MAKING AND LOSING PULP STRENGTH IN BLEACHED KRAFT MILLS

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ABSTRACT

A research-based methodology is useful in addressing the challenge of where kraft pulp strength comes from and how it might be made better. It brings a systematic benchmarking approach to the characterization of pulp strength along a mill’s fibreline, and sets the maximum potential strength in each of the primary fibreline operations (i.e., pulping, oxygen delignification, bleaching).

In kraft mills today, most digester systems fail to achieve the pulp strength potential inherent in their original wood furnishes. Of the strength which goes “missing”, the biggest part happens in digester operations, usually for a combination of chemical and physical reasons. In strength delivery terms, the deficits are usually 25% ± 10%. It is possible to prevent most of this brownstock strength loss, but only in modern liquor displacement batch digester systems with pumped discharge.

The same systematic analysis, when applied to downstream operations, shows that oxygen delignification and bleaching typically make pulp weaker, while pulp drying dramatically changes its refining characteristics.

Because kraft pulp production is complex and expensive, continual attention is required on how to do it well, and how – when the rare opportunity arises – to make changes for the better in choosing process equipment and operating practices. Combining all the best factors can result in impressive gains in the physical performance of kraft pulps.

INTRODUCTION

“Among woodpulps, kraft pulps dominate the marketplace. They are clean, strong, and stable in appearance, which makes them ideal for manufacturing high-quality printing papers. But the unique attribute of softwood kraft pulps is physical strength above and beyond that offered by any other type of commercial woodpulp [1].”

“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 pulp-making operations [2-5]. Digester operations, both batch and continuous, were the main culprits, typically being responsible for about a 25% shortfall in tear-tensile strength in the production of bleachable-grade softwood pulps. Curiously, short-fibered hardwood pulps have no such strength deficit.”

The situation described in these two paragraphs in 1994 [1] has not changed much in the past ten years, but the passage of time has allowed the collection of substantially more information on fibreline performance with respect to pulp strength delivery. More than twenty fibrelines have been analyzed with the same approach described in 1994, and the database now includes virtually all types of kraft digesters and oxygen delignification systems. Most bleach plants, on the other hand, have converged toward a common type – ECF (i.e., elemental chlorine free), of either three, four, or five stages. Although ignored earlier, pulp drying machines have now been analyzed in considerable detail.

Kraft market pulp is routinely analyzed for physical properties in the form in which it is sold to customers, i.e., bleached and dried. But how it acquires those “final” properties depends heavily on the equipment and process conditions along the complete fibreline in a mill – and in reality, all the way back to the trees in the forest. To know what is achievable in kraft pulp strength, the whole spectrum of fibreline operations needs to be understood.

Although this challenge appears to be entirely mill-based, a research methodology is useful in addressing it for at least two reasons: (1) it can bring a systematic, outside-the-mill benchmarking approach to the characterization of “pulp strength” along a mill’s fibreline (then equally applied at other mills), and (2) the research versions of the primary fibreline operations (e.g., pulping, oxygen delignification, bleaching) can be performed with the greatest chemical precision and least amount of incidental mechanical action on the fibres. It was from this kind of approach, particularly in the 1980s, that the inferior strength of mill-made, unbleached kraft pulps from softwoods was confirmed anew, some twenty-five years after the same phenomenon was identified during the early development of vertical continuous digesters [6-8].

Almost all digester systems producing softwood kraft pulps, whether continuous and
batch, still share this problem. Of the pulp strength which "goes missing" in mills, much of the problem resides in digester operations, usually for a combination of chemical and physical reasons. In strength delivery terms, the deficits are usually 25% ± 10%. It is possible to prevent most of this brownstock strength loss, but only in modern liquor displacement batch digester systems with pumped discharge.

Systematic analysis of the unbleached side of a kraft mill can be expanded readily to downstream operations – oxygen delignification, bleaching, and pulp drying. The first and second of these usually make pulp weaker, while the third dramatically changes its refining characteristics. Although the profile of a kraft mill’s fibreline can resemble a downhill ski slope in many key parameters (e.g., tensile strength properties, tearing resistance, apparent density, average fibre length, etc.), it can exhibit significant increases in others (stretch, curl, light scattering coefficient). Not all fibreline operations change pulp strength in the same direction or to the same degree; pulp drying, for example, has unique effects not measured elsewhere. And when pulp strength problems arise in a mill, the first indication is often in the testing of bleached, dried pulp, providing a very big territory (all the way back to the wood) to examine for causal factors. This can't be done rapidly – or perhaps at all – in the absence of a reliable profile of typical pulp strength along the complete fibreline. But what profile (Figure 1)? Only the comprehensive testing and analysis of a fibreline can reveal the true profile.

