measured with the FQA and the FS-200. The length-weighted and the weight-weighted means, $\ell_{\ell w}$ and ℓ_{ww}, for the same fractions are compared in **Figs. 2 and 3**, respectively. Clearly, the FQA-measured fiber lengths agreed closely with those obtained with the FS-200.



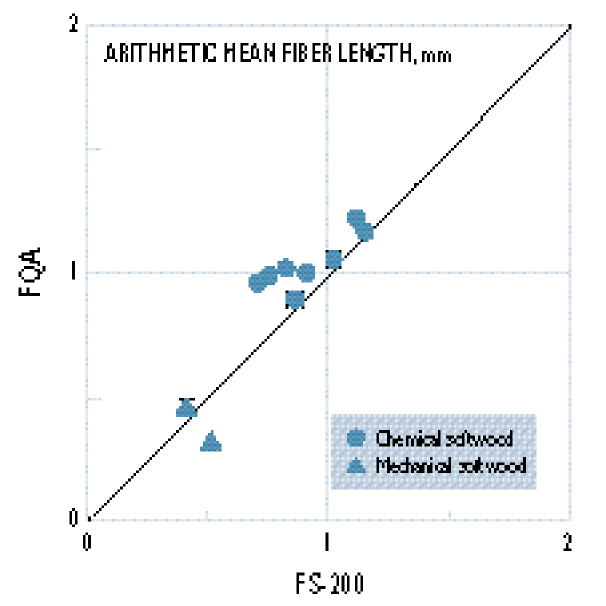
1. *Arithmetic mean fiber length as measured by FQA and FS-200 for various pulp fractions and debris-free whole pulps (37 samples). Error bars in this and subsequent figures depict 95% confidence limits on the mean. Note that error bars may be smaller than the symbols*



2. *Length-weighted mean fiber length as measured by FQA and FS-200 for various pulp fractions and debris-free whole pulps (37 samples)*

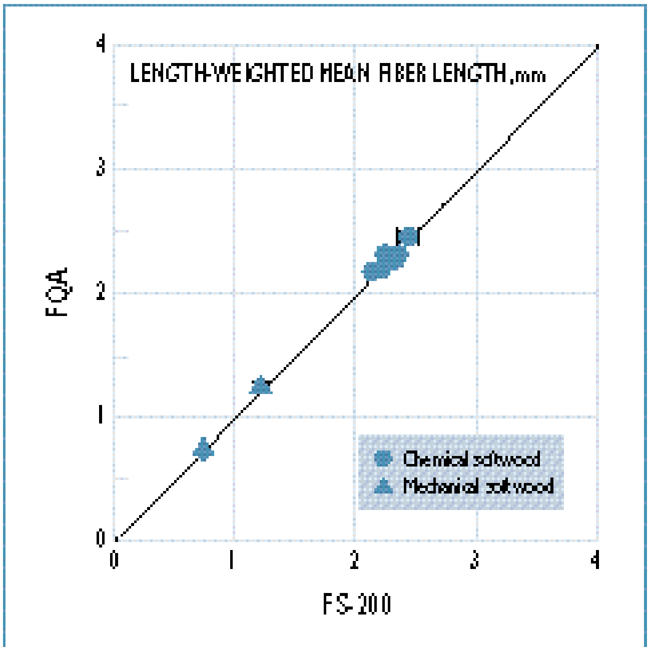


3. *Weight-weighted mean fiber length as measured by FQA and FS-200 for various pulp fractions and debris-free whole pulps (37 samples)*

