Pulp strength delivery along complete kraft mill fiber lines

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ABSTRACT: Kraft pulps are prized for their superior physical properties. Some strength is lost in digester operations, but what happens along the rest of the fiber line? Not surprisingly, that depends on the design of the mill and on how it is operated. When pulp performance is measured from samples taken along a complete fiber line, papermakers can see how the kraft pulp changes physically as it progresses through oxygen delignification and bleaching. Such a characterization of a kraft mill's fiber line can identify where improvements are needed.

KEYWORDS: Bleaching, chemical reactions, chemical treatment, delignification, kraft mills, mechanical properties, mills (factories), oxygen, performance, plant departments, pulp mills, pulp properties, sampling.

Kraft pulps dominate the marketplace for wood pulps. They are clean and strong, and they are stable in appearance. These qualities make them ideal for manufacturing high-quality printing papers. But the unique attribute of *softwood* kraft pulp is physical strength above and beyond that offered by any other type of commercial wood pulp.

Research in the 1980s demonstrated that softwood kraft pulps could be even stronger if only the strength potential inherent in a wood supply were preserved in kraft pulpmaking operations (*1–4*). Digester operations, both batch and continuous, were the main culprits in undermining strength, being responsible for a shortfall of about 25% in tear–tensile strength in the production of a typical bleachable-grade softwood pulp. Curiously, short-fibered hardwood pulps have no such strength deficit.

In bleachable-grade pulping, digesters routinely achieve more than 90% delignification of the wood. Afterward, extensive operations are needed to remove the small amount of residual lignin and render the fibers white.

Based on earlier studies of strength delivery in digesters, then, it is natural to pose questions about the rest of these fiber line operations. Do oxygen delignification and individual bleaching stages cause further deteriorations in strength? If so, by how much? What other physical characteristics of fibers change along fiber lines? And are there significant differences in pulp strength delivery between modern fiber lines and their predecessors in older mills?

In earlier studies, the investigation of pulp strength loss in conventional hot-blown batch digester operations (*5*) led to ways to overcome most of the problem (*6*), but a comparable understanding of pulp strength deterioration in continuous digesters has yet to be gained. The brownstock processing line that follows cooking is unlikely to damage the pulp (*7*). Unfortunately, information on strength delivery from brownstock storage to the end of bleach plants is sparse. We need this knowledge to ensure that top-quality bleached fiber is available for papermaking.

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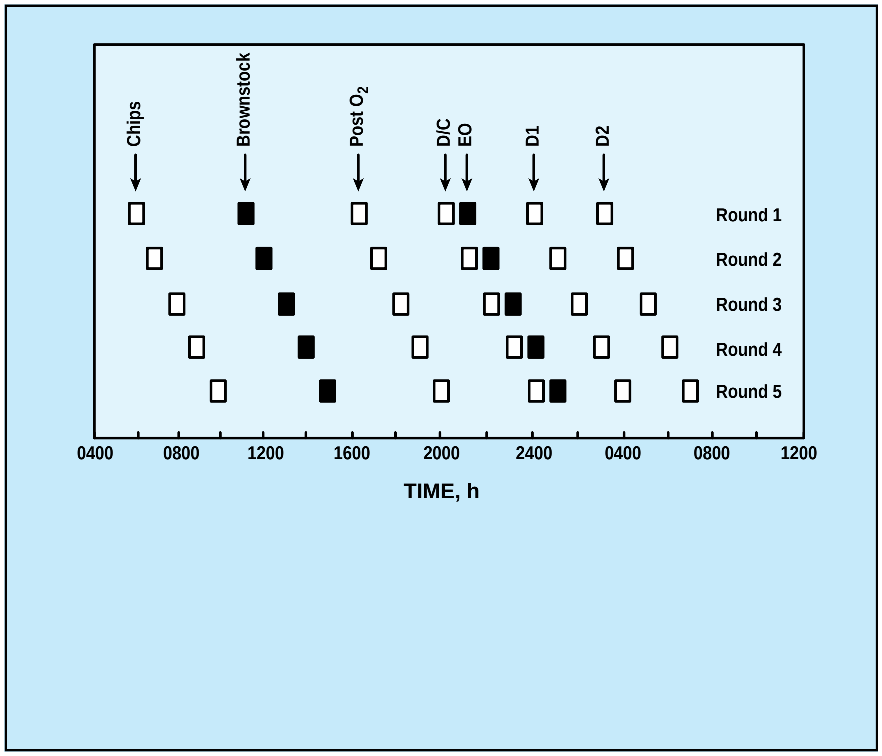
Picture the main chemical operations along a modern kraft mill fiber line: pulping, oxygen delignification, and three or four stages of bleaching. A database of pulp strength characterization exists for the first of these (*8*). As for the downstream operations, little comparable information is available, and what information there is usually pertains to mills of an earlier era. Here are two examples:

- Samples of softwood kraft pulp were taken along a CEHDED bleach plant. Breaking length values decreased significantly toward the end of bleaching. Simultaneously, stretch more than doubled, where brownstock was compared with the fully bleached pulp. This increase in stretch was ascribed to cumulative curling of fibers as the pulp passed through pumps and mixers at medium consistency (*9*).
- A CEHED bleach plant was converted in the late 1970s to CEHDED, and the fully bleached softwood kraft pulp gained 12% in "intrinsic strength" (tearing resistance at constant tensile strength) (*10*). When the process was operated as a CEDED or CEWDED sequence, a further 15% strength gain was possible. But because the bleaching stages weren't tested individually, it cannot be said that the strength problem was exclusively in the chemistry of the hypochlorite (H) stage.

These examples suggest that to achieve the physical properties one wants in bleached kraft pulp, it is necessary to have a comprehensive knowledge of what happens to the pulp as it progresses along the fiber line. With softwoods, a considerable amount of strength is lost just in the pulping operation, so we can ill afford to lose more in the operations that follow. If further strength losses are taking place, the causes need to be characterized and corrected.

1. Five samples are collected at one-hour intervals at each of the locations of interest.



Strength considerations in kraft pulp manufacturing and marketing are becoming more critical than ever. With the advent of the extended delignification era, much more is being demanded of pulping systems. Kappa number targets are usually lower by a third or more from traditional levels (e.g., from kappa no. 30 down to 20 or less with softwoods). Oxygen delignification often follows extended delignification and is expected to bring the kappa number down to the low teens. Bleaching, then, has far less chemical work to do than in the past. Still, the use of hydrogen peroxide and perhaps ozone may mitigate against the preservation of pulp strength where the common use of chlorine dioxide would have caused no problems.

Furthermore, consider the possibilities for fiber damage during stock preparation ahead of paper machines. The intention is to make the fibers more flexible, but at what price in strength? It is easy to see that great care needs to be taken to preserve kraft fiber strength all the way from pulping to the end of bleaching. The first step is to characterize the complete kraft mill fiber line.

Fiber line sampling

To begin with, the mill must be operating at steady-state conditions. The aim is to characterize operations that are under control and on target. In other words, each unit operation does its job effectively and passes the pulp on to the next unit.

We assume that plug flow exists through each process unit and storage vessel. The time lags between sampling points in a mill are estimated from the production rate, from the volumes and retention times of the vessels, and from the collective experience of knowledgeable production and technical people at the mill. Where uncertainty exists, retention times must be measured by tracer techniques.

We pay close attention to operating parameters and process condi-

I. Domtar classifications of softwood chips being sent to the digester systems in five mills making bleachable-grade pulps

	<2 mm	*2–8 mm*	*>8 mm*
Mill 1	8	78	14
Mill 2	10	78	12
Mill 3	3	84	13
Mill 4	4	87	9
Mill 5	2	95	3

Each value is the average of five samples, expressed as a percent of total mass.

II. Average measurements of basic density, solids content, and bark content of chip samples from Mills 5 and 6

	Mill 5 (softwood)	*Mill 6 (hardwood)*
Basic density, g/cm^3	0.46	0.53
Solids content, %		
Average	47.5	57.9
Range	46.9–48.3	57.1–59.4
Bark content, %	1.0	. . .

tions. The mill's operating log sheets provide a proper context for the information obtained during the sampling run. Essential to this context are the log sheets that cover the period from at least 24 h before sampling to 24 h afterward.

Second, the flow of chips and that of pulp must be sampled, processed, and analyzed systematically. To do this, we first choose locations of interest along the fiber line, usually after each of the major chemical operations. We sample chips at an accessible drop point closest to where they enter the chip bin or chute feeding a digester. Pulp samples are taken at locations that are at atmospheric pressure or close to it, preferably at the exit sides of pulp washers or at permanent pulp sampling stations installed for the purpose. We make use of sampling valves on the discharge sides of stock pumps, pipe samplers in drop chutes from diffusion washers, and "paddle" sampling from the pulp mats on the faces of vacuum drum washers.

Our usual strategy is to acquire five samples at one-hour intervals at each chosen sampling point along the fiber line. Usually, we take pulp samples of about 1 kg each (on an oven-dry basis). We also acquire five chip samples (about 20 kg each, o.d. basis) from which we later make five pilot-plant reference pulps. Our sampling procedures have been described in detail elsewhere (*2*, *4*). When the sampling work is finished, we have a matrix of samples and times such as that illustrated in **Fig. 1**.

At the brownstock sampling point, we also take small pulp samples (about 100 g, o.d. basis) every 10 or 15 min. These samples are processed in the same way as the larger brownstock samples, and their kappa numbers are measured to produce a kappa variability picture over the sampling time. Ten-minute frequency is faster than what most mills manage at this location, even those with automatic kappa number analyzers.

Sample characterization

We use the following methods and measurements to characterize the samples.

Chips. Wood chips are measured for thickness distribution (Domtar classifier), basic density, bulk density, solids content, and bark content.

Pulp acquisition and processing. At each sampling point, we take small samples (about 100 g, o.d. basis) every minute for ten minutes and consolidate them into a single composite sample. The composite sample is immediately washed with clean mill water on a 200-mesh stainless steel screen basket until the filtrate is clear and colorless. The pulp is squeezed by hand into pulp balls, and these balls are sealed in plastic bags. Back at Paprican, we rewash the samples thoroughly with cold water on a 200-mesh screen and screen them on a vibrating flat screen having 0.25-mm slots. The screen rejects are dried, weighed, and recorded as a percentage of the pulp mass originally sampled.

Kappa number and viscosity. Kappa numbers are measured on screened pulp according to CPPA-Technical Section Standard Method G.18. To measure pulp viscosities, the samples are first delignified in mild acidic chlorite solution for 18 h, then dissolved in 0.5% cupriethylenediamine solution and measured in capillary viscometers according to CPPA-Technical Section Standard Method G.24P.

Reference pulp preparation. The detailed procedures have been described previously (*3*). Our goal is to conduct conventional kraft batch cooks of mill chips under precise control, using chemical and process conditions closely approximating those recorded in the mill at the time of pulp sampling. Nothing is removed from the chip samples prior to pulping.

A 2-kg portion of each chip sample is cooked in a 20-L forced-circulation digester to produce a pilot-plant reference pulp with a kappa number matching that of its time–coordinated, mill-made brownstock sample. We use conventional kraft cooking conditions meant to closely model those in the mill being studied. Usually the values fall within the following ranges: 17–19% active alkali on wood, 25–35% sulfidity, liquor:wood ratio of 3.5:1 to 4.5:1, and a 70–90 min period of increasing temperature to a maximum cooking temperature of 162–172°C. Cooking times are suitable to reach the target kappa numbers.

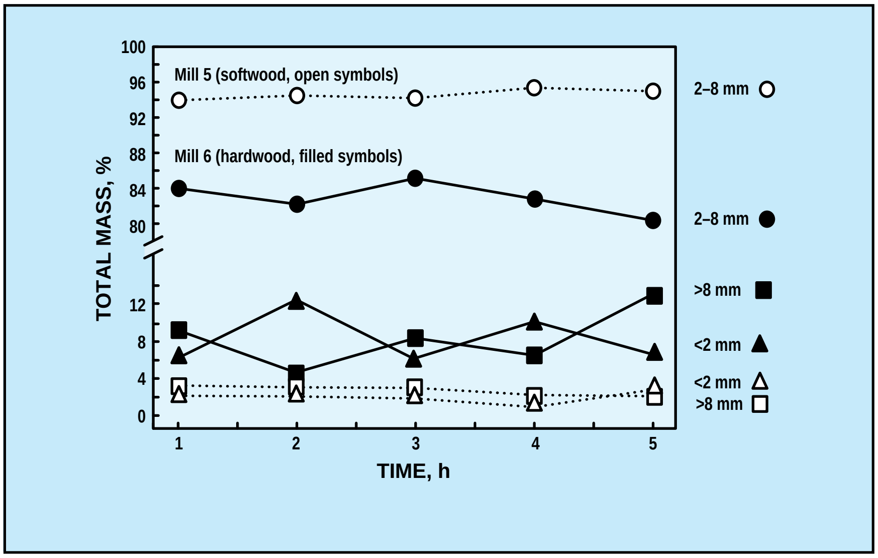
Pulp testing. On a routine basis, we conduct PFI mill beating runs and measure the following physical properties of handsheets made from each pulp sample: grammage, apparent density, burst, tear strength, tensile strength, stretch, tensile energy absorption, scattering coefficient, absorption coefficient, opacity, brightness, and zero-span tensile strength. CPPA-Technical Section standard methods are used.

Chip quality

Because we need mill chips from which to make pilot-plant reference pulps, the timed work in a mill always begins with chip sampling. We take at least five chip samples, one hour apart. Each of these hourly samples is composed of ten subsamples taken at one-minute intervals. The sampling point must provide access to the full cross-sectional flow of chips nearest to where they enter the digester system. The reference pulps made from these chips serve as a basis of comparison between different mill fiber lines.

Table I lists chip thickness results from five different mills, all making bleachable-grade softwood kraft pulp. Each number is the average of the values measured on five samples.

2. At Mill 5, the accepts fraction (2–8 mm chips) was high and steady, and the rejects fractions were low. The rejects fractions at Mill 6 were larger and more variable.



- The chips at Mill 1, a 1970s-vintage mill, had 8% undersize material (<2 mm thick) and 14% overthick material (>8 mm). Mill 1 had pneumatic blowing of chips to and from the chip pile, and it had no system for screening chips by thickness.
- Mill 2 had a disc scalping screen, reciprocating accepts screens, and pneumatic blowing of chips. In thickness distribution, its chips were comparable to those of Mill 1.
- Mills 3, 4, and 5 had modern chip thickness screening systems—disc scalping, disc screening for accepts, slicing of overthick material, and fines separation. Equipment for each of these plants was purchased from a different manufacturer, but all three had comparable specifications for chip size control.

Mill 5 had few overthick chips and only half as much undersize material as the next closest case. Mill 4 controlled its overthick material well but had twice the amount of material of less than 2 mm as had Mill 5. Mill 3 had too much material in both categories.

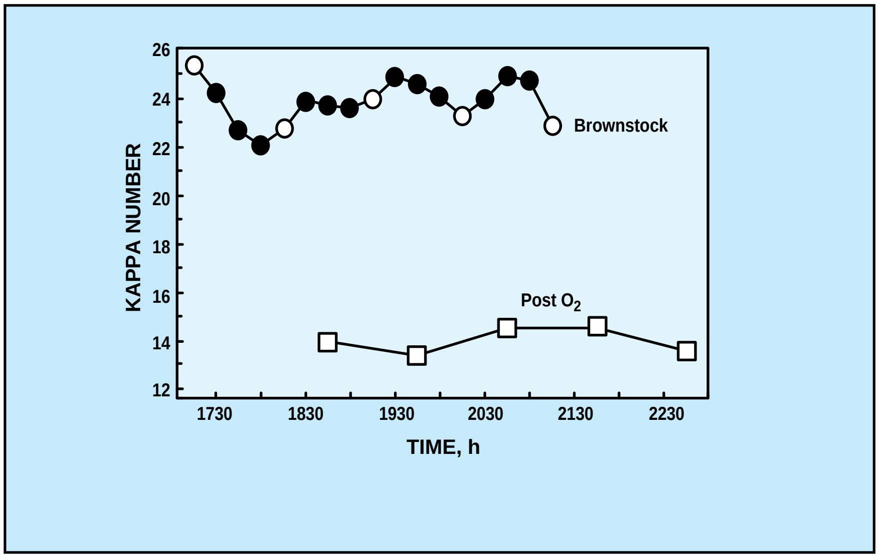
This comparison points out that it is not enough simply to operate a properly specified, complete chip thickness sereening system. Regular monitoring is necessary to determine whether the system is indeed delivering the desired chips to the digester plant. It is probable that as much variability comes from the chip furnish as from any other single source in a kraft mill, so vigilance is important here.

We routinely measure other facets of chip quality with the same chip samples. **Table II** and **Fig. 2** show examples of results from Mill 5 and Mill 6 (a mill producing bleachable-grade hardwood pulp).

Reference pulps

The rate and yield data from the reference pulping provide direct information on realistic numbers that characterize these aspects of mill operations. People at mills already have their own pulping rate data, but often they do not have factual yield/kappa information. Our work provides such data, specific to each mill's chip furnish.

3. These brownstock and post-oxygen kappa number patterns were found at Mill 5.



Physical properties of mill-made pulps

Kappa number trends

To determine whether or not a digester system is running under good control, we plot the brownstock kappa numbers against time. We compare the results with those values determined in routine mill testing. **Figure 3** shows results from Mill 5, a good case. Across this four-hour window, the kappa variability of the brownstock at 15-min intervals was 7.5% of the average value (at 95% confidence limits). The best case we have ever measured, for a single-vessel hydraulic Kamyr digester running on a mixed softwood furnish, averaged kappa no. 20.0 with a variability of ± 0.7 kappa units.

If the variability in kappa number is too large (e.g., >20% of the average value), then the pulping cannot be considered close to steady-state, and the entire set of samples must be abandoned. Thus, the mill's brownstock kappa number picture is always the first thing we determine back at our pilot plant.

We routinely measure the kappa number pattern after oxygen delignification too. Here, only hourly samples are taken and processed. Figure 3 shows the post-O_2 results from Mill 5. Oxygen delignification averaged 41% during the test period, with an average post-O_2 kappa number of 14.1 and a variability of 1.1 kappa units (at 95% confidence limits). You can also see the correspondence between the brownstock and post-O_2 kappa numbers—when the brownstock number moves up or down, the post-O_2 number usually mirrors the shift. This suggests that our assumption of plug flow of pulp is correct.

In Mill 5, we also measured the DC and EO kappa numbers of the hourly samples. The kappa numbers for the DC samples averaged 3.6, the EO kappa numbers averaged 1.5, and variability was low at both locations (**Table III**).

Pulp viscosities

Pulp viscosities do not predict pulp strength delivery values correctly, but they do provide a picture of the depolymerization of the polysaccharides in the pulp passing along the fiber line.

In Mill 5, the brownstock samples averaged 32.8 mPa·s, slightly higher than the pilot-plant pulps (30.9 mPa·s). After oxygen delignification, the mill pulp averaged 24.7 mPa·s, or 75% retention of the degree of depolymerization (DP) of the brownstock. After the second D stage, the average pulp viscosity was 18.8 mPa·s (57% retention of DP from the brownstock).

As we will see, these viscosity losses were much greater than the tear–tensile strength losses measured with the same pulp samples.

Fiber length

The weight-weighted average fiber length data from Mill 5 are summarized in **Table IV**. Relative to the pilot-plant reference pulps, the mill-made brownstock had a deficit of 0.15 mm in average fiber length. This difference might seem small, but it indicates the likelihood of pulp strength problems because Mill 5 pulps softwoods.

A further loss of 0.11 mm occurred across the oxygen delignification system, after which no further reductions in fiber length took place.

Strength losses along a fiber line, though, are not always mirrored reliably by changes in average fiber length. Other factors are also involved.

Tear–tensile strength

The tear–tensile data are at the heart of pulp strength delivery studies. By comparing the tear–tensile performance of each mill-made pulp sample to that of its corresponding pilot-plant reference pulp, strength delivery values (on a percentage basis) can be calculated (*4*). They show how much "overall strength" a mill's fiber line retains relative to what is inherently possible from its wood furnish.

Figure 4 presents strength delivery results at Mill 5. The values were calculated from tear indexes, each at a fixed, mid-range breaking length. The unbleached pilot-plant pulps (PP) are defined as having 100% tear–tensile performance. These measured values were used as the reference points of strength delivery for all comparisons with the mill-made pulps, regardless of the sampling location along the fiber line.

The mill's brownstock averaged 82% tear–tensile strength delivery, the oxygen-delignified stock (O_2) averaged 77%, and the fully bleached stock (D2) averaged 72%. There were small strength delivery deficits through the bleach plant, about evenly distributed across the four stages.

Sometimes, a lower-than-average or higher-than-average result was observed in the mill's brownstock, such as the lower-than-average strength for the brownstock in Round 4. Such a pattern tended to continue along the fiber line until the variability was so low that the pattern disappeared. Once again, this is a reflection of plug flow through the mill. Variability in absolute pulp strength across time was very small at any particular location of sampling.

When the strength deficit in brownstock was separated into its tear and tensile strength components, about two-thirds of the total was missing tear strength, and one-third was missing tensile strength. **Figure 5** illustrates this result as a strength vector diagram *(11)*.

Other physical properties

Once we have acquired extensive physical testing data for characterizing a complete fiber line, many types of comparisons are possible. Here are some examples, taking the properties of freeness, bulk, and stretch, as presented in Table IV.

Freeness. Mill 5's brownstock and the corresponding pilot-plant samples were close in unbeaten freeness, and only small decreases occurred during oxygen delignification and bleaching.

In Mill 6, a hardwood mill, the average brownstock freeness was 56 mL higher than that of the pilot-plant pulps. After bleaching, a 53-mL drop in freeness had taken place in the mill-made pulp.

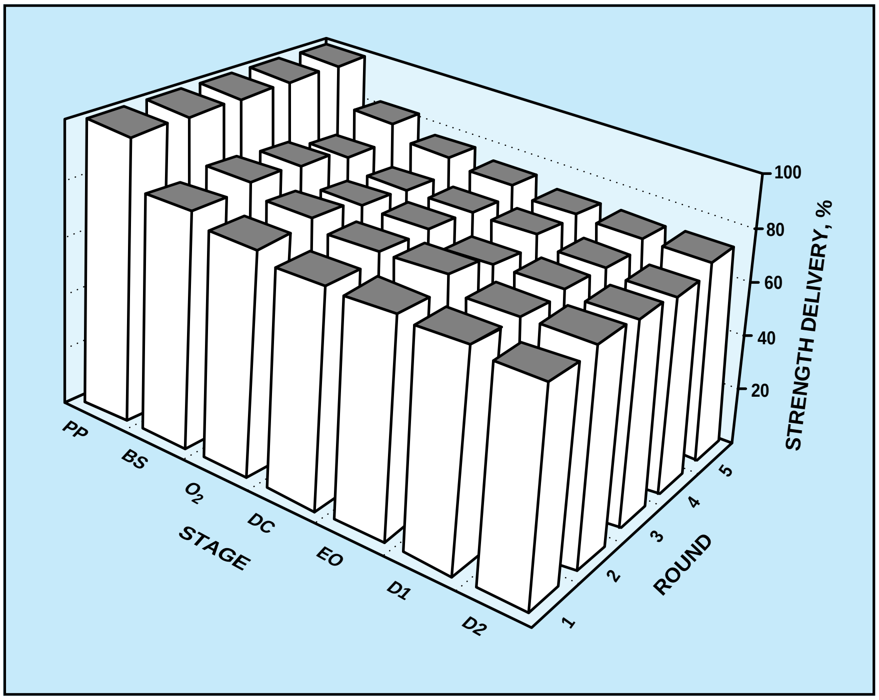
Bulk. The initial bulk values of the brownstock samples from Mill 5 were similar to those of the reference pulps. Initial bulk was reduced substantially through oxygen delignification and less so across the bleach plant. Final bulk (at 7000 PFI revolutions) was also most affected in the O_2 system.

The average bulk of Mill 6's unbeaten brownstock was higher than that of the reference pulps; it decreased only slightly through the bleach plant.

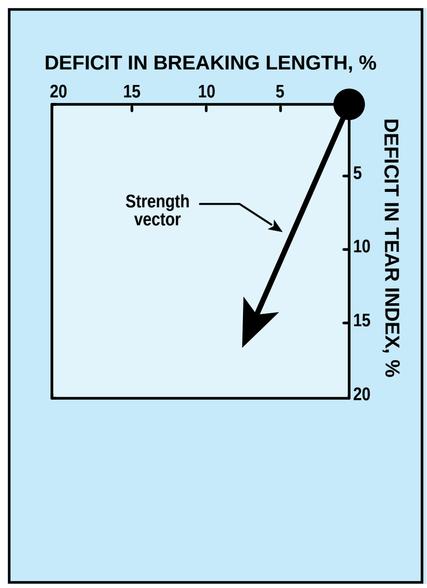
Stretch. In Mill 5, initial stretch went progressively upward from the unbleached end of the fiber line to the bleached end. The mill-made brownstock had higher initial stretch than did the pilot-plant brownstock. These are the normal cumulative effects of passage of pulp through a succession of medium-consistency pumps, mixers, and similar devices (*9*). Also, the less lignin left in the fibers, the more apparent is this effect.

The same pattern of increasing stretch was found along the fiber line of Mill 6.

4. Pulp strength delivery at Mill 5.



5. A deficit in tearing resistance was two-thirds of the problem in Mill 5.



Discussion

The systematic study of pulp performance along a kraft mill's fiber line establishes a profile of how well it can deliver strength from the chip furnish to the finished pulp. Among the examples presented here, it is apparent that overall strength, when

III. Kappa numbers of the pulps acquired in Mill 5

	Round						
	R1	*R2*	*R3*	*R4*	*R5*	*Mean*	*95% conf.*
Brownstock	25.3	22.8	22.9	24.0	23.3	23.7	2.1
Post O_2	14.0	13.5	13.6	14.6	14.6	14.1	1.1
After DC	3.4	3.6	3.5	3.8	3.9	3.6	0.5
After EO	1.5	1.5	1.4	1.5	1.6	1.5	0.1

95% conf. = 95% confidence limit

IV. Properties of unbeaten pulps from Mills 5 and 6

	Pilot plant	*Digester*	*O_2*	*DC*	*EO*	*D1*	*D2*
	Average fiber length, mm						
Mill 5 (softwood)	3.65	3.50	3.39	3.38	3.40	3.40	3.40
Mill 6 (hardwood)	0.97	0.91	. . .	. . .	0.88	0.87	. . .
	Freeness, mL CSF						
Mill 5	725	734	727	719	718	721	720
Mill 6	495	551	. . .	. . .	518	498	. . .
	Bulk, cm^3/g						
Mill 5	2.16	2.20	2.02	1.95	1.90	1.91	1.88
Mill 6	1.70	1.82	. . .	. . .	1.69	1.72	. . .
	Stretch, %						
Mill 5	1.72	1.96	2.53	2.84	3.05	3.09	3.24
Mill 6	1.97	1.96	. . .	. . .	2.70	2.84	. . .

measured as tear–tensile performance, can be significantly worse than we might expect from kraft pulping and common bleaching chemistries.

In bleached softwood pulp operations, a large strength penalty occurs in the digester system. This loss is then compounded by smaller but cumulative strength losses in oxygen delignification and bleaching. Expressed as strength delivery numbers, a very good mill could produce brownstock at 85%, post-O_2 pulp at 80%, and fully bleached pulp at 75%. More broadly, the brownstock in softwood kraft mills usually falls in the range of 70–85%, and the bleached pulp falls in the range of 60–75%.

The biggest single strength problem still resides with digester systems, so it is appropriate to ask where the upper limit of pulp strength delivery lies. Currently, the answer seems to be 95–100%, as demonstrated in referenced tests of one liquor-displacement batch mill (*12*). The stronger brownstock made this way retains its extra strength after bleaching, and its superior physical performance will be advantageous in papermaking (*12*).

In general, small-scale laboratory bleaching appears to cause no mechanical damage to fibers. Very selective lignin removal results in pulps at least equal in strength to their parent unbleached pulps and often in pulps that are even a little better. This outcome is clearly not the case in bleach plants in mills, where strength losses of 5–10% are often found.

The strength picture for oxygen delignification in laboratory equipment is not well documented, so its comparison to mill operations is uncertain. Our work indicates that oxygen delignification systems in mills have strength delivery penalties of 5% or more. It is not clear how much of this problem can be attributed to improper chemistry and how much to physical damage of fibers. This lack of knowledge is similar to that which existed in regard to batch digester operations before the puzzle of missing strength was solved (*5*, *6*).

Other aspects of kraft pulp strength can be studied comprehensively once a complete fiber line profile is in hand. For example, studies of brownstock strength delivery from digesters showed the way to improved retention of fiber and pulp strength (*2*, *4*, *5*). Does this extra strength carry forward to the end of bleaching? The answer was "yes" in at least one case (*12*). The work we have reported here demonstrates that the increment of strength loss diminishes as one proceeds along a fiber line. So an improvement in brownstock strength can reasonably be expected to carry to the end of a bleach plant.

What can we expect from the new "extended delignification" digesters now found in some kraft mills? It depends on the components of the whole fiber line. A new digester system may be better or no different from earlier ones in brownstock strength delivery (*8*). A new bleach plant, especially an ECF one, will probably cause less strength loss than older plants. An oxygen delignification plant will add a strength penalty, but it may be small. How these considerations balance out depends more on strength delivery from chips to brownstock than on any other factor. There is no "one-size-fits-all" case.

Because kraft pulps are refined before they're used in papermaking, that aspect of strength must also be linked to the fiber lines which produce the bleached pulps. Fiber changes that occur in an industrial stock refiner appear to be strongly related to deformities in the pulp coming to it (*13*). Thus, strength delivery studies along pulp mill fiber lines must be extended to stock preparation areas before a truly comprehensive body of knowledge is available.

Bleached fiber performance obviously depends on the original wood source too. Whatever the nature of that material (e.g., managed-growth timber, old-growth wood, previously unused residuals), it will inevitably affect the quality of the finished pulp.

To improve kraft pulp strength in any one area of a mill's fiber line, then, one must have a comprehensive view, covering every aspect of fiber performance from wood to pulp ready for a paper machine. Only with a systematic approach can one hope to make sense of it all. TJ

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