Kraft Pulp Strength Along *Research Fibrelines*

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Abstract

When a strength delivery study is done in a kraft mill to measure pulp strength along its fibreline, the base for comparison is unbleached pilot-plant reference pulp made from the mill's chips. Strength delivery, defined as the ratio of tear index at mid-range tensile strength of the mill's pulp to that of the reference pulp, has been measured in more than thirty kraft mills; the values were generally 75% ± 10%. When downstream fibreline operations were later examined, the unbleached pilot-plant reference pulps continued to provide the basis of comparison. But why not use mill-to-laboratory ratios after oxygen delignification and after bleaching instead, thereby comparing at equivalent process points along a fibreline? As it turns out, the use of such a "research fibreline" requires considerable extra lab work and physical testing for no benefit, because carefully done oxygen delignification and ECF bleaching experiments at laboratory scale do not change the tear-tensile strength of the pilot-plant reference pulps. Inappropriate laboratory procedures, however, can impair reference pulp strength, and will thereby render the strength delivery values of the corresponding mill-made pulps artificially high.

Introduction

Pulp strength delivery, a field of research dedicated to measuring the ability of kraft mill fibrelines to maximize pulp strength at all of their main process operations, began in the 1980s and expanded considerably in scope in the ensuing two decades. Originating on the unbleached sides of kraft pulp mills [1-4], the concept grew beyond pulping to include oxygen delignification, bleaching, and pulp drying, i.e., complete fibrelines [5-6]. It has also been applied to niche areas: brownstock screening, the components of pulp drying machines [7], and stock refining prior to a fine paper machine. These narrowly focused cases were then set in the broader context of the corresponding (and previously measured) fibrelines.

Because pulp strength delivery was originally defined in the brownstock world, the strength results from pilot-plant reference pulps (made from mill chips) continued to be used as the basis for comparison when the research moved forward to major downstream operations in mills [5]. Although there were good reasons to base complete fibreline analyses on unbleached reference pulps, it could be postulated that research procedures for oxygen delignification and bleaching should also be applied so that every main area of chemical operations in a mill was tested against its corresponding laboratory or pilot-plant analog. Such an approach can be termed a ***research fibreline***, beginning with mill chips.

Note that because almost all kraft mills have significant strength deficits in brownstock [8-11], it was reasonable at the start to assume that the other major operations along a mill's fibreline could not make the pulp stronger, and there was some published literature suggesting that the pulp moving downstream became progressively weaker [12]. But scientific data on what really happened along fibrelines was scarce.

The big three chemical areas of kraft mill fibrelines are pulping, oxygen delignification, and ECF bleaching. By trying to match the chemical and other process conditions in small-scale research equipment, we were trying to determine the process outcome in terms of the physical performance of the pulps. Standard PAPTAC physical testing procedures were always employed. We were not trying to closely match any physical factors inherent in mill machinery nor the hydrodynamics of flowing pulp suspensions, but were aware that mechanical effects could occur (see, for example, the consequences of hot-blown discharge and the use of blow-line samplers in [2]).

Although we could speculate on the shape of a complete fibreline pulp strength delivery profile (Figure 1), we did not know the reality. Now we do.

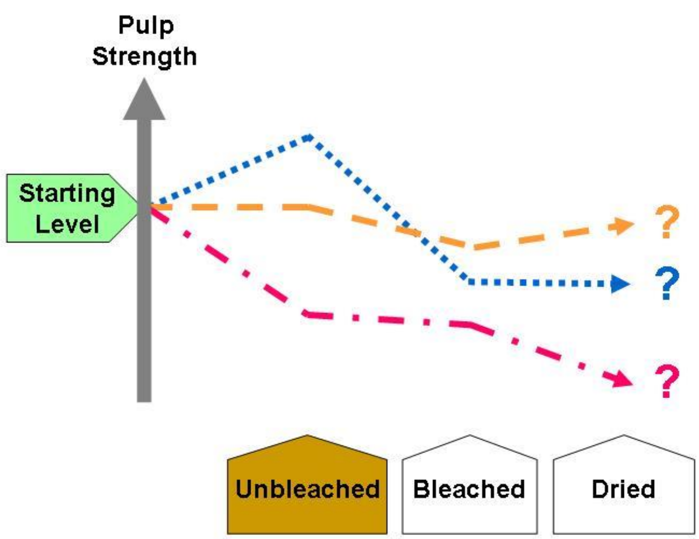

Figure 1. Conceptual pulp strength delivery along a kraft mill's fibreline: where does it begin and end? How does it change along the way? What is a typical strength profile?

Experimental Procedures

The mill work was conducted in systematic fibreline sampling campaigns of chips and pulps, and has been described in detail previously [5]. A few campaigns had five sets of samples at one-hour intervals at each sampling location. Later, we changed to three sets at two-hour intervals. The sampling was never done in less than triplicate because kraft pulp making in mills always has some inherent variability. We tracked this as kappa variability at the brownstock, post-oxygen, and first caustic extraction locations along each of the fibrelines.

The pilot-plant and laboratory procedures have been published [5,6]. The strength delivery profiles were measured in twenty bleachable-grade mills whose original engineering designs covered the era from about 1970 to 2000. A few mills were tested both before and after a major equipment change, such as the addition of an oxygen delignification operation or a change to ECF bleaching from an earlier bleaching sequence. Several mill were examined in both softwood and hardwood operations along the same fibreline.

Pulp strength delivery values (in percent) were calculated according to the original definition [4]: tear index at mid-range breaking length times 100 (Figure 2). Many other properties of the pulps were also determined.

