Fiber deformation and sheet strength

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ABSTRACT

Fiber deformation in commercial kraft pulps was studied. Pulps from six mills were sampled in different positions: unbleached, oxygen-bleached, and fully bleached. Fiber deformations were classified and counted. Deformations that changed the direction of the fiber axis were detrimental to tensile index and tensile–stiffness index. The degree of deformation—evaluated as curl index or as zero-span tensile index—correlated strongly with the number of deformations that changed the direction of the fiber axis. Fiber curl also influenced the strength improvement observed with increasing wet pressing, with curlier fibers showing the least improvement.

Application:

Fiber deformation is an important predictor of commercial pulp quality. Despite its importance, it is usually neglected, since conventional methods of pulp evaluation are insensitive to fiber deformation.

Fiber deformation is not usually considered as a factor when discussing the relationships between fiber properties and sheet properties. There are two main reasons for this. The first is that measurement of fiber deformations is difficult and tedious. The second is that fiber deformations are an "industrial" fiber property, which means that extra care must be taken when fiber deformations are studied in the laboratory. Pulp handling in the laboratory does not introduce fiber deformations to the same extent as in the mill, and the commonly used laboratory beating procedures remove those that are there.

In industrial applications, fiber deformation is a very important fiber characteristic, since all commercial pulps have deformations. In mechanical pulps, the latency effect is a well-known example of fiber deformation *(1)*. In this case, however, the deformation can be easily removed by heat treatment. For chemical pulp, the effect is not so well documented, and industrial methods for removing deformations are not presently available.

The inclusion of fiber deformation with other fiber characteristics in pulp evaluation could greatly improve the understanding of the relationships among fiber properties, pulping and papermaking processes, and paper quality. Excluding fiber deformations from the discussion is like trying to print a color picture using only two colors; a lot of information is lost or misinterpreted.

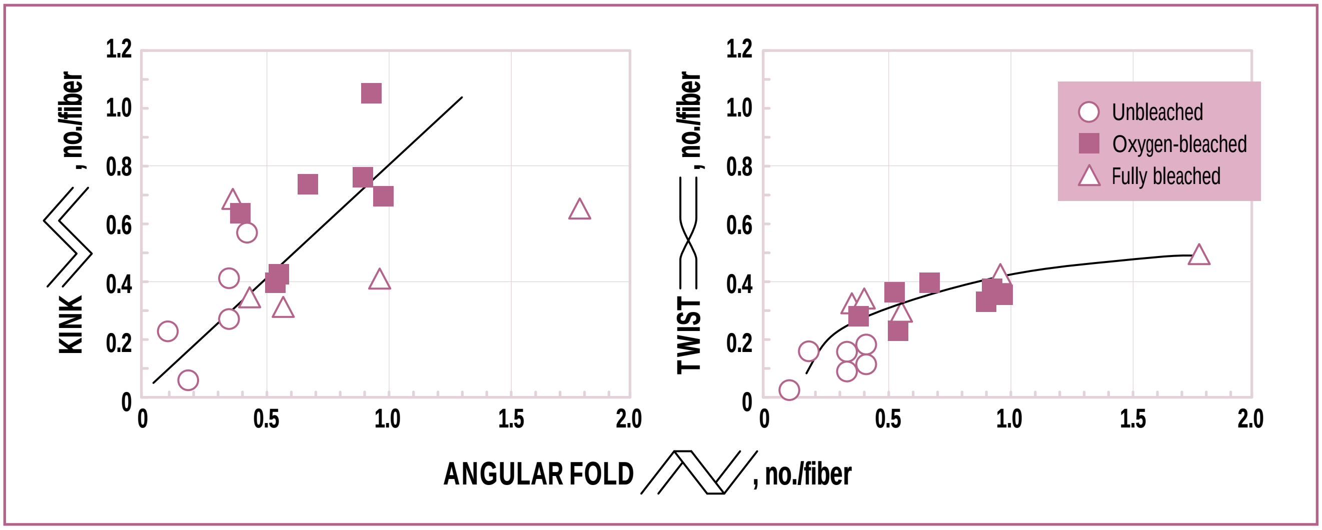
The literature on fiber deformations and their effect on paper properties is limited. In 1985, Page *et al. (2)* reviewed the current knowledge and emphasized the importance of fiber deformations: "Curl and microcompressions are among the most important factors affecting pulp and paper properties of all pulps. Major property differences occur between pulp and paper products caused by these unrecognized differences. There have been many surprises in research and production enterprises because of failure to recognize the importance of these fiber features."

The development of image-analysis techniques since 1985 has made it much easier to quantify fiber curl. Recent work has also shown that the zero-span tensile index can be used to quantify fiber deformations *(3)*. However, there is still no suitable technique for quantifying microcompressions.

Our present interest in fiber deformations was initiated by the observation that the difference in strength development between industrial refining and laboratory beating was due to the different effects that these two methods of beating had on fiber curl *(4)*. Page had earlier shown that laboratory beating straightens the fibers, and this was confirmed by Mohlin *(4)*. Industrial refining, on the other hand, hardly removed any fiber deformation. Comparing strength properties at the same degree of fiber bonding ability, i.e., at the same water-retention value (WRV), it was found that tensile index, tensile–stiffness index, burst index, and compression strength were all reduced as a result of the inability of the industrial refining to straighten the fibers. Neither the tensile energy absorption nor the tear–tensile relationship was influenced by the method of refining. A simple linear model including WRV and a measure of fiber deformation could explain all the differences observed in, e.g., tensile index when different methods of beating were compared.

In industrial pulps, fiber deformations introduced during pulping and bleaching thus have an effect on paper quality that is hidden by laboratory beating. When pulps are ranked by standard laboratory methods, it is easy to overlook differences in the degree of fiber deformation between pulps, which leads to false conclusions. Several such discrepancies were found when laboratory evaluations of pulp were compared with evaluations on STFI's FEX pilot paper machine.

From beating studies, it was concluded that what happens to the fibers during pulping and bleaching



1. Covariation among three types of fiber deformation—kink, twist, and angular fold—that changed the direction of the fiber axis for six commercial pulps

is even more important than has hitherto been recognized. MacLeod *et al.* have shown that the strength potential of the fibers is reduced more during industrial processing than in the laboratory *(5)*. Their pulp evaluation procedure, however, included PFI-mill beating. The strength delivery they discussed should thus be further reduced by the effect of fiber deformation, which is hidden by the fiber straightening that occurs in the PFI mill.

The present study was undertaken in an effort to learn more about fiber deformation introduced during pulping and bleaching. Samples of unbleached, oxygen-bleached, and fully bleached pulps were obtained from six mills for use in this study. This article presents results of the study and discusses the relationship between fiber deformation and paper strength. Some observations concerning the effect of fiber deformations on strength development during wet pressing are also presented.

EXPERIMENTAL

Pulp preparation

Samples of unbleached, oxygen-bleached, and fully bleached softwood kraft pulps were obtained from six Swedish mills. The pulp mills were chosen to represent different types of process layouts. All the mills were producing conventional bleached kraft pulp. The tested pulps were never dried.

All the results presented here are for unbeaten pulps. As mentioned before, PFI-mill beating would remove most of the deformation, so laboratory-beaten pulps are not of interest. For practical reasons, it was not possible to use industrial refining on the mill samples.

Pulp evaluation

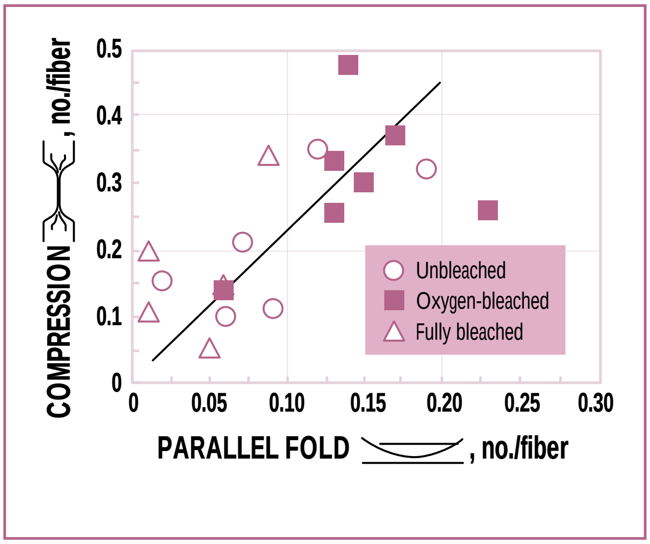
Fiber deformation was evaluated in three different ways: by counting and classifying the deformations in a light microscope, by measuring zero-span tensile index, and by determining curl index.

In the microscope study, fiber deformations were classified in seven classes: angular fold, kink, twist, microcompressions, parallel fold, compression, and mechanical damage. The different deformations were counted, and the results were presented as the average number of deformations per fiber. In the case of microcompressions, this was probably not an ideal way to quantify them, since the size of the microcompressions varied widely.

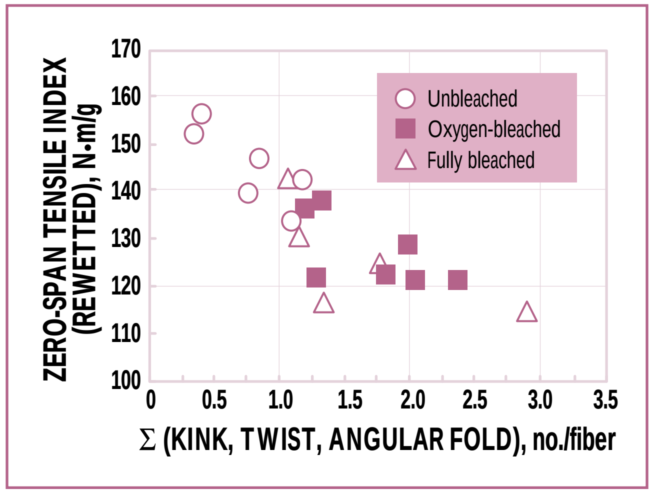
At least 300 fibers per sample were measured. The reproducibility was judged by double-testing some of the samples. The maximum difference obtained for number of deformations per fiber for a certain type of deformation was less than 10%.

The zero-span tensile-index method was originally developed to measure fiber strength, but recent work shows that it is also sensitive to fiber deformation *(3)*. The measurement can be done either on dry sheets or on rewetted sheets *(6)*. Rewetted sheets were used to avoid the possibility that fiber bonding would conceal the effect of fiber deformation.

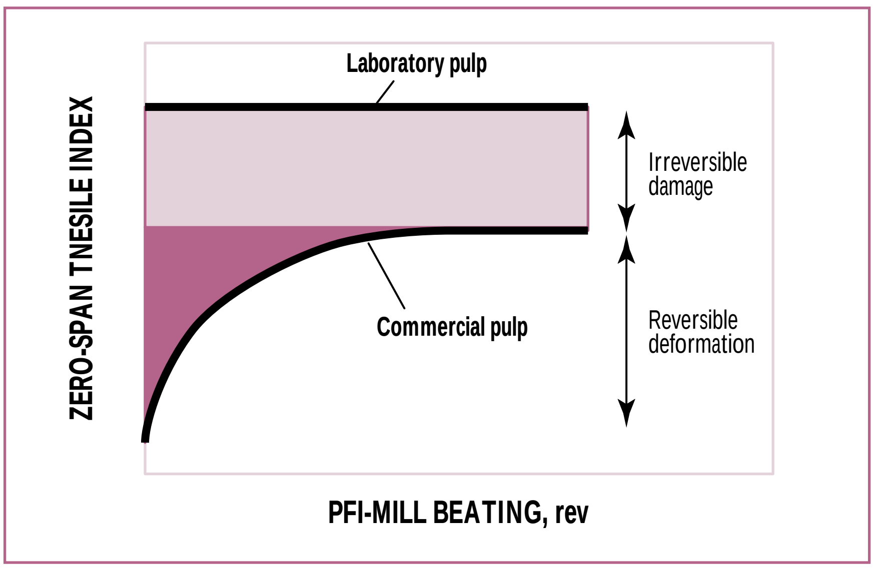
The degree of fiber curl was determined in the STFI FiberMaster, an instrument developed at STFI but not yet commercialized *(7)*. The device measures fibers in suspension using image analysis. About 10,000 fibers are measured in each sample. Data are obtained for fiber length, fiber width, and fiber curl. Fiber curl was evaluated as the shape factor, which was calculated as the ratio between the length of the diagonal in the circumscribed rectangle and



2. Covariation between two types of fiber deformation—compression and parallel fold—that did not change the direction of the fiber axis for six commercial pulps



4. Zero-span tensile index for rewetted sheets is sensitive to the number of deformations that change the direction of the fiber axis



3. Fiber defects in commercial pulps can be looked at as two separate effects: irreversible damage and reversible deformations. Reversible deformations can be removed with PFI-mill beating.

the length of the fiber. A shape factor of 100 is a completely straight fiber, with lower numbers denoting progressively greater fiber curl. A shape factor of 50 corresponds to a double-folded fiber. A difference between pulps in shape factor of 0.4 units is significant.

Strength properties were measured according to SCAN standards on laboratory handsheets.

Wet-pressing study

The pulp used in the wet-pressing study was a sheet-dried commercial bleached softwood kraft pulp.

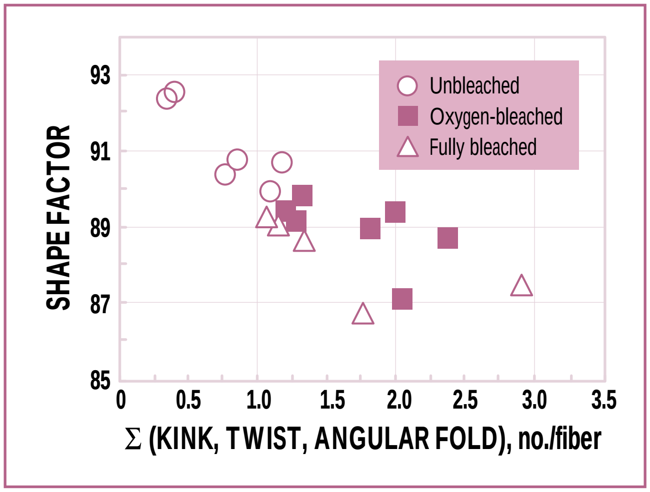
The pulp was beaten in a PFI mill to three levels and in a 24-in. double-disc refiner (Beloit) to two levels, one at a low specific edge load that hardly changed the degree of fiber deformation and the other at a higher specific edge load that further increased the degree of fiber deformation.

Handsheets were made according to SCAN standard methods, except that the wet-pressing pressure was varied to obtain different degrees of sheet densification.

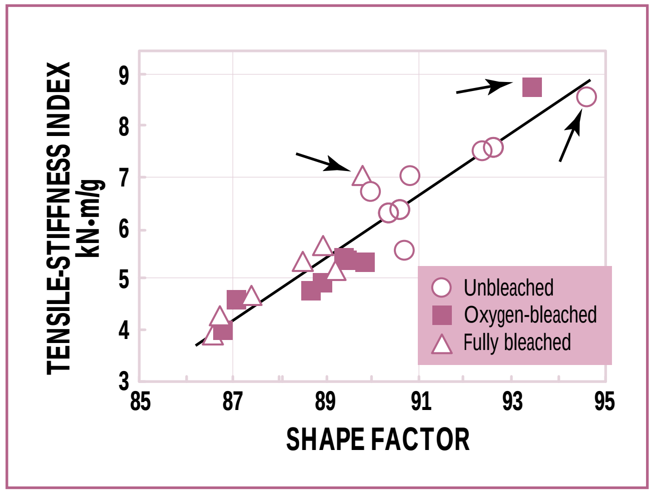
RESULTS AND DISCUSSION

There are many types of fiber deformations, and their effects on sheet properties may differ. It therefore was decided to study the different types of deformations using light microscopy. The microscope studies, however, are tedious compared with the other two techniques for evaluating fiber deformation.

Both curl index and zero-span tensile index correlated with the number of deformations seen in the microscope. The three methods, however, measure different properties, and it cannot be expected that the good correlations found here are generally valid and independent of



5. Shape factor (curl index) is sensitive to the number of deformations that change the direction of the fiber axis. Fully bleached fibers show a trend towards a lower shape factor at the same number of deformations compared with oxygen-bleached pulps.



6. Tensile-stiffness index decreased with decreasing shape factor, i.e., with increasing degree of fiber deformation (curl). Points marked with an arrow represent unbeaten laboratory pulps; all other pulps were unbeaten and commercially produced.

the treatment to which the pulps have been exposed.

Microscope study

The different types of fiber deformation were quantified as the number of deformations per fiber. Since there was no significant difference in average fiber length among the different pulp samples, this was an acceptable approach.

The various types of fiber deformations were divided into two groups. The first group included angular fold, kink, and twist, all of which changed the direction of the fiber axis. The other group included parallel fold and compression that did not change the direction of the fiber.

Figure 1 shows the covariation between angular fold, kink, and twist. The two most frequent types of fiber deformation were angular fold and kink. Kink was more dominant in summerwood fibers and angular fold in springwood fibers.

As can be seen from the figures on the axes, the number of deformations was quite large, and it was not uncommon for each fiber to have several deformations. The number of deformations increased further down the pulping line. Unbleached pulp fibers were less deformed than oxygen-bleached fibers, which in turn were less deformed than fully bleached fibers.

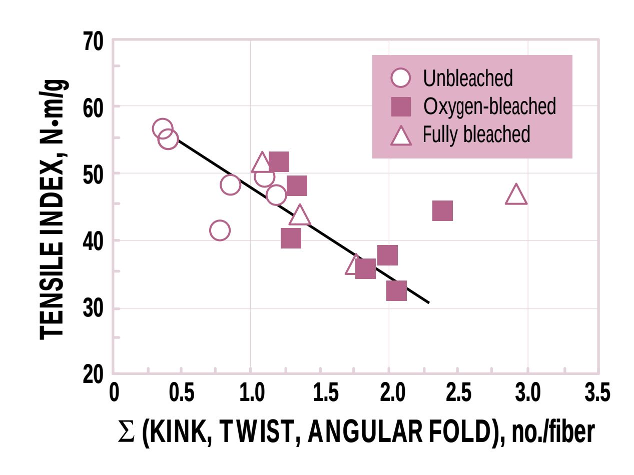
Parallel fold and compression also showed some degree of covariation, as seen in Fig. 2. These types of deformations were less frequent than those shown in Fig. 1, at the most one in every second fiber. It was not possible to detect any effect of these two types of deformation on sheet properties, so they will not be discussed further.

Zero-span tensile index as a measure of fiber defects

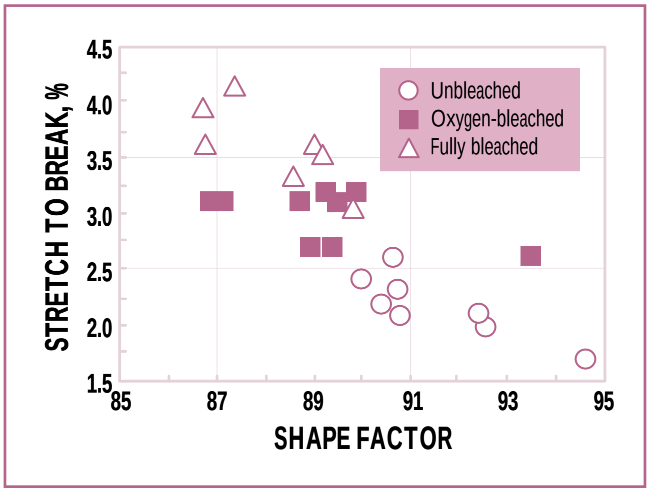
Zero-span tensile strength was originally developed to measure fiber strength. This is really only the case when the fibers are straight, since fiber deformations will influence the results. Thus if zero-span tensile index is to be used as a measure of fiber strength, the measurement should be made on pulps containing only straight fibers.

If a laboratory pulp is carefully handled so that it consists only of straight fibers, the zero-span tensile index does not change with beating. If the pulp is a commercial pulp in which the fibers are deformed, the zero-span tensile index increases initially with beating to reach a plateau after about 3000–4000 revolutions *(5)*. This increase is due to the fact that the PFI mill straightens the fibers. When they are straight, no further change in zero-span is observed.

In order to systematize the factors that influence the contribution of the fibers to sheet strength, two types of fiber defects have been defined, namely irreversible damage and reversible deformation. The concept is illustrated in Fig. 3. Irreversible damage was defined as the difference in zero-span tensile index between an undamaged and a damaged fiber when both are straight, i.e., after beating in a PFI mill. This difference is due mainly to chemical degradation during pulping, but it can also include mechanical damage to the fibers. This difference corresponds to what MacLeod *et al.* have



7. Tensile index for unbeaten commercial pulps correlated with the number of deformations that changed the direction of the fiber axis.



8. Stretch-to-break for the unbeaten commercial pulps decreased with increasing shape factor, i.e., with decreasing fiber curl.

called "strength delivery" when comparing laboratory and industrial pulping *(5)*.

The other defect is reversible deformation, the main theme of this paper. It was defined as the increase in zero-span tensile index achieved by laboratory beating. This increase is due to the straightening of the fibers, i.e., mainly to the removal of angular fold and kinks. For commercial pulps, the irreversible damage and the reversible deformation are of the same magnitude.

Figure 4 illustrates that the defects that changed the direction of the fiber axis—the sum of angular fold, kink, and twist—had a large influence on zero-span tensile index. No systematic effects were found for pulp type, pulping process, or mill equipment.

Curl index as a measure of fiber deformation

There was a good correlation between shape factor and the number of deformations that changed the direction of the fiber axis, as seen in Fig. 5. Because the shape factor (also called the curl index) measures the total change of direction of the fibers, this indicates that fiber bending originates from distinct fiber deformations and not from a smooth fiber curvature. There was a slight tendency for the fully bleached pulps to have a lower shape factor than the other pulp types, i.e., they were more curled at a given number of fiber deformations. However, this can probably be explained by the microscope observation that the kinks were sharpest in the fully bleached pulps.

Sheet properties and strength properties

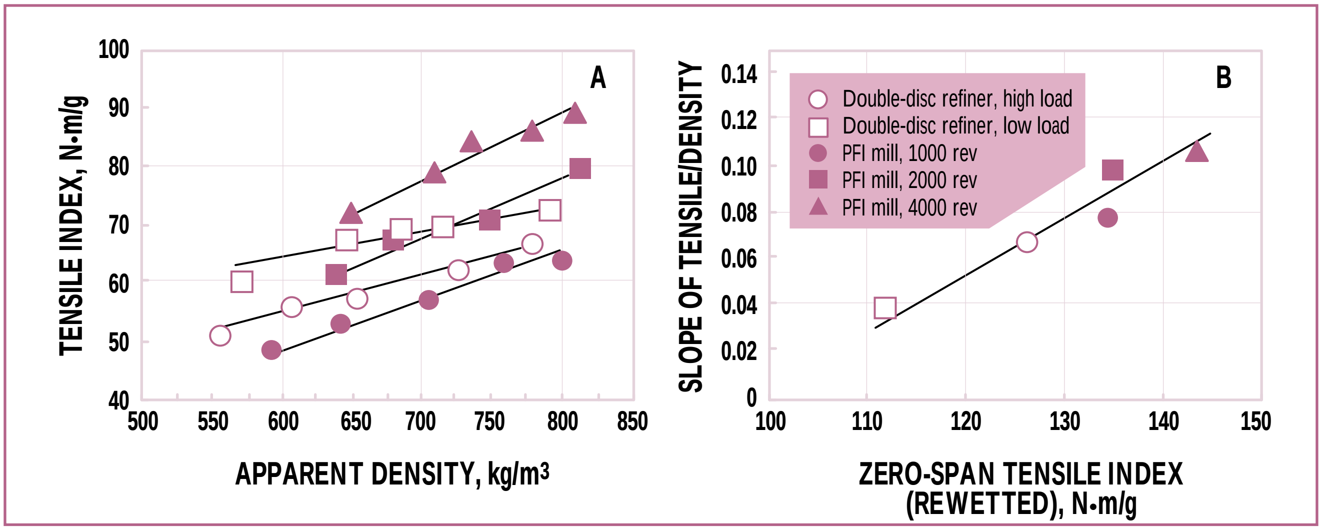
Handsheets were made from the unbeaten pulps to study the relationships between sheet properties and fiber deformation. The comparison between laboratory and industrial beating showed that tensile-stiffness index, tensile index, stretch-to-break, burst strength, and compression strength were the strength properties most influenced by reversible fiber deformations. In the present study, only tensile properties were evaluated.

Figure 6 shows the tensile–stiffness index for the unbeaten commercial pulps as a function of the shape factor. The shape factor was in this case the measure that gave the best correlation. Nearly all of the variation in tensile–stiffness index can be explained by the differences observed in shape factor or curl index. The range of tensile–stiffness index was quite large, from about 8 down to 4.

The study of commercial pulps was also extended to include laboratory pulps produced from chips collected in one of the mills at the same time as the pulp samples. In Fig. 6, the data points for these pulps (indicated by arrows) are also included, and they fall on the same line. It is worth noticing that the level of the tensile–stiffness index for the straightest fibers is close to what can be obtained after beating in the PFI mill.

In the case of tensile index, the best correlation for the commercial pulps was obtained with the sum of angular fold, kink, and twist, i.e., the sum of fiber deformations that changed the direction of the fiber axis. The results are presented in Fig. 7.

One interpretation of these results is that for the tensile index (Fig. 7), the number of deformations is most important, whereas for the



9. Strength development in wet pressing depends on how curled the fibers are. A: The industrially beaten pulps show much less strength increase for a given density increase than for the PFI-mill-beaten pulps. B: This behavior could be explained by the different degree of deformation, evaluated as zero-span tensile index, remaining in the pulp after beating.

KEYWORDS

Beating, bleached pulps, curl, deformation, fibers, kraft pulps, mechanical properties, microscopy, oxygen, tensile strength, unbleached pulps, wet pressing, zero span tensile strength.

tensile-stiffness index (Fig. 6), the extent to which the direction of the fiber axis was changed also influenced the value obtained. It was mentioned earlier that for the fully bleached pulps, the kinks seemed to have a sharper angle than the other pulps, and this decreased the shape factor for a given number of deformations.

Stretch-to-break also showed good correlation with the shape factor, as seen in Fig. 8. In this case, however, the stretch-to-break increased with increasing degree of deformation, i.e., with decreasing shape factor. A correlation between stretch-to-break and the number of microcompressions might have been expected. No such correlation was evident from our data, but it cannot be excluded, since the method of quantifying microcompressions needs to be improved.

Deformation and strength gain on wet pressing

Pulp beating and increased wet pressing are the two methods that are usually applied to improve the mechanical strength of paper made from a given stock. It has earlier been noted that industrial beating does not straighten the fibers in the same way as laboratory beating. Indeed, industrial beating at high specific edge load can deform fibers further *(8)*. A lower strength level therefore is obtained after industrial beating than after laboratory beating.

A separate investigation was carried out to study the influence of fiber deformation on the strength improvement achieved by increasing wet pressing. It was carried out on handsheets made from a bleached kraft pulp beaten to different levels both in the laboratory and on an industrial scale. The various density levels were achieved by changing the wet-pressing pressure.

Figure 9 shows tensile index as a function of sheet density. Very different slopes were obtained for the differently refined pulps. Wet pressing was very efficient for improving the strength of the PFI-mill-beaten pulps, and efficiency increased with the degree of beating. For the industrially beaten pulps, the slope was much less.

These different responses to wet pressing were related to the degree of fiber deformation. There was a direct correlation between the slopes in Fig. 9A and the degree of fiber deformation. The more deformed the fibers were, the slower was the increase in tensile index.

CONCLUSIONS

The study of six commercial pulp samples showed that most fibers in commercial pulps are deformed and that fully bleached pulps are more deformed than unbleached pulps. The deformations that have a negative effect on such properties as tensile index and tensile-stiffness index—and probably also on burst strength and compression strength—are those that change the direction of the fiber axis, i.e., kinks, angular fold, and twist. It was not possible in this study to separate the effects of these three types of deformation. Deformations that did not change the direction of the fiber axis did not significantly influence the sheet properties.

Fiber deformation is a very important fiber property that can probably explain many of the confusing and contradictory results that are found in the literature. In the future, fiber deformation will be more extensively studied, since tools to quantify the different type of deformation are now available. These tools will probably also be further developed, e.g., a method for quantifying microcompressions is still lacking.

If methods to control fiber deformation are developed, they can be used to improve product quality not only by avoiding deformations that are detrimental to the desired properties, but also by learning how to use them to improve other properties that might be important.

Special care has to be taken if fiber deformations are to be studied on a laboratory scale, since the experimental equipment used in the laboratory is very different from that employed in the mills. TJ

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