With the sheer complexity and expense of kraft pulp production, continual attention must be placed on how to do it well, and how – when the rare opportunity arises – to make changes for the better in choosing process equipment and operating practices. Final pulp strength in a softwood kraft mill falls well below its real potential, mainly a result of excessive chemical and physical phenomena in pulping, plus the unintended physical damage of fibres along the rest of the fibreline. The biggest opportunity for improving the strength of bleached kraft pulp resides in pulping equipment. Combining all the best factors can result in astounding gains – doubling the unbeaten tensile strength of a softwood pulp, for example. With such knowledge, why would anyone settle for the status quo?

This paper describes a comprehensive approach to fibreline examination, characterization, and trouble-shooting, starting with wood chips and finishing with bleached, dried pulp.

**SAMPLING AND ANALYZING KRAFT MILL FIBRELINES**

**What constitutes a fibreline?**

Figure 2 shows a simple schematic diagram of the "big block" components along a generic kraft mill fibreline. These include the main chemical operations (i.e., pulping, oxygen delignification, bleaching) plus wood chips and pulp drying. A bleach plant can be considered a single block simply by analyzing the unbleached pulp going into it and the corresponding bleached pulp coming out. Alternatively, a bleach plant can be divided into its individual bleaching stages for analysis. Depending on the case, we have taken both approaches. In the era of ECF bleaching, the “big block” approach is often adequate, but an unusual result across the block may trigger the need for a stage-by-stage analysis.

Complex operations sometimes require quite detailed examinations. Examples are the multiple stages in a cascading brownstock screening system, the feeding and mixing components of an oxygen delignification system, or the forming, pressing, and drying operations of a pulp machine. The last of these will be shown later.

The information requirements dictate the pulp sampling locations, and the results of a first approach may prompt the examination of the details within one of the big blocks.

**How to acquire systematic sample sets?**

The sample grid shown in the lower part of Figure 2 has been satisfactory for most of our fibreline analyses done during the past twenty years. It is practical to do (usually by two or three people), with sampling locations chosen for representative access to fibre flow (and for safety!). Time lagging along the fibreline is an integral part of the planning. Three sets of samples, usually separated by two-hour intervals, constitute a sampling campaign; multiple sets provide a sense of variability over time at all of the sampling locations. Each sample (by location and time) is a unique 10-minute composite of the material at the chosen location.

**Why sample chips when the focal point is mill-made pulp?**

In the beginning, pulp strength rests on wood fibre morphology, chemistry, and quality. The better the chips and the fibres in them, normally
the better the pulp. Characterization of chips includes species identification, moisture content, chip bulk density, relative wood density, and chip size distribution. Other things might be considered, such as bark and decay content.

We then use the mill’s chips to make unbleached kraft reference pulps in 20L pilot-plant digesters, copying the mill’s pulping recipe and process conditions as closely as possible, and matching the kappa numbers of the pilot-plant pulps to those measured in the mill brownstock. It is also possible to use the mill’s white liquor, but it’s not a normal research practice. The physical properties of these reference pulps will be compared with those of the mill brownstock samples from the same chip flow, an essential part of the methodology. Without the reference pulps, the pulp strength inherent in the wood furnish cannot be known.

Wood and chip quality may be the largest source of variability in the fibreline, especially in mills with mixed-species furnishes. And downstream from the digester system, two things contribute to a gradual homogenization of pulp fibres: (1) the continual mixing of billions of fibres, and (2) the fact that less chemical work in operations beyond pulping provides ever less chance for things to go wrong and cause a deterioration in pulp strength. It is particularly important to note that a mill needs to make strong unbleached pulp in the first instance, because it can’t be made stronger downstream along the fibreline.

**What chip characteristics affect pulp strength?**

Among the key factors affecting chip quality, chip size distribution is especially important. There is a general consensus in the scientific literature that chips in the 2-8 mm thickness range are ideal for kraft pulping. Chips thicker than 8 mm cannot be completely penetrated with cooking liquor and delignified beyond the fibre liberation point in normal kraft pulping, resulting in a higher-than-normal kappa number in the fibrous pulp, plus uncooked cores (“knots”) which are still wood. At the other end of the spectrum, the “fines” below 2 mm in thickness cook faster than the 2-8 mm chips, resulting in too-low kappa numbers and inferior pulp yields. Pulp from the fines fraction may also depress overall pulp strength when (wood) fibre length has been significantly shortened and/or too much chemical damage to the cellulose has occurred during pulping.

A great starting point for pulp quality would be to have chip size control like that in Figure 3. This case is close to ideal in maximizing the proportion of 2-8 mm chips and in exhibiting low variability in all size fractions; the pulping should be reasonably uniform, and the pulp strength good. But in Figure 4, in a hardwood mill, the picture is much worse: a significantly lower proportion of 2-8 mm chips, and considerable variability in both the oversized and undersized fractions. Whereas this might have little effect on hardwood pulp strength, the same picture in a softwood mill would almost certainly penalize strength.

Some of the effects of chip quality on kraft mill operations may have little to do with pulp strength but a lot to do with yield, a topic of importance as wood inevitably becomes scarcer and more expensive. Bark content in chips is an example. In kraft pulping, bark has no practical yield of papermaking fibres [9], so any bark in a wood chip supply automatically carries a penalty. As little as 2% bark in chips can cause a $4 million annual shortfall in pulp not made and sold in a 1000 tpd kraft mill. Or imagine the consequence of a chip furnish containing 10% fines. Here, there is a yield deficit plus a strength penalty amounting to about $2 million per year.

Figure 5 shows a hardwood case in which the mill’s pulping chemistry was changed from kraft to polysulphide-anthraquinone, providing a yield gain of ~2% [10-11]. Associated work demonstrated that another 5.5% yield gain could be assigned to factors such as “perfect” wood chips, rigorous species control, and uniform pulping. Would any of these translate into better pulp strength? The process change did not have any effect in this hardwood case; it would, however, in a softwood case, with both positive and negative aspects to consider. Regardless, the yield “potential” illustrated here would greatly improve any kraft mill’s economic picture.

**Fibreline profiles – which ones to choose?**

Figure 6 presents profiles from four different softwood fibrelines, but there are as many possible profiles as there are physical properties to be measured and mills to be examined. How good a job a fibreline is doing can be assessed in innumerable ways, both in pulp fibre characterization and in pulp handsheet strength. Hardwood mill profiles might be quite different. Improving final pulp strength at the product end (i.e., in bleached, dried pulp) requires practical knowledge of what is possible all along a mill’s operations beyond pulping provides ever less chance for things to go wrong and cause a deterioration in pulp strength.
fibreline, including monitoring of what comes in wood and chip quality entering the mill.

Some profiles are particularly useful in establishing that “steady-state normal behaviour” existed in a mill during the sampling campaign. Brightness is an example – with softwood bleachable-grade pulp, it is expected to begin in the mid-20s, rise by about 10 points during oxygen delignification, and then leap upward during bleaching to ~90% ISO in market pulp mills. If this is not the case, something out of the ordinary must have been happening along the fibreline during the sampling period. Similarly, initial stretch (which is associated with fibre curl) will increase dramatically along a fibreline especially through medium-consistency machinery in oxygen delignification and bleaching; it will then fall back somewhat during pulp drying. On the other hand, average fibre length will decline to the end of a bleach plant, then remain constant in pulp drying. Note that these comments concern fibreline patterns, and that the absolute test values will differ according to pulp fibre morphology, especially with respect to wood species.

Where pulp strength is made – research version

Imagine that a master sample of chips from a mill is split into six sub-samples, and research pulpers around the world set out to make duplicate reference pulps at the same kappa target [12]. The data points in Figure 7 are the actual tear-tensile results for twelve such pulps, all tested at one laboratory; reproducibility was good.

Now hypothesize that the mill’s brownstock had the lower curve shown in Figure 7, and that its reference pulp is the average of the twelve data sets. The resulting tear index at a mid-range breaking length of 8 km is 17 mNm²/g for the mill pulp and 21.2 mNm²/g for the reference pulp, hence a strength delivery value of 81%.

There are many procedural steps to getting this value, so a conservative approach in the use of strength delivery numbers is advisable. For general purposes, a difference of five percentage points or more should be considered “real”, but two or three should not.

Since all twelve reference pulps were made from a common chip source, it is expected that they would all have the same average fibre length. Figure 8 demonstrates that this was the case – a length-weighted average fibre length of 2.83 mm, and a prediction range of 2.80-2.86 at 95% confidence.

These results, along with other evidence [12], suggest that the reference pulp making on which the pulp strength delivery concept rests is a satisfactorily reproducible practice.

Where pulp strength is made – mill version

Because our interest is primarily in mill-made pulps, their physical performance where first produced – as brownstock – is the crucial point of comparison with the reference pulps from the same chips. Over the years, a broad database has been built which characterizes many mill digester systems operating on a wide spectrum of chip furnishes.

Figures 9 and 10 provide strength delivery values for some of these systems. These digesters represent a wide range of sizes, eras of installation, operating modes, etc., all of them producing bleachable-grade softwood kraft pulps. In each case, the pilot-plant reference pulps set the potential (always defined as 100%), and the corresponding mill-made pulps had the values shown.

With hardwood pulps, the strength delivery value in the mill-made pulps is always 100%, whether from batch or continuous digesters, because short-fibered hardwood pulps have very narrow ranges of tearing resistance, quite unlike softwood pulps. This does not mean that mill-made hardwood pulps are as good as pilot-plant ones in every respect. As will be shown later, they can be quite deficient in tensile strength properties.

Where pulp strength is lost – mill version

In a tear-tensile strength delivery sense, once you have made the brownstock in a kraft mill, you can only go sideways or downhill from there. In Figure 1, therefore, the normal profile is the lowest one. Declines are routinely measured in oxygen delignification systems and in bleaching. As the remaining lignin is being removed, the pulp gets ever higher in cellulose content. Each chemical operation has some potential to decrease the degree of polymerization, and there is substantial mechanical action on the pulp fibres in the many pumps, mixers, and pipes. Among the things that happen is that average fibre length (in fact, fibre length distribution) decreases along a kraft mill fibreline, as is illustrated in Figure 11 for softwood and hardwood pulps made on the same fibreline in a swing mill.

Oxygen delignification, whether in high-consistency or medium-consistency pressurized systems, or in mini-O₂ systems, typically
accounts for another ~5% loss in tear-tensile strength delivery (Figure 12). In some cases, the loss is very small.

Another 5% is usually lost in ECF bleach plants, but it is distributed across the stages rather than taking place in any one stage. Before the ECF era, the first two stages of bleaching (e.g., CdEo) accounted for a larger share of a larger overall strength loss. Sole use of chlorine dioxide may be the best thing we’ve ever done for pulp strength preservation in the oxidative stages of bleaching.

Figure 13 shows a seven-location fibreline investigation in a softwood kraft mill designed for the 1990s. The sampling rounds had one-hour separations. Each bleaching stage (of four) was examined.

On average, the tear-tensile strength delivery values were 82% in brownstock, 77% after single-stage medium-consistency oxygen delignification, and 72% after D/CEoDED bleaching. Only by summing all the strength deficits across the bleach plant do you get a 5% drop in strength delivery; stage-by-stage strength loss is usually so low that its analysis is unjustified in effort and expense.

Figure 13 also shows evidence of variability over time at sampling locations, and tracks it along most of the fibreline. For example, the strength delivery value for brownstock in Round 4 is lower than average, as are the corresponding values after oxygen delignification and the D/C stage. Farther across the bleach plant, however, the small stage-to-stage differences make the pattern increasingly hard to see.

When a fibreline is modified, is it possible to track the changes in pulp strength delivery? Figure 14 provides an answer. Two average tear-tensile strength delivery profiles are shown for the same mill, before and after a major fibreline renovation. The 1985 version has a continuous digester followed by a conventional (for those days) CdEoDED bleach plant. In the renovation, a medium-consistency oxygen delignification system was added, and the bleaching sequence was converted to ECF, i.e., DEopDED. The digester system was not changed.

In terms of pulp strength delivery, the brownstock was unchanged, as would be expected. The addition of oxygen delignification brought a modest penalty. It was compensated by zero strength loss through the ECF bleach plant. In the end, there was an overall strength delivery gain of ~5% from one era to the other.

Is it normal to have bleach plants with no strength loss? It was probably never the case prior to ECF bleaching. From audits across more than a dozen ECF bleach plants in the past five years, the common factors for superior pulp strength retention appear to be these: three stages rather than four or five, normal rather than extremely high brightness targets, and modern, medium-consistency design coupled with steady operations.

Among bleach plant chemistries in use over the decades, the ECF bleaching that is common to so many bleach plants today might logically be expected to have the least impact on kraft pulp strength. It ought to be better than TCF sequences with high charges of hydrogen peroxide and high temperatures, for example, and also better than sequences from yesteryear which used high charges of chemicals such as chlorine and hypochlorite at the “front end” of bleaching. It is reasonable to expect that using only chlorine dioxide for final lignin removal and brightening in bleaching sequences will least affect pulp strength because it is a “precision” chemical, dissolving residual lignin while leaving the polysaccharides essentially untouched. In such circumstances, pulp strength delivery probably becomes an issue of unintended mechanical damage to fibres, chemical degradation being nil.

Is pulp strength lost in drying?

Getting to the end of a bleach plant does not conclude the pulp strength story in market kraft mills – there’s still drying to consider, and it can change pulp strength in many ways.

Figure 15 shows the usual result of water removal. Conventional pulp drying machines do not change the overall tear-tensile strength of bleached softwood kraft pulp, but they do affect its refinability or beatability because of fibre stiffening which accompanies the high degree of water removal from the fibre cell walls. Where the PFI-based data for the bleached slush pulp and its corresponding couch trim are alike, those for the Flakt-dried pulp have shifted to higher tear values and lower tensile ones. Nevertheless, all three sets of data points fall on one curve.

To get a more precise picture of what’s happening, a standard pulp drying machine running on bleached softwood kraft pulp was systematically sampled on the way to a scheduled shutdown. The sampling points are indicated in Figure 16, time-lagged along the machine.

Although some minor changes in physical properties could be measured along the machine, the serious consequences of drying were those
highlighted in Figure 17. No major tensile strength changes occurred from the blend tank through the press section. In the Flakt dryer, where the sheet solids content increased from about 45% to 90%, there were large decreases in all tensile properties. Afterward, no further changes took place.

Fibre saturation point declined by 40% in the Flakt dryer, where a critical amount of water is removed from the fibres and their swelling ability is considerably reduced (i.e., the hornification effect [13]). Something – usually mechanical action in a stock refiner – has to be done to the dry fibres after reslushing to regain the swollen state they were in before the Flakt dryer. This, of course, carries the danger of fibre degradation.

Is it possible to construct a “grand synthesis” of pulp strength delivery?

With detailed information on many fibrelines, it is now possible to synthesize an overall picture of pulp strength delivery in kraft mills. It will show us good, neutral, and bad aspects of process equipment and operating practices, and identify where improvements are feasible.

Figure 18 is the tear-tensile pulp strength delivery profile of a normal softwood bleachable-grade pulp mill. Four points are shown – the pilot-plant reference pulp (PP), the mill’s brownstock (BS), the bleached pulp (D2), and the dried pulp (MC). Starting at 100% (the level defined for pilot-plant pulps), the value drops to ~80% in mill brownstock and ~70% after bleaching. The result is unchanged in pulp drying (but the data have shifted along the tear-tensile curve – Figure 15). Oxygen delignification was eliminated from Figure 18 for simplicity, but is incorporated into the result at D2.

Now imagine a new fibrel ine to replace this one (Figure 19). What would be the best choice of processes and equipment? For pulping, modern liquor displacement batch offers the best proven strength delivery from chips to brownstock: 95% is realistic. Medium-consistency oxygen delignification and ECF bleaching (three or four stages) are the obvious mainstream choices after pulping. Pulp drying is a neutral factor.

The overall outcome is a gain of at least 20% in strength delivery, something that was not achievable prior to advances in the late 1980s. All of this improvement could well be attributed solely to the pumped discharge technique used in modern liquor displacement batch pulping operations [14,15]. Note that the new, improved line-up in Figure 19 is the result of equipment selection – no unusual choices in process chemistry play any part in it. It is also significantly better than either of the strength delivery profiles in Figure 14.

Another way to look at mill profiles might be in terms of tensile strength alone. Figure 20 provides a case. Tensile strength declines all the way along kraft mill fibrelines. These are profiles of maximum tensile strength along a modern fibrel ine which swings between softwood and hardwood. The overall tensile strength loss was 2.7 km in softwood pulp and 3.7 km in hardwood pulp. In percentage terms, the hardwood case is obviously worse, a loss of about 40% of the potential represented by the pilot-plant reference pulp versus a 20% loss in the softwood case.

Alternatively, one might choose the analysis shown in Figure 21, this time the average initial tensile strength profile in a geographic group of softwood mills all using comparable chip furnishes. The largest strength deficits occur in pulping and in pulp drying. The many operations composing the middle of the fibrel ine have much less effect, so this is not a natural territory in which to look for tensile strength gains or losses. The vertical position of the line on the field of the graph depends heavily on the wood species (or, in this case, mixture) being used, but its pattern is unlikely to change.

If you now choose a wood species offering superior tensile strength, and adopt the new fibrel ine described in the upper part of Figure 19, what would be the outcome? It is illustrated in Figure 22, wherein balsam fir (Abies balsamea), a common boreal forest softwood in Canada, provides reasonably long, slender, thin-walled fibres, and the fibrel ine is designed to retain this advantage all the way to bleached pulp. Despite the tensile strength loss that is inevitable in pulp drying, the upper profile in Figure 22 demonstrates that the final result is monumentally better than that in Figure 21.

Innumerable other profiles are possible, both real and imagined. They depend on the interests of the analyst. Everything rests, of course, on the extent and quality of the original chip and pulp sampling campaigns in mills, the operational stability in those mills, and the range of physical testing data emanating from the samples.

Bringing pulp strength delivery to the simplest comparisons, one arrives at Figure 23. In softwood kraft pulp mills, most digester systems generally fail to capture the strength
potential inherent in the chip furnishes fed to them (Figure 23-A). In fact, the values can be far worse (Figure 23-B). Figure 23-C demonstrates that oxygen delignification systems and bleach plants also cause strength losses, fortunately in amounts much lower than those in digesters. Pulp drying is neutral in the sense of tear-tensile strength delivery; it is not, however, in its effects tensile strength, or in many other physical properties.

It should be clear from these graphs that considerable room remains for improvement in just how strong commercial kraft pulps could be.

SUMMARY

A research-based methodology is useful in addressing the challenge of where kraft pulp strength comes from and how it might be made better. It brings a systematic benchmarking approach to the characterization of pulp strength along a mill’s fibreline, and sets the maximum potential strength in each of the primary fibreline operations (i.e., pulping, oxygen delignification, bleaching).

In kraft mills today, most digester systems fail to achieve the pulp strength potential inherent in their original wood furnishes. Of the strength which goes “missing”, the biggest part happens in digester operations, usually for a combination of chemical and physical reasons. In strength delivery terms, the deficits are usually 25% ± 10%. It is possible to prevent most of this brownstock strength loss, but only in modern liquor displacement batch digester systems with pumped discharge.

The same systematic analysis, when applied to downstream operations, shows that oxygen delignification and bleaching typically make pulp weaker, while pulp drying dramatically changes its refining characteristics.

Because kraft pulp production is complex and expensive, continual attention is required on how to do it well, and how – when the rare opportunity arises – to make changes for the better in choosing process equipment and operating practices. Combining all the best factors can result in astounding gains.

REFERENCES

Figure 1. Pulp strength along a kraft pulp mill’s fibreline: Where does it begin? How does it change along the way? What kind of strength is being examined?

Figure 2. The “big block” approach considers the main chemical operations as units. Thus, one block may include an entire bleach plant, or a pulp drying machine. This sampling plan adapts easily to most kraft mills. The sampling locations are the fewest needed to properly describe the fibreline in pulp strength terms, and variability across time is recognized by having three sample sets at two-hour intervals [1].

Figure 3. Chip size control which maximizes 2-8 mm thick chips provides a great starting point for superior pulp making.

Figure 4. The greater the chip size variability, the greater the heterogeneity of the pulp that is made. Significant penalties can accrue to comparatively small proportions of oversized and undersized particles.
Figure 5. Many factors contribute to optimum pulping yield, such as process chemistry, chip size control, uniformity of pulping, and species control. The better they all are, the more likely that the yield of brownstock from wood will be optimized, as will the physical performance of the pulp [10].

Figure 6. Fibreline profiles can be as numerous as the tests used to determine pulp performance. These ones are quite typical of bleachable-grade softwood kraft pulp mills. PP = Pilot-Plant (Reference) Pulp; BS = Brownstock; O2 = Post-Oxygen; D2 = Bleached; MC = Machine-Dried.
Figure 7. Reference pulp making is reproducible, an important point when fibreline profiles are then anchored to the pilot-plant results [12].

Figure 8. The twelve pulps plotted in Figure 7 all had essentially the same average fibre length [12].

Figure 9. These are brownstock tear-tensile strength delivery values for batch digester systems (softwood unless indicated):

1. Reference pulp in 20L R&D digester (this case is defined as 100%)
2. Mill pulp from short-fibred hardwoods
3. Conventional hot-blown batch
4. Conventional hot-blown batch
5. Conventional hot-blown batch
6. Case 5 converted to pumped discharge
7. Liquor displacement batch – pumped discharge
8. Liquor displacement batch – air-blown discharge

Average for the conventional batch digesters: ~75%
Figure 10. These are brownstock tear-tensile strength delivery values for continuous digester systems (softwood unless indicated):

9. Mill pulp from short-fibred hardwoods
10. Two-vessel LoSolids (same digester as Case 9)
11. Single-vessel converted to MCC
13. Single-vessel conventional
14. Single-vessel conventional
15. Single-vessel conventional
16. Single-vessel conventional
17. Two-vessel vapour-phase conventional
18. Conventional sawdust digester
19. M&D sawdust digester
Average for these continuous digesters: ~80%

Figure 11. Although quite different in absolute values, the patterns of average fibre length across this softwood/hardwood swing mill were basically the same.

Figure 12. Medium-consistency oxygen delignification is by far the most common type of O₂ system; Cases 20-24 are of that type, running at 35-45% delignification. Typically they have tear-tensile strength delivery deficits of 5% ± 2. Case 25 is a mini-oxygen system, running at 25-30% delignification; it is comparable to the MC systems. The dotted lines are the strength levels in the parent brownstock pulps. Pilot-plant oxygen delignification should result in no strength loss. The same is true with hardwood pulp in a mill system.
Figure 13. In this comprehensive examination of pulp strength delivery in a softwood kraft mill, there were seven sampling locations and five rounds of samples. The profile along the fibreline was similar in all rounds. At the end of the bleach plant (i.e., D2), pulp strength delivery was 72% on average [1].

Figure 14. In this before/after comparison, the renovation of a kraft softwood mill brought a penalty in oxygen delignification, a benefit in ECF bleaching, and an overall increase of 5% in tear-tensile strength delivery in the bleached, dried pulp (MC).

Figure 15. During final drying, the pulp fibres shrink significantly, causing a shift in tearing resistance and tensile strength. Even so, the pulp simply moves upward to the left along the same overall curve.

Figure 16. These sampling locations were used to do a detailed strength delivery study of a complete pulp drying machine.
Figure 17. For the machine in Figure 16, the primary change in pulp properties was the significant decline in all tensile strength values in the Flakt dryer, accompanied by fibre shrinkage measured as fibre saturation point.

Figure 18. This tear-tensile strength delivery profile characterizes the average of a group of four kraft mills all pulping similar mixed softwood chips.

Figure 19. Eliminating any constraints, the final value of ~70% in Figure 18 could be raised to 90% by appropriate choice of digester equipment and modern bleaching.

Figure 20. Along this swing mill’s fibreline, the softwood and hardwood tensile strength values were naturally quite different, but the patterns were the same.
Figure 21. This profile shows the normal pattern of tensile strength in softwood kraft mills, with a significant decline between pilot-plant reference pulp and mill brownstock, another during pulp drying, and not much change between them.

Figure 22. By removing all constraints, an optimal choice of wood species (with long, slender fibres) and digester system could double the initial tensile strength of kraft pulp.
Figure 23. In softwood kraft pulp mills, almost all digester systems fail to capture the strength potential inherent in the chip furnishes fed to them (A = best, B = worst). Oxygen delignification systems and ECF bleach plants cause modest strength losses, lower in total than what happens in pulp-making (C). In pulp drying, the main problem is loss of tensile strength; it can be as significant as what happens in pulping.