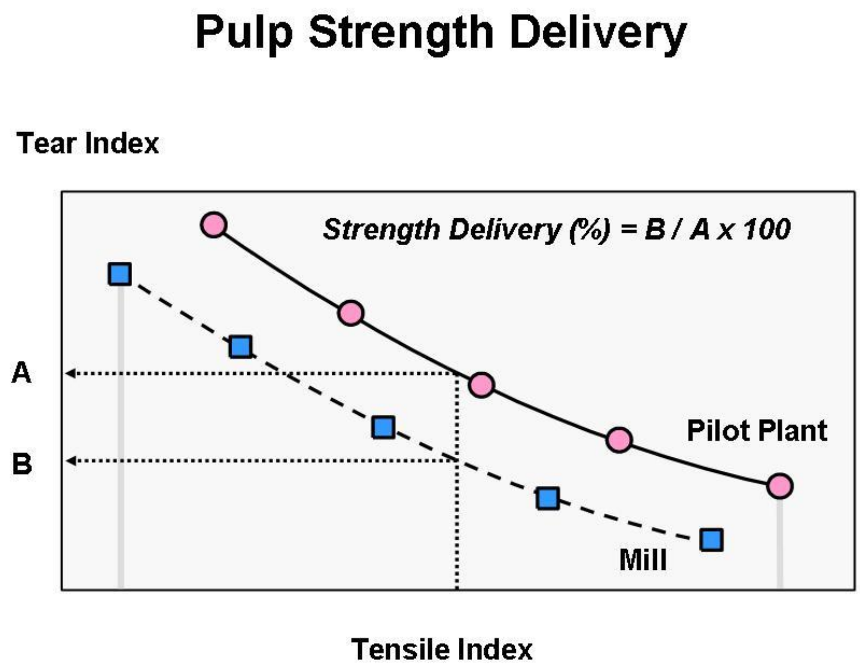

Figure 2. Pulp strength delivery is defined as the ratio of the tear index of a mill-made pulp (B) to that of its pilot-plant reference pulp (A), both at a constant mid-range breaking length [2,9].

Results and Discussion

What pulp strength delivery values pertain to digesters in softwood kraft mills?

Figure 3 illustrates average brownstock strength delivery values for 32 mill digesters, all of them measured in at least triplicate. They include almost all types and sizes of vertical continuous digesters designed in the past 30 years, conventional and liquor-displacement batch digesters, and inclined digesters pulping sawdust. The chip furnishes were species-pure softwoods or (more commonly) softwood mixtures. Two of the mills were pulping softwood sawdust. Most of these mills were making bleachable-grade pulp, but one was making linerboard base stock and another was producing unbleached kraft paper-grade pulp.

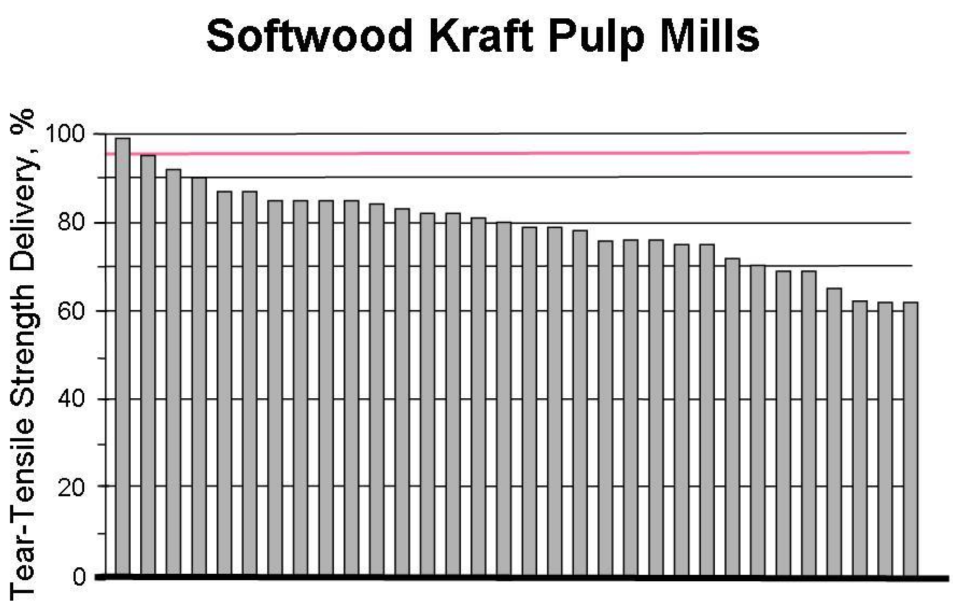

Figure 3. These strength delivery results were measured in the digester operations of more than thirty softwood kraft mills over a period of twenty-five years. Each case is the average of either three or five replicates of sampling mill chips and brownstock and making the corresponding pilot-plant reference pulps. Only two cases scored 95% or better; both were liquor-displaced, pumped-discharge batch systems.

The strength delivery values in Figure 3 range from 99% to 62%. The only two cases at or above 95% were liquor-displacement batch operations with pumped discharge. The lowest two results came from an Esco continuous digester and a Kamyr vertical continuous sawdust digester, both pulping chips. Most of the others clustered in the range 70-85%. Hot-blown batch digesters generally had lower values than conventional continuous digesters (by 5-10%). Only in a few cases was it possible to predict the average value of a particular digester – there were simply too many factors in equipment and operational practice to find one or two clear reasons for the outcome.

And only in one case was a very deliberate strength improvement made which had a clear explanation, namely changing a conventional hot-blowing batch digester to terminal liquor displacement and pumped discharge [8].

What happens to pulp strength along modern pulping/O_2/bleaching fibrelines?

The most common fibrelines today usually have a continuous digester system at the start, a one- or two-stage medium-consistency oxygen delignification system in the middle, and an ECF bleach plant at the end. Triplicate tear-tensile strength profiles along such a mill in softwood operations are shown in Figure 4; the profiles are almost superimposable across the locations, a sign of steady operations. This mill had averages of 76% strength delivery in brownstock, 73% after O_2 delignification, and 71% after bleaching (Figure 5). The strength level at D2 rose marginally in the pulp dryer, but this is an artifact – the absolute tear and tensile data are shifted (along the same curve) to higher tear/lower tensile due to the fibre stiffening which occurs in a Flakt dryer [6,7]. In hardwood operations on this same fibreline, all of the tear-tensile strength delivery numbers were 100% – the fibres were so short and thin-walled that the values of tear index across the beating range were essentially alike at every location along the fibreline [5].

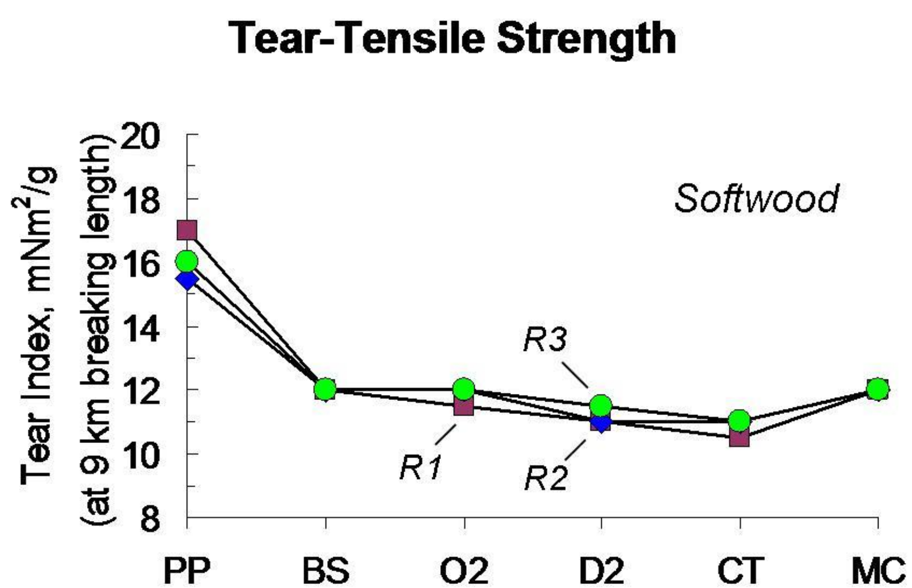

Figure 4. In this mill, the tensile-tear profiles of the three rounds were essentially alike.The largest deficit was in pulping: 24% on average. From brownstock onward, the further loss of only ~3% along the rest of the fibreline was significantly better than in most softwood bleached kraft mills. PP=pilot plant, BS = brownstock, O2 = after oxygen delignification, D2 = end of bleach plant, CT = couch trim, MC = end of pulp drying machine (i.e., layboy).

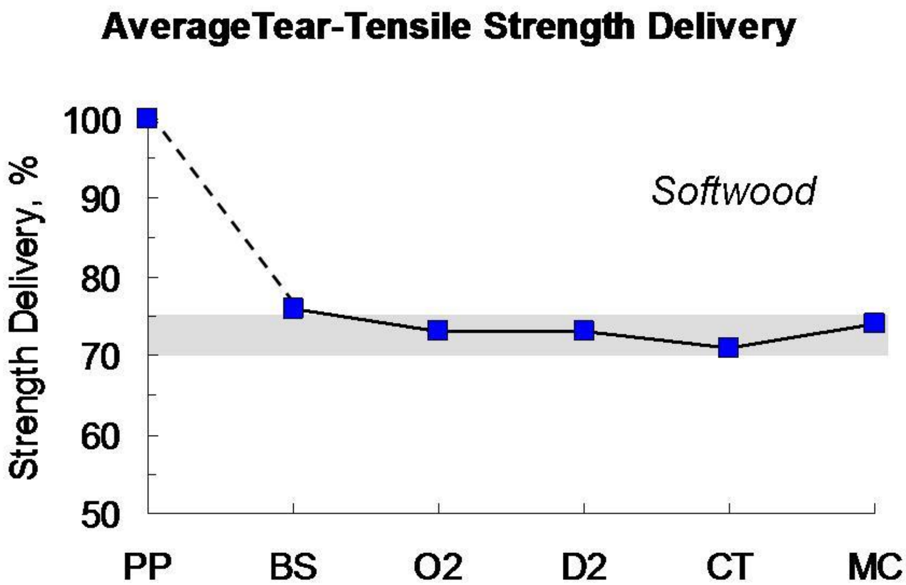

Figure 5. *(Same mill as in Fig. 4)* Strength delivery to brownstock was average for a large, modern continuous digester. It declined only marginally along the rest of the mill's fibreline, an unusually good result. The grey bar conveys the sense that inside it, all of the results are statistically alike.

Five more softwood fibrelines from kraft mills in Canada and the U.S. are illustrated in Figure 6. Their strength delivery values are not precisely alike, but their profiles are always similar in shape. The largest strength deficit is in making the unbleached pulp, with much smaller deficits across O_2 delignification and bleaching. All of these cases are based on the tear-tensile strengths of the respective unbleached pilot-plant reference pulps (defined as 100%).

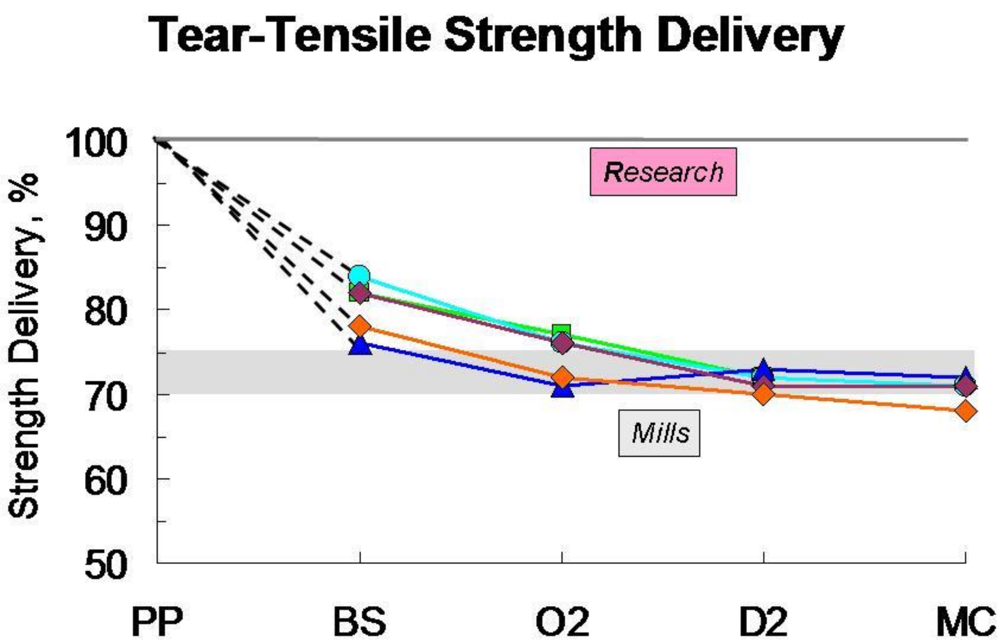

Figure 6. In these softwood pulp mills, the shapes of the strength delivery profiles were similar, but their positions were not all superimposable. The research fibreline for all of these cases would be uniformly at 100% end-to-end.

How about using a "research fibreline" for a complete pulp strength comparison?

Let's assume that we take a pilot-plant unbleached reference pulp and oxygen-delignify it in laboratory equipment, then bleach that pulp in the laboratory. Using this experimental approach, we can create a "research fibreline" which allows us to make paired pulp strength comparisons after each of the three main chemical operations in both the mill and lab fibrelines.

Figure 7 shows the outcome of such an approach in absolute tear and tensile data. The research-scale pulps (i.e., R-labeled unbleached, O_2-delignified, and bleached) are all superimposable, and the mill pulps are in a separate, lower group, with marginal strength differences. When done appropriately, medium-consistency oxygen delignification in lab equipment without continuous mechanical agitation results in no strength loss at all, even when taken to 50% lignin removal. Mill-scale MC oxygen delignification systems apply the same chemistry, have no mixers inside the reactors, and do rather little damage to pulp strength, so this outcome seems reasonable. Similarly, laboratory ECF bleaching (done in sealed bags submerged in hot water baths) results in no strength loss, a result which is easy to understand given that the precise chemical reaction of chlorine dioxide with very small amounts of residual lignin in the pulp does not degrade cellulose, and there is no mechanical action on the pulp.

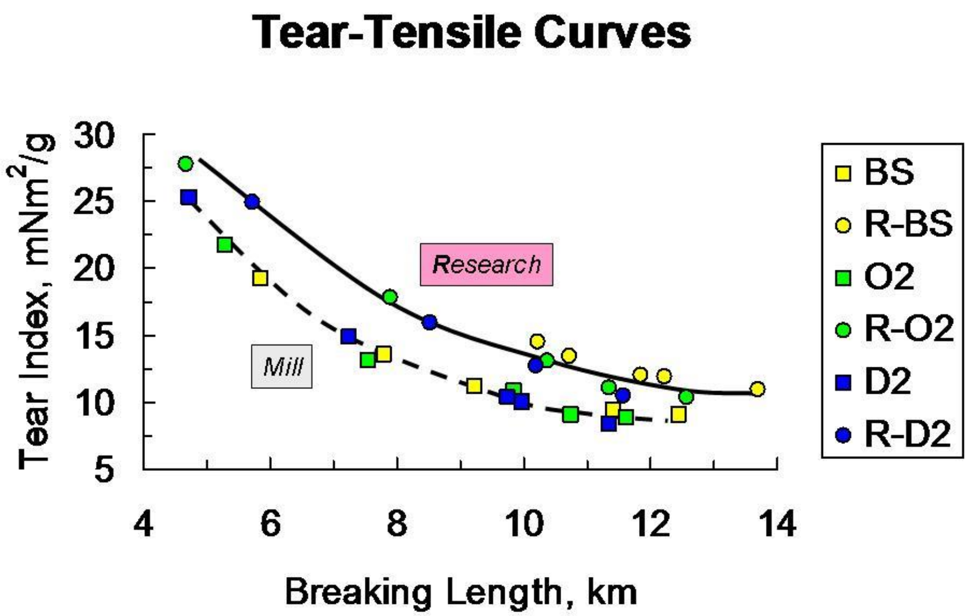

Figure 7. In this mill, the tear-tensile data for the pilot-plant brownstock (R-BS), the laboratory post-O_2 pulp (R-O2), and the lab bleached pulp (R-D2) were equivalent, the reason why the “Research” line in Fig. 6 is constant at 100%. The mill-made pulps were all significantly weaker.

A couple of instructive cases are illustrated in Figures 8 and 9 – whatever the exact type of reference kraft pulp or the chip furnish from which it was made, lab bleaching resulted in no strength loss at all [3]. This was true in the days of chemically more aggressive bleaching sequences using chlorine in the first stage, and remains the same in today’s ECF era. Adding lab O_2 delignification to the overall picture does not change the result. Thus, the research fibreline maintains 100% strength delivery through the second and third major chemistries, exactly matching the tear-tensile strength originally measured in the parent unbleached reference pulp.

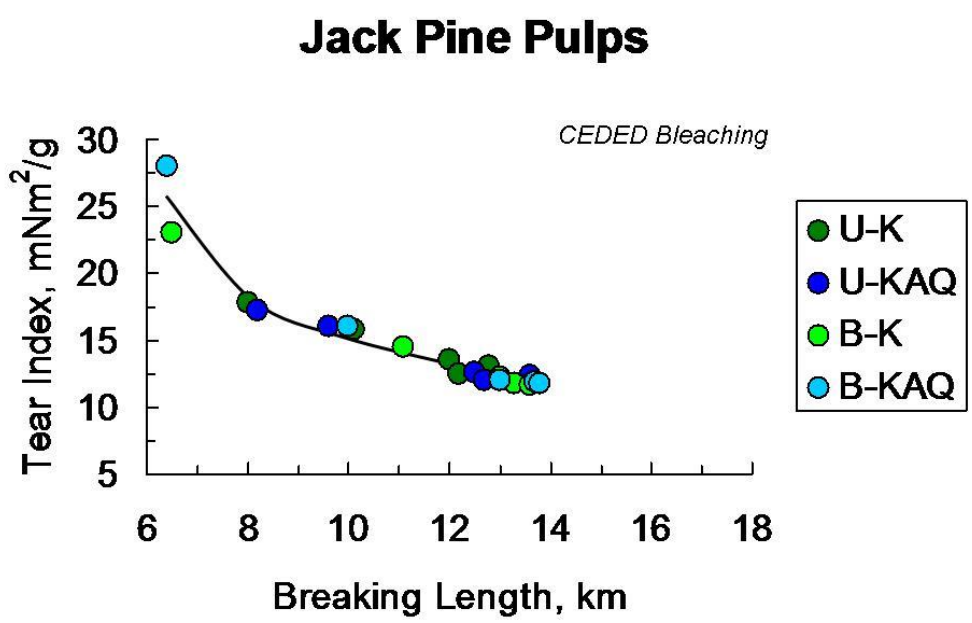

Figure 8. With these species-pure jack pine pulps, neither the pulping process (kraft vs. kraft-AQ) nor whether the pulps were bleached or unbleached affected overall pulp strength.

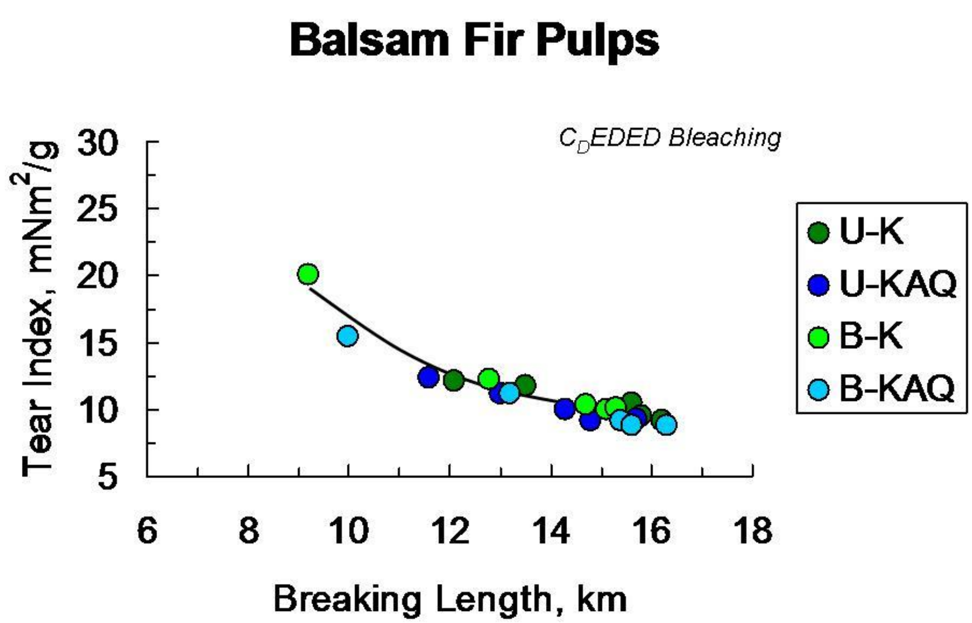

Figure 9. As in Figure 8, these pulps from species-pure balsam fir were all alike in tear-tensile strength. Bleaching did not affect their strength.

<u>Is it possible to get less than 100% strength delivery in a "research fibreline"</u>?

Yes – both intentionally and unintentionally. First, imagine the strength delivery results from a campaign along a mill fibreline (Figure 10). The research brownstock (R-BS from the mill's chips) is highest on the field of the tear-tensile graph. The mill's brownstock is weaker (80% strength delivery), followed by the mill's post-O_2 pulp (72%) and its fully bleached pulp (also 72%).

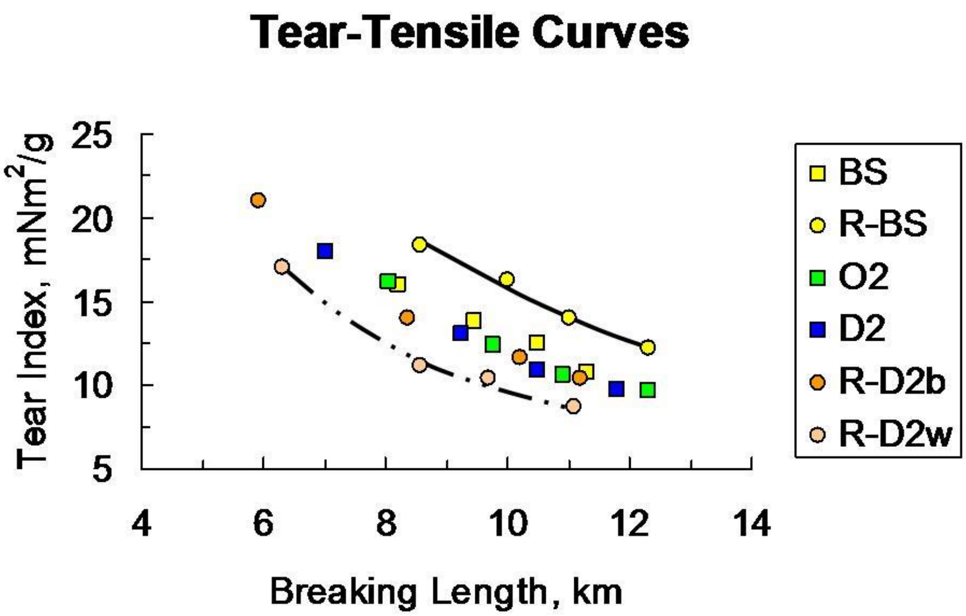

Figure 10. As usual, pilot-plant brownstock (R-BS) was strongest in this mill case. The mill's brownstock (BS), post-O2 pulp (O2), and bleached pulp (D2) clustered closely together and lower. Research-scale bleaching of the mill's post-O_2 pulp caused no further change when done in "best" process conditions (R-D2b), but lost 11% strength delivery (R-D2w) when done in conditions comparable to worst mill operations.

The mill's oxygen-delignified pulp was used for two further experiments: ECF lab bleaching at process conditions representing the best possible research practice, versus lab bleaching at process conditions representing potentially "worst" mill practice. The former produced bleached pulp at the same strength delivery as after O_2 (Figure 11). The "worst" case caused a loss of 11% on the strength delivery scale. Table 1 provides the experimental conditions used in this comparison. Thus, it *is* possible to degrade pulp strength in lab bleaching: use excessive charges of bleaching chemicals, allow pH to get out of control, and push to too-high pulp brightness. This, of course, is not normal practice, and most of the ECF bleach plants we have measured have quite modest strength delivery deficits, usually 5% or less.

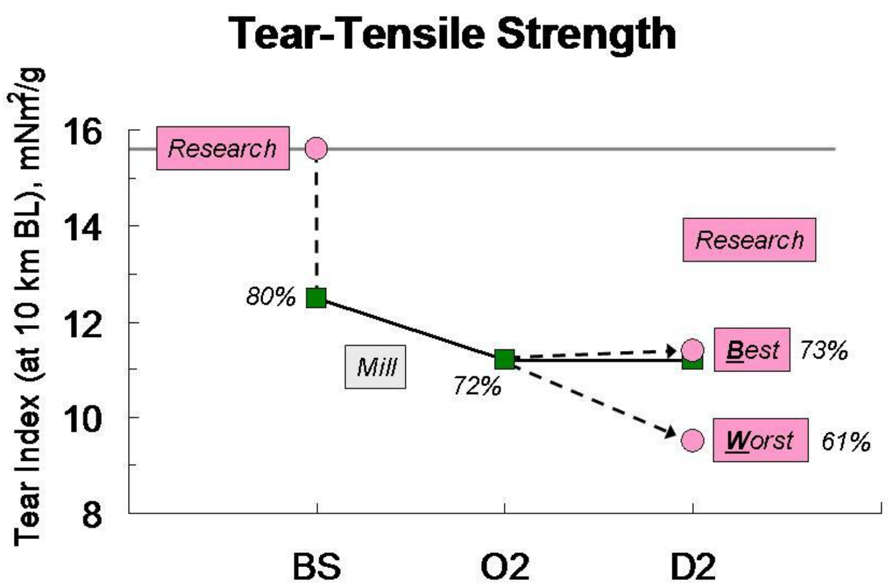

Figure 11. The mill in Figure 10 had 80% strength delivery to brownstock, and then lost 8% in oxygen delignification. When the mill's post-O_2 pulp was the starting material for "best" and "worst" ECF lab bleaching experiments, the best case left pulp strength unchanged, whereas the worst lost another 11% in strength delivery.

Cases of unintentionally degrading pulp strength in research fibrelines can be found in Marcoccia et al. [13]. In a thorough examination of six kraft mills, mainly using the methods stated above plus the addition of research-scale O_2 delignification and laboratory ECF bleaching in each case, pulp strength comparisons were made at the three main points along both the mill and research fibrelines.

Brownstock strength delivery was normal in all six mills (72-82%, averaging 78%) (Figure 12). But strength delivery after oxygen delignification was highly variable: a high of 89% (i.e., an *increase*) to a low of 64%, averaging 75%. Further, strength delivery across ECF bleaching in the mills also varied significantly, from 90% (also an *increase*) down to 66%, coincidentally averaging 75%. In our examinations of 15 ECF bleach plants, we have never measured a strength delivery increase; it usually decreased by 5% or less.

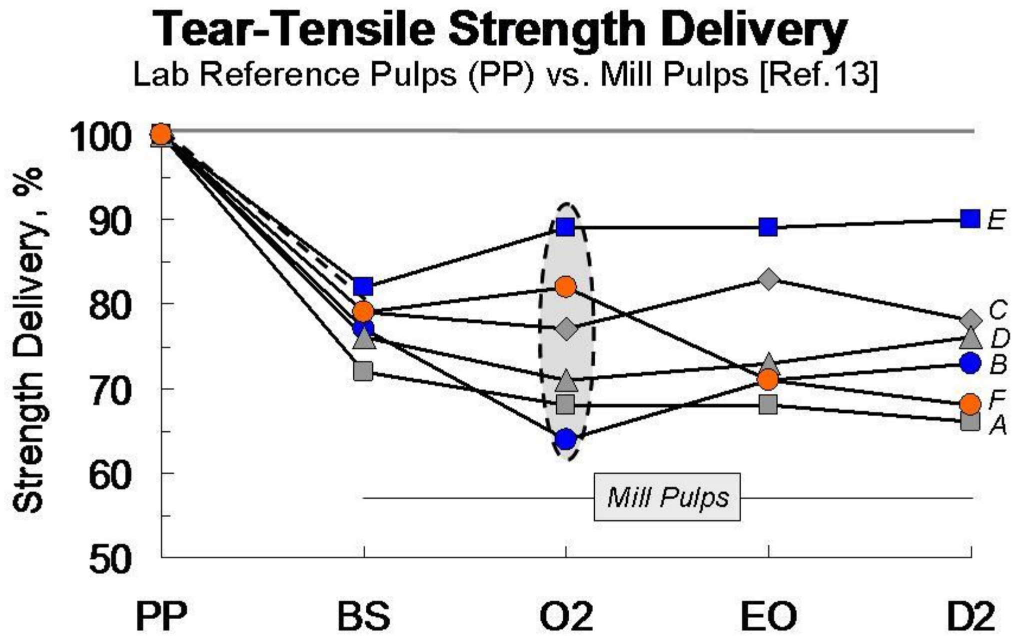

Figure 12. Results from Reference 13 provided the data for these strength profiles for **six different softwood kraft mills**. Brownstock strength delivery clustered in a typical range from 72% to 82% (averaging 78%), similar to the results in Fig. 6. The range across oxygen delignification was much larger: 64% to 89% (average = 75%), with two of the cases *increasing* and one significantly decreasing. Across bleaching, the values were also highly variable (66% to 90%, averaging 75%).

Another aspect of the work reported by Marcoccia et al. [13] can be seen in Figure 13. Taking the research fibreline approach, they oxygen-delignified all six of the research unbleached reference pulps in lab equipment, and produced post-O_2 strength delivery values averaging 84% (range: 81-89%). This should simply not happen in lab-based O_2 delignification (see Figure 7), and is about three times the strength loss both they and we have measured in mill O_2 systems. Nevertheless, they carried on through laboratory ECF bleaching, producing still more variability in pulp strength results – one pulp went up by 9%, another down by 9%, and one went down by 14% (through EO) and then up by 24%!

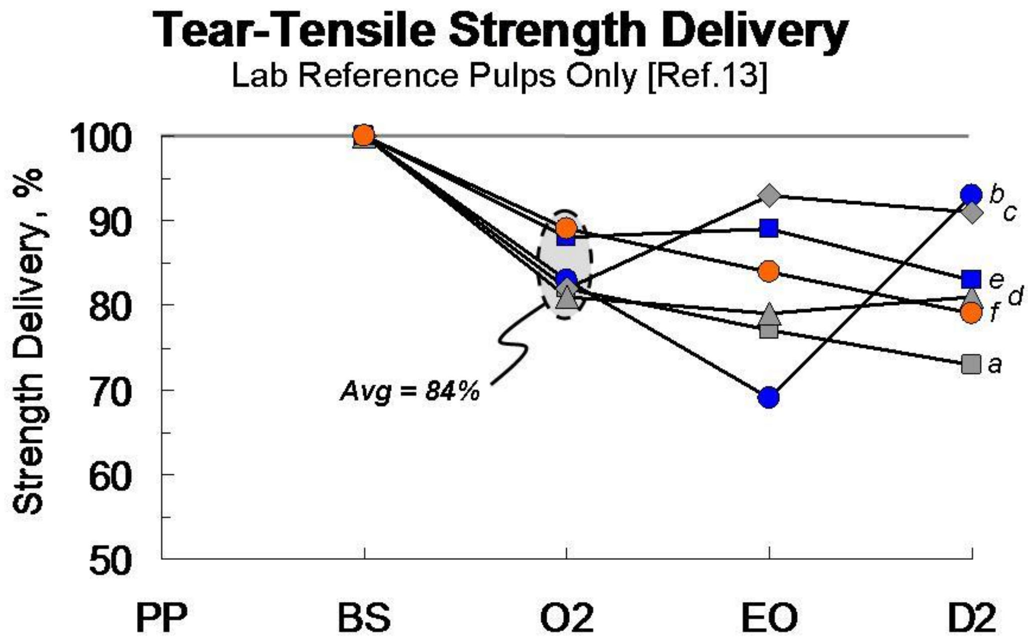

Figure 13. From Reference 13, these data were obtained for **research fibrelines** (i.e., all fibreline operations done at lab scale). Defining the lab brownstock pulps at 100% tear-tensile strength delivery as normal, the oxygen-delignified pulps averaged 84%, and the D2 pulps averaged 83% (range: 73-93%); one case decreased to 69% in EO and then rose to 93% at D2. As in Figure 12, a large amount of scatter was apparent.

Thus, in Reference [13], the usefulness of the research fibreline concept fails entirely. Its purpose is to determine the best possible results in pulp strength using lab equipment and procedures, and then test those values against the ones measured in the corresponding mill-made pulps. But these six research fibrelines don't demonstrate a common strength profile, and all of their values are significantly below the uniform 100% level described earlier. As a consequence, they produce unusually high pulp strength delivery values along mill fibrelines because of the artificially low strength values from laboratory oxygen delignification and/or ECF bleaching procedures (Figure 14). Although the corresponding mill-made pulps appear to have higher strength delivery values, their absolute tear-tensile strengths have not changed at all. It is the weaker lab reference pulps which provide that illusion.

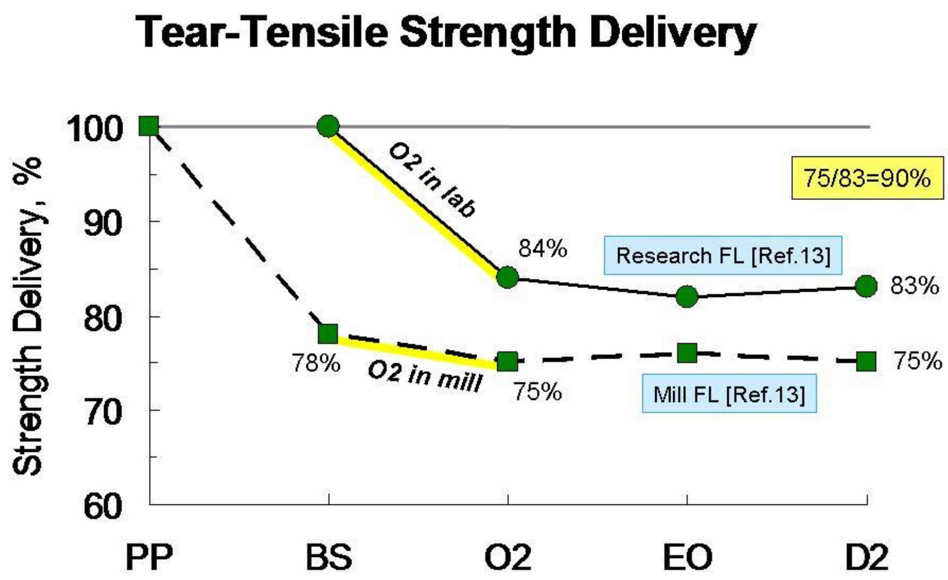

Figure 14. When the strength delivery results from Reference 13 were plotted, the average research fibreline (100% in brownstock) was 84% at O2 and 83% at D2. The average mill fibreline [13] had 78% strength delivery to BS, 75% at O2, and 75% at D2. In this analysis, the ratio of the mill D2 result over the research D2 result equals 90%.

So, is a research fibreline really necessary?

No. When done correctly in the lab, neither oxygen delignification nor ECF bleaching causes any tear-tensile strength loss relative to the parent unbleached reference pulp (Figure 15). In mill operations, oxygen delignification rarely causes more than a 5% loss in strength delivery. ECF bleaching in mills causes even less strength loss (and sometimes none), which makes good sense because an extremely selective delignification reagent (ClO_2) is being used to remove very small amounts of residual lignin from pulp.

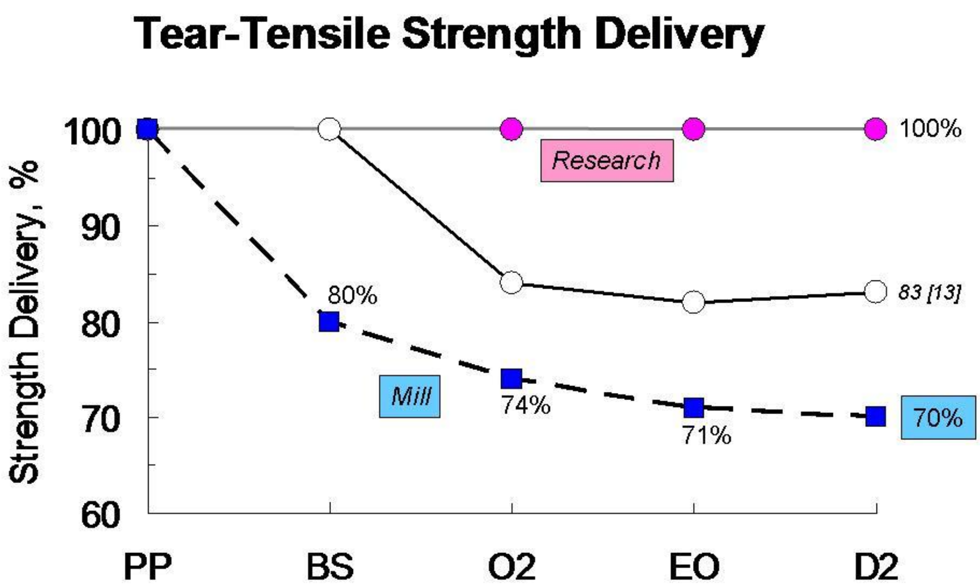

Figure 15. Using a proper research fibreline maintaining 100% strength delivery all the way, and the average mill fibreline profile from Fig. 6, the strength delivery to bleached pulp is 70%; it was 75% in Fig. 14. The lab O_2 delignification in Reference 13 caused three times more strength loss than occurs in most mills, thereby lowering the reference point artificially, and simultaneously inflating the mill values (e.g., the profile ending at 83%).

Further, the considerable extra work to do the laboratory O_2 delignification, bleaching, and physical testing – an expensive proposition – is not justified because the strength delivery profiles for mills are already properly anchored by the unbleached pilot-plant reference pulps made from mill chips.

Summary

Pulp strength delivery values in unbleached softwood kraft pulps from mill digester systems range from almost 100% down to about 60%. These results generally decline further in the other main operations along a mill's fibreline, i.e., oxygen delignification and bleaching (typically by about 5% in each). Since the strength delivery values are based on unbleached pilot-plant reference pulps made from mill chips, it was natural to ask whether different results would be obtained with further reference pulps made in laboratory oxygen delignification and in ECF bleaching. The answer is no – when properly done in the laboratory, these downstream processes do not change the tear-tensile strength of the original unbleached reference pulp.

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Table I. ECF laboratory bleaching of mill-made post-O_2 softwood kraft pulp.

	Best Practice [a]	**Worst Practice [b]**	**Mill Target**
D0 Stage (63°C, 80 min)			
“Active chlorine” multiple	0.22	0.32	
ClO_2 on pulp, %	1.2	1.7	
Final pH	2.4	2.0	3.5
Brightness, % ISO	51.6	59.2	46-52
Eop Stage (63°C, 80 min)			
NaOH on pulp, %	1.5	2.0	
H_2O_2 on pulp, %	0.4	0.4	
Final pH	11.2	11.9	11.2
Kappa number	2.4	1.4	2.0-2.5
Brightness, % ISO	73.1	78.3	60-65
D1 Stage (78°C, 150 min)			
ClO_2 on pulp, %	1.0	1.7	
NaOH on pulp, %	0.4	0.7	
Final pH	3.3	3.8	3.9
Brightness, % ISO	89.0	91.4	82-85
D2 Stage (78°C, 150 min)			
ClO_2 on pulp, %	0.23	0.23	
Final pH	2.9	3.1	4.5
Brightness, % ISO	89.9	91.8	90+

[a] Best chemical practice of bleaching using mill times and temperatures.
[b] “Worst” chemical practice of bleaching using mill times and temperatures.