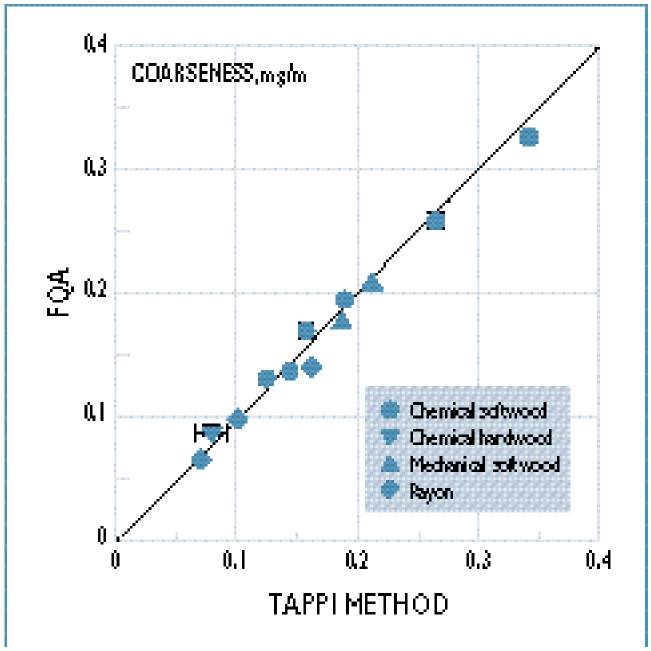


4. *Arithmetic mean fiber length as measured by FQA and FS-200 for whole pulps (10 samples)*

The arithmetic mean lengths measured with the FQA and FS-200 for some whole pulps are shown in **Fig. 4**. The results here are somewhat more scattered. Since the two instruments have different abilities to sample and detect fines—and because the arithmetic means are sensitive to the number of fines—the results differed. However, **Fig. 5** shows close agreement for the length-weighted means, since these means are less



5. Length-weighted mean fiber length as measured by FQA and FS-200 for whole pulps (10 samples)



6. Coarseness as measured by FQA and TAPPI T 234 cm-84 for various pulp fractions and debris-free whole pulps (12 samples)

sensitive to the presence of fines in the fiber populations.

MEASUREMENT OF FIBER COARSENESS

Pulp coarseness is defined as a mass of fibers per unit length. Accurate determination of fiber coarseness in pulps has always been a challenge *(5)*. One of the methods now commonly used relies on the measurement of the total length of a known mass of pulp fibers with an optical fiber-length analyzer. Coarseness is obtained by dividing the pulp mass by the total measured length of the fibers. In practice, coarseness C is obtained from Eq. 4.

$$C = \frac{m}{n\,\ell_n} \tag{4}$$

where

m = very small ovendry mass of fibers supplied to the analyzer

ℓ_n = arithmetic mean length of the fibers

n = total number of fibers in the mass m.

The length ℓ_n and the number n are provided by the analyzer.

The accuracy of coarseness determined from Eq. 4 depends on how well the three factors in the equation are measured or estimated. If the optical fiber-length analyzer provides accurate ℓ_n and n, then the accuracy of the measured coarseness depends on the accuracy of m. A method to deliver an accurately known small fiber mass m to an analyzer, based on an indirect weight determination, has been discussed *(9)*. However, we used a direct-weight dilution method. In this method, a representative pulp sample is air-dried under standard conditions in a room with constant temperature and humidity, and a small mass m is directly weighed to an accuracy of 0.01 mg using an analytical balance. This mass is subsequently soaked, dispersed, and diluted, and the weighed aliquots deliver the appropriate fiber concentration to the fiber analyzers.

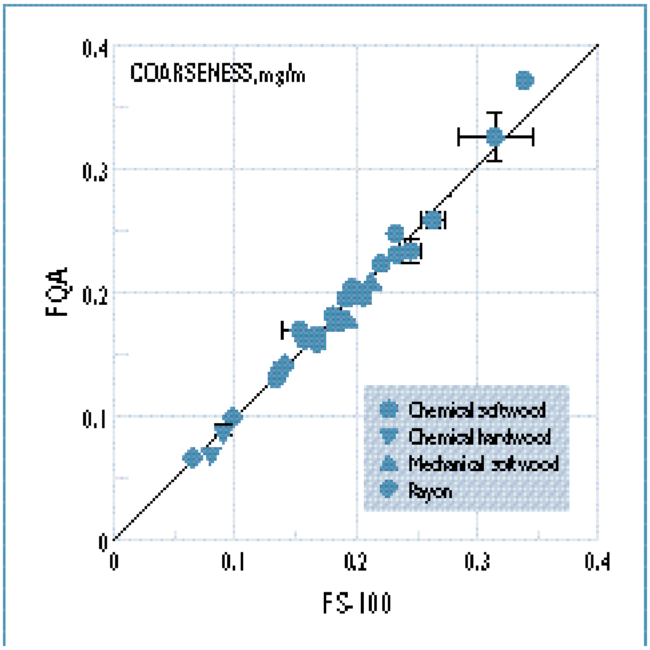
The other method of coarseness measurement is based on the principle of the statistical geometry of a fiber network *(5)*. According to this approach, coarseness C is related to the number N of fibers intersecting length L of a scan line in a random network of low grammage W by Eq. 5.

$$C = \frac{2WL}{\pi N} \tag{5}$$

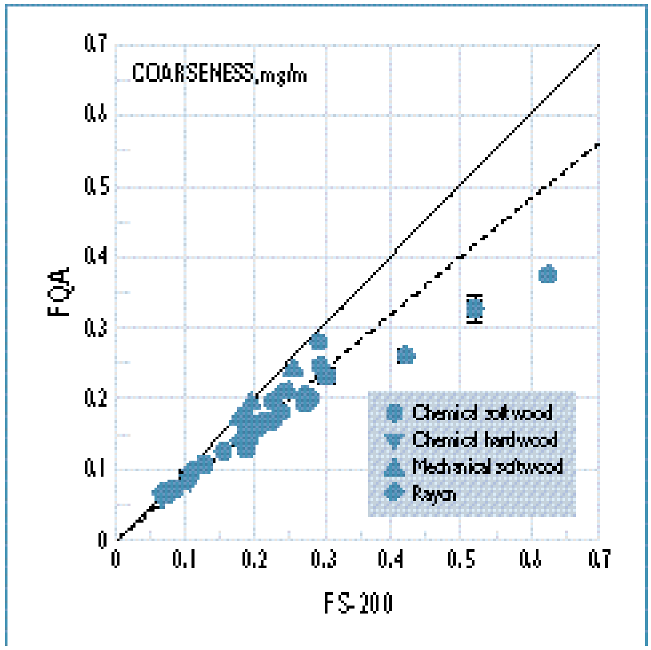
The mass of fibers deposited per unit area in the network has to be known accurately, and a large number of fiber crossings along the scan lines has to be counted to obtain fiber coarseness with sufficient accuracy. The TAPPI test method for measuring fiber coarseness *(10)* is based on this principle.

We have compared fiber coarseness as measured with the FQA against coarsenesses obtained from the optical fiber analyzers (Kajaani FS-100 and FS-200) and the TAPPI method. The optical analyzers were operated according to the manufacturer's specifications *(6, 7, 11)*. An important requisite in coarseness measurement is that the pulp sample must be debris free *(5, 9, 10)*. Therefore, the comparisons were made using Bauer–McNett fractions of various pulps or on whole pulps from which the debris had been removed. A variety of chemical and mechanical pulps were employed.

The results in **Figs. 6–8** show the FQA coarseness measurements vs. those obtained with the TAPPI method, the FS-100, and the FS-200, respectively. While the FQA vs. TAPPI and the FQA vs. FS-100 results



7. Coarseness as measured by FQA and FS-100 for various pulp fractions and debris-free whole pulps (27 samples)



8. Coarseness as measured by FQA and FS-200 for various pulp fractions and debris-free whole pulps (36 samples)

agreed closely, the FQA vs. FS-200 did not. For the typical coarseness range (0–0.3 mg/m), the FS-200 was approximately 30% higher than the FQA, while for high-coarseness pulps (>0.3 mg/m), the FS-200 was on average 65% higher than the FQA.

MEASUREMENT OF FIBER CURL AND KINK

Fiber curl describes the deviation from straightness of the fiber axis. Fibers in wood are straight. They become curly during pulping, mixing, and refining through exposure to bending and axial compressive stresses, particularly at medium and high consistencies. The curl is set-in during drying. Fiber curl index is illustrated in **Fig. 9** and defined by Eq. 6 *(4)*.

$$CI = \frac{\ell}{L} - 1 \qquad (6)$$

where

CI = curl index
ℓ = fiber contour length
L = longest dimension

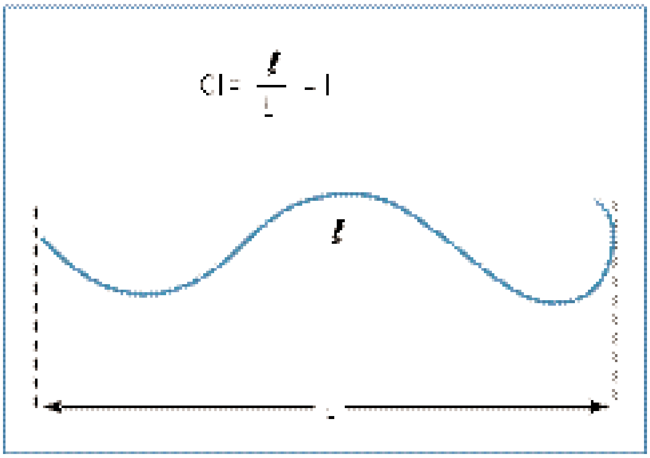
Thus curl index is the relative increase in the length of a fiber when it is straightened but not stretched. For very conformable fibers, the wet-web stretch at low solids is proportional to the curl index *(4)*.

The mechanisms of curl induction, removal, and retention in pulp fibers have been discussed *(4)*. In mechanical pulps, curl is manifest as stress or deformation in the lignocellulosic matrix of the fiber wall. Fibers straighten as the stress is relaxed. This occurs during latency removal, when fibers are stirred at low consistencies and at elevated temperatures. In chemical pulps, on the other hand, curl results from deformation in the amorphous, viscoelastic regions of the cellulosic fibrils.

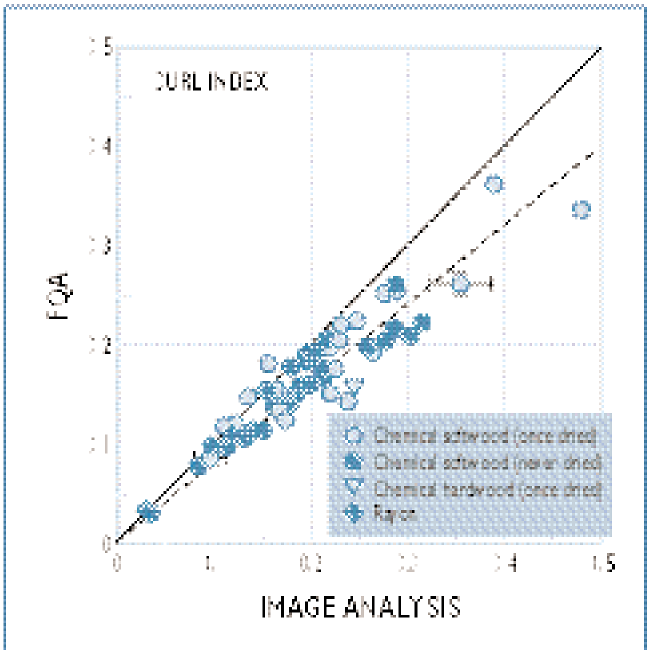
Fiber curl can change with mechanical treatment. We have shown that curl index can decrease quickly during the first few minutes of mechanical disintegration, e.g., in a British standard disintegrator. Therefore, when comparing curl in different samples, similar gentle disintegration procedures should be employed.

We measured the curl index of fibers using the FQA and compared the results with curl index as measured "manually" by image analysis. The "manual" curl index was obtained using conventional image analysis *(4)* on suspensions placed in a flat glass dish. This is consistent with the approach used in our earlier validation of the IFA *(1)*. We measured curl on a variety of chemical pulps having a range of fiber curl. These included laboratory-made and commercial, dried and never-dried pulps, some beaten or refined and curlated. Most of the never-dried pulps were taken from different bleaching stages in various mills, and the once-dried samples were commercial dry laps. Each pulp was gently dispersed in water, and similar samples of this dilute suspension were used for the manual and FQA measurements.

For fibers of similar curvature, shorter fibers have a lower curl index, i.e., shorter fibers are straighter. Because manual image analysis may not reliably count all of the short fibers, the manual and FQA measurements for each sample were compared for fiber populations of similar length distributions obtained from the same parent sample. This was achieved by comparing the mean curl index of fibers longer than 1.0 mm or 1.5 mm, depending on the sample.



9. *Definition of fiber curl index*



10. Curl index as measured by FQA and manually (image analysis) for various pulp fractions and debris-free whole pulps (54 samples)

Figure 10 shows a comparison of the FQA-measured curl index against the manually measured curl index. The FQA curl, on average, was approximately 20% lower than the manually measured curl. The reasons for this are not entirely clear, despite careful efforts to compare the two methods.

We did not attempt to compare FQA-measured kink index because manual measurements were not available.

PRECISION STATISTICS

Table I shows the precision statistics for the fiber quality analyzers. The data are based on three pulp samples tested by 11 different laboratories. The tests were carried out according to TAPPI T 1200 sp-91, "Interlaboratory evaluation of test methods to determine TAPPI repeatability and reproducibility." The whole pulps were commercial, dried, bleached kraft produced from softwood or hardwood. The R-14 Bauer–McNett fraction of the softwood pulp was also tested. The samples were provided as slurries of known fiber concentrations. Similar testing procedures were followed by each laboratory. Ten measurements were made for each test. The results were adjusted according to TAPPI T 1205 sp-92, "Dealing with suspect (outlying) test determinations." The precision statistics were obtained following TAPPI T 1206 sp-91 "Precision statement for test methods." The repeatabilities and reproducibilities indicate the limits within which agreement can be expected 95% of the time between two test results obtained on similar samples tested under similar conditions.

	HARDWOOD	SOFTWOOD	
	Whole pulp	Whole pulp	R-14 fraction[a]
Length-weighted fiber length			
Grand mean, mm	0.65	2.22	3.09
Repeatability,[b] %	4.1	2.7	2.2
Reproducibility,[b] %	8.7	7.9	8.3
Coarseness			
Grand mean, mg/m	0.085	0.140	0.146
Repeatability,[b] %	12.0	11.0	6.6
Reproducibility,[b] %	29	14	23
Curl index			
Grand mean	0.070	0.125	0.137
Repeatability,[b] %	6.1	6.7	6.1
Reproducibility,[b] %	19	21	17

[a] Fiber fraction obtained by retention on a 14-mesh screen in a Bauer–McNett fiber-length classifier.
[b] Limits within which agreement can be expected 95% of the time between two test results obtained on similar samples tested under similar conditions. Repeatability refers to replicate measurements within a single laboratory; reproducibility refers to test results obtained from different laboratories.

I. Precision statistics for fiber quality analyzers

CONCLUSIONS

We measured fiber length, coarseness, and fiber curl for a variety of papermaking pulps using a new commercial apparatus, the fiber quality analyzer (FQA). The results were compared with measurements obtained using other available methods. We found that:

1. The FQA fiber length measurement is similar to fiber length as measured by the FS-200 fiber-length analyzer.
2. The FQA coarseness measurement is similar to coarsenesses obtained using the FS-100 or TAPPI T

234 cm-84. However, the FS-200 provided coarseness measurements that were approximately 30% higher than the other methods.

3. The FQA curl index measurement was approximately 20% lower than manual measurements obtained using image analysis.
4. The FQA was free from plugging for all samples tested, indicating that it should be suitable for online measurements. TJ

Robertson and Olson are research engineers; Allen and Chan are technical specialists; and Seth is head of the Fibre and Product Quality Section. This article was written while all were affiliated with PAPRICAN, 3800 Wesbrook Mall, Vancouver, BC, Canada V6S 2L9. Robertson is now with Morphometrix Technologies Inc., and Olson is now with the Dept. of Mechanical Engineering at the University of British Columbia.

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