

Measuring the bonding ability distribution of fibers in mechanical pulps

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ABSTRACT: Currently, the pulp and paper industry mainly uses average values of mechanical pulp properties to characterize fibers, while printing paper grammages keep decreasing, making every fiber more important for strength, surface, and structure properties. Because fibers are inhomogeneous, average values of the whole pulp may not be enough for proper fiber characterization. This paper reports results from the development of a method to measure the distribution of fiber bonding ability in mechanical pulps.

Fibers from two commercial TMPs were fractionated into five hydrocyclone streams, using a four-stage hydrocyclone system. The fiber bonding ability of Bauer McNett fractions R16, P16/R30 and P30/R50 collected from each stream was analyzed. Five different methods of evaluating fiber bonding ability all showed that fibers were separated in the hydrocyclones according to their bonding ability.

Long fiber handsheets of the highest bonding fibers had up to 2.5 times higher tensile strength for the P16/R30 fraction than handsheets from the lowest bonding fibers. We also found that both the degree of fibrillation and collapse resistance index (CRI) of the fibers obtained from optical measurements are sufficient to predict quite accurately the tensile strength of handsheets made from fiber fractions. Further, we propose how to describe the distribution in fiber bonding ability for mechanical pulps, by combining some of these five different methods. A method to calculate fracture toughness of long fiber handsheets based on acoustic emission is also illustrated.

A more rapid way to characterize fibers in mechanical pulps with respect to their bonding ability distribution needs to be developed in the future. It appears that it is time to move on from characterizing pulp suspensions and handsheet properties using conventional approaches based on average values.

Application: Inhomogeneous raw material (annual rings in the wood) results in a distribution of fiber properties among the fibers to be used in printing paper. By characterizing the fibers with respect to their distribution in bonding ability, the fibers in the mechanical pulp can be more accurately characterized than from mere average values.

BACKGROUND

Current optical methods allow the characterization of fibers and shives with respect to their size distributions; e.g., length, and for shives, also width. Mechanical pulp quality parameters such as strength, drainability, and the bonding ability of fibers are usually reported as average values. Over time, the share of mechanical pulps with higher content of long fibers has increased in the production of printing grades. Due to increasing quality demands on paper and board products, it is important to consider not only the average value but also the distribution of bonding ability of different fibers.

In 1963, Forgacs presented a classic paper in which he showed that at least two quality variables are needed in order to characterize the physical properties of mechanical pulps [1]. These quality variables could be defined by two measurements or factors: the shape-factor (S); i.e., the specific surface of the P48-R100 Bauer McNett fiber fraction, and the length-factor (L), the fraction by weight retained on a 48-mesh screen.

In the 1980s, Strand introduced a somewhat different approach by using factor analysis, a type of multivariate data analysis [2]. The principle is that the variations in all measured pulp and handsheet properties can, to a great extent, be explained by only two independent common factors that de-

scribe fundamental fiber properties. Factor 1 is referred to as “fiber bonding” and Factor 2 as “fiber length”. These factors correlate well with Forgacs’ S- and L-factors.

Several years ago, Stora Enso started to apply factor analysis to quality-related pulp data from on-line and lab measurements in some mills [3]. The F1 factor is related to fiber bonding and the F2 factor to long fiber influence. However, variations in shives content would not seem to be included in either of these factors [4]. This implies that at least three fundamental parameters are required in order to characterize the physical properties of mechanical pulp: fiber bonding, long fiber influence, and shives. Recently developed methods allow the characterization of shives in a way more relevant than laboratory screening or devices based on optical devices [5]. The importance of the bonding ability of long fibers was also reported by Mohlin in 1989 [6]. However, because wood contains a wide distribution of thin-walled and thick-walled fibers, it is also important to evaluate mechanical pulp fibers with respect to the distribution of their bonding ability.

Our study was inspired by the work of Karnis and co-workers [7], among other researchers, who used multi-stage hydrocyclone fractionation to evaluate the specific surface distribution of different mechanical pulps. Hydrocyclones have also been used more recently for fractionating fibers with different

morphologies [8]. In addition, it has been shown that screens and hydrocyclones separate fibers based on different mechanisms with respect to independent common factors F1 and F2 [3]. In brief, screens separate fibers mainly by length (F2), while hydrocyclones separate fibers by specific surface (F1) [4].

During recent years, many studies have focused on the importance of fiber properties by using cross-sectional SEM images of fibers and papers [9-13]. The rapid development of optical analyzers enables a fast, yet more detailed characterization of fiber attributes, such as fibrillation, diameter, and wall thickness [14], as well as collapse resistance index (CRI) [15]. A relatively new method, acoustic emission (AE), was developed for the evaluation of fracture properties [16, 17].

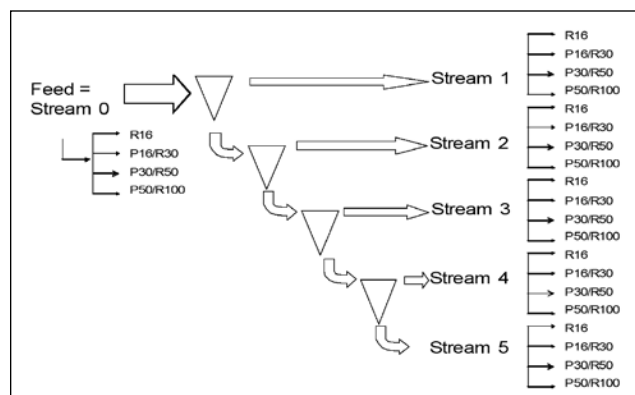
The main objective of our study was to develop a method to characterize fibers with respect to their distribution in bonding ability. Fibers were fractionated from two commercial thermomechanical pulps (TMP) into five streams in a four-stage hydrocyclone system. The fibers from different fiber length classes from all five streams were analyzed with respect to their bonding ability. Since there is no common definition of “bonding ability,” we analyzed the fractionated fiber streams of each pulp in five different ways:

1. the split of fibers by weight in each stream;
2. tensile strength, fracture toughness, and apparent density of handsheets produced from long fiber fractions;
3. optical measurement of fiber width, fiber wall thickness, and external fibrillation of long fiber fractions;
4. cross-sectional SEM images of long fibers; and
5. acoustic emission (AE) of oriented handsheets made from long fiber fractions.

EXPERIMENTAL

Fractionation of fibers

In this study, we used two commercial newsprint grade thermomechanical pulps, Pulps A and B, produced from Norway spruce. These pulps were fractionated in an arrangement of hydrocyclones at the Noss AB pilot plant in Norrköping, Sweden, as shown in **Fig. 1**. This produced five separate pulp



1. Fractionation trial set-up of hydrocyclones. Each hydrocyclone stream and feed stream was also fractionated with respect to fiber length in a Bauer McNett.

streams, with fiber bonding ability predicted to be the highest in Stream 1 and the lowest in Stream 5, with consecutively reduced bonding between streams.

Pulp A was fractionated first with about 20% of the R100 Bauer McNett fiber fraction in each stream. In the Pulp B fractionation, the process condition settings during the trial were the same as those for Pulp A, which allowed fibers to end up in the corresponding stream according to their properties. We calculated the amount of fibers by weight in each stream on the basis of flow and consistency.

Analytical determinations

Fibers collected in each hydrocyclone stream were fractionated further using the Bauer McNett classifier according to SCAN-CM 6:05 standard. Handsheets were produced from the R16, P16/R30, and P30/R50 Bauer McNett fiber fractions. Tensile strength was measured according to ISO 1924-3 standard and apparent density according to SCAN-P 88:01 standard.

The external fibrillation (fibrillation index), fiber wall thickness (fiber wall thickness index), and fiber width were measured using the FiberLab™ analyzer [13]. Between 5,000 and 10,000 fibers were measured in each FiberLab run, with triplicate testing yielding total measurement of 15,000 to 30,000 fibers.

We calculated the collapse resistance index (CRI) according to the method described by Vesterlind; et al., in Equation 1 [15]. CRI is based on the assumption that fibers are circular and that fiber walls have the same E-modulus throughout the whole fiber length. Since the FiberLab fiber wall thickness measurement was not calibrated to a reference standard, we assume the calculated CRI values to be proportional to a “true” value.

$$\text{Collapse Resistance Index (CRI)} = \frac{2t^2}{w - t} \quad 1$$

t - fiber wall thickness

w - fiber width

We obtained the fiber wall thickness distribution from the cross-sectional SEM images of the P16/R30 Bauer McNett fiber fraction, using the image analysis software at Stora Enso Research Centre, Falun, [9-13], as well as manually.

We produced oriented, calendered sheets, using a Formette Dynamic sheet former, from the P16/R30 Bauer McNett fraction obtained from each pulp stream. The oriented sheets were analyzed for fracture toughness defined as J-integral (SCAN-P 77:95). The direct fracture toughness measurements were later compared to the parameter W_c from the acoustic emission test data.

The acoustic emission (AE) method was developed earlier for analyzing papers and is described in [16, 17]. In this study, however, the AE was introduced as a method for measuring the physical properties of fibers.

For more details about experimental performance, references 18 and 19 are recommended.

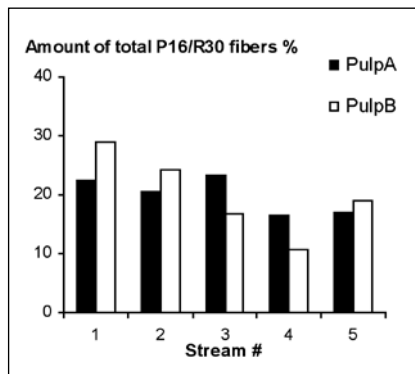
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RESULTS AND DISCUSSION

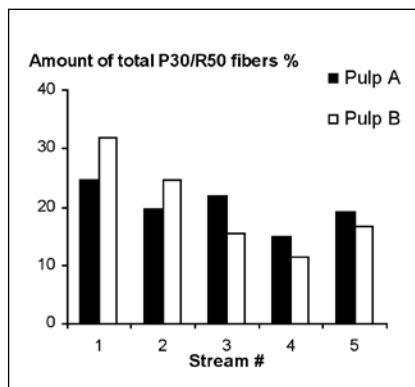
Split of fibers by weight

To set reference conditions, the Pulp A R100 fraction was divided into five streams with about 20% of the R100 fibers per stream. However, at similar process conditions, fractionation of Pulp B resulted in a higher amount of fibers in Streams 1 and 2, suggesting that Pulp B contains a larger amount of fibers with high bonding ability (Figs. 2a and 2b).

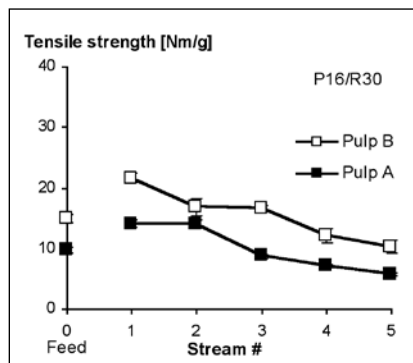
The split of the P16/R30 fiber fraction (Fig. 2a) was similar to the split of the whole R100 fraction. The higher amount of P16/R30 fibers in Streams 1 and 2 for Pulp B compared to Pulp A suggests that Pulp B had a higher proportion of fibers with high bonding ability in this particular fraction. Correspondingly, the amount of fibers in Streams 3 and 4 was lower for Pulp B. In order to understand these differences in the proportion of fibers going to Streams 1 and 2 better, we measured the properties of the fibers in each stream.



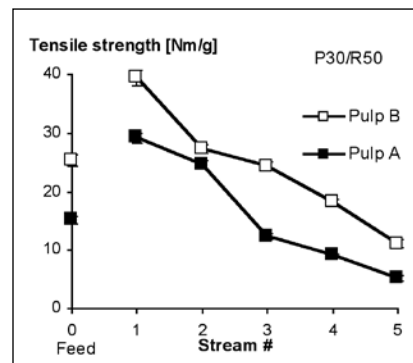
2a. Percent of total amount of P16/R30 fibers per stream.



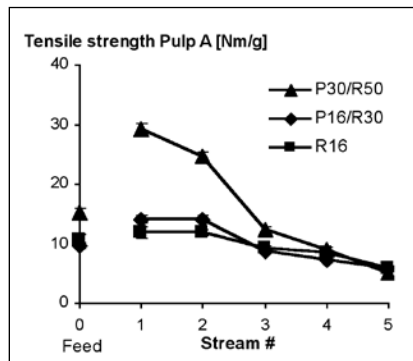
2b. Percent of total amount of P30/R50 fibers per stream.



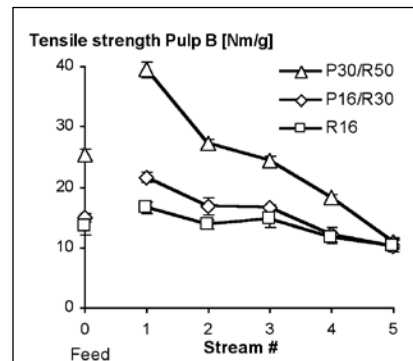
3a. Tensile strength per stream, P16/R30 fraction.



3b. Tensile strength per stream, P30/R50 fraction.



4a. Tensile strength of Pulp A fractions.



4b. Tensile strength of Pulp B fractions.

Physical properties of lab sheets

Results for the P16/R30 and P30/R50 fractions are presented in Figs. 3a and 3b. As expected, fibers with the highest bonding ability concentrated in Stream 1 (for Pulp A, Stream 1 and 2), as measured by the tensile strength of the handsheets (Figs. 3a and 3b). Fibers with the lowest bonding ability were found in the last reject stream, Stream 5. This is valid for both Pulps A and B.

The tensile strength for Pulp B is higher than that of Pulp A for the whole feed pulp, as well as throughout all streams (Figs. 3a and 3b). This suggests that the Pulp B fibers have a higher bonding ability than Pulp A fibers, which is also supported by the "Split of fibers by weight" evaluation (Figs. 2a and 2b). Both the tensile strength and the apparent density measurements of the handsheets suggest that the hydrocyclones separated fibers according to their bonding ability.

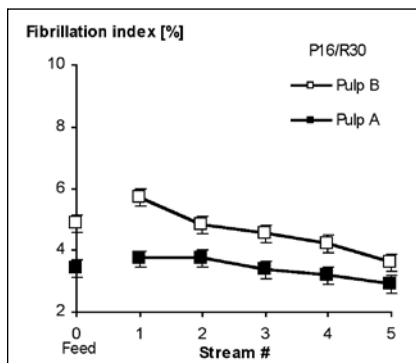
Figures 4a and 4b show the tensile strength of all three long fiber fractions R16, P16/R30, and P30/R50 for each pulp. Remarkably, for both Pulps A and B, the fibers with the lowest bond-

ing ability show a tendency to converge toward a similar tensile strength value in Stream 5, regardless of the Bauer McNett fraction; i.e., the fiber length. This indicates that fiber bonding and fiber length are independent of each other and that the hydrocyclone fractionation was performed with respect to fiber bonding and not to fiber length.

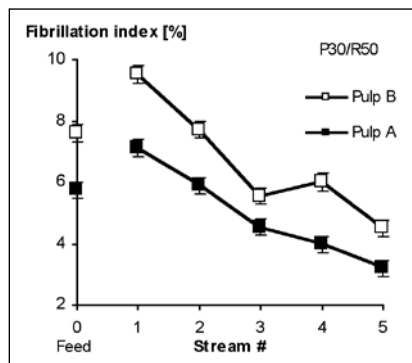
To get another indication of how fibers were separated with respect to their quality, we measured fracture toughness defined as J-integral for oriented sheets produced from the P16/R30 fraction. (Fracture toughness is further discussed in the acoustic emission section below, with related figures.) For both pulps, the fracture toughness was the highest for Stream 1 and the lowest for Stream 5 with consecutively reduced fracture toughness values in between. Also, the Pulp B fibers had a higher fracture toughness overall than the Pulp A fibers.

Optical measurements of fiber properties

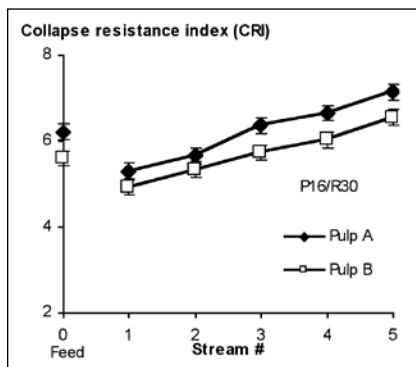
We also studied how the long fibers had been fractionated in hydrocyclones with respect to more fundamental fiber prop-



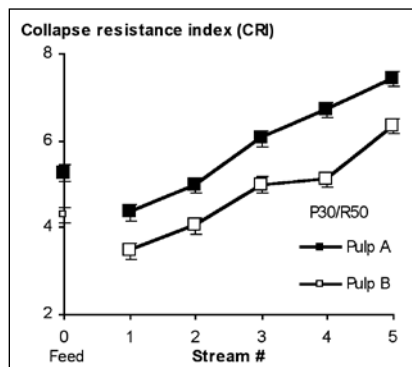
5a. Fibrillation index of the P16/R30 fraction.



5b. Fibrillation index of the P30/R50 fraction.



6a. Collapse resistance index, CRI, for the P16/R30 fraction.



6b. Collapse resistance index, CRI, for the P30/R50 fraction.

erties, compared to the testing of strength properties of handsheets. We analyzed all streams for fiber wall thickness, fiber width and degree of fibrillation of individual fibers. **Figures 5a and 5b** show that hydrocyclones separated fibers according to the degree of fibrillation.

In Streams 1 and 5, the difference in values of the fibrillation index of the P16/R30 fiber fraction was fairly small. The standard deviation of the measurement was in fact very small for all streams. It appears that external fibrillation is only one of several parameters affecting fiber bonding ability. Therefore, the hydrocyclones fractionated fibers not only by the degree of fibrillation, but also by other parameters that affect fiber bonding; e.g., fiber wall thickness and fiber width. The fiber wall thickness index was higher for the Pulp A fibers than for Pulp B fibers. Considering that external fibrillation was also lower for Pulp A (Figs. 5a and 5b), it would appear that the Pulp B fibers were peeled and fibrillated to a higher degree than the Pulp A fibers, which resulted in overall thinner fiber walls for the Pulp B fibers.

CRI was lowest for Stream 1 fibers

and the highest for Stream 5 fibers of the P16/R30 fraction (**Fig. 6a**) as well as for the P30/R50 fraction (**Fig. 6b**). The fibers with the lowest CRI (i.e., more likely to collapse) are the fibers that exhibit the highest bonding ability, as measured by the tensile strength of the handsheets (Figs. 3a and 3b).

At a given collapse resistance index, the Pulp B fibers exhibit a slightly higher tensile strength of the handsheets. This

suggests that the bonding strength between the fibers in Pulp B is somewhat higher. One indication that supports this is that the Pulp B fibers are more fibrillated at a given tensile strength. A good correlation was found between tensile strength and degree of fibrillation, as well as CRI of the fibers, but it was specific for each pulp type. Correspondingly, measurements of the fibrillation index and/or CRI of the fibers alone are not enough to predict tensile strength.

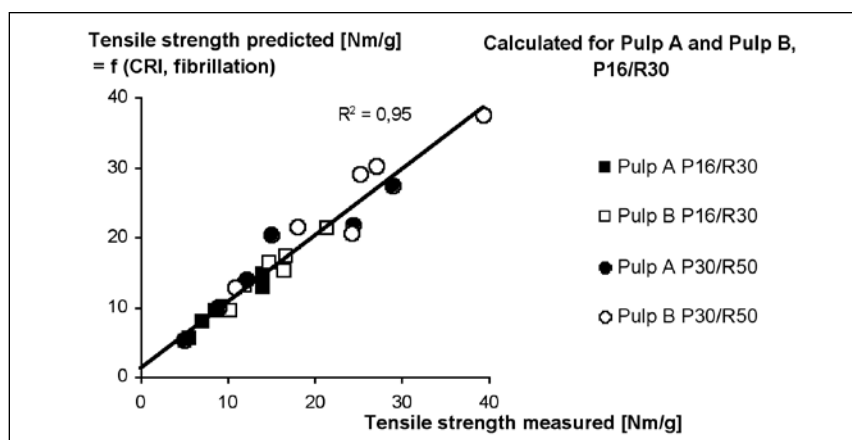
By the use of linear regression, however, it was possible to combine CRI and degree of external fibrillation to predict the tensile strength of Pulps A and B quite accurately and get a unique correlation (**Fig. 7**). The general equation for calculating the predicted tensile strength is shown in Equation 2.

$$\text{Tensile strength} = A + B \cdot \text{CRI} + C \cdot \text{Fibrillation} \quad 2$$

This correlation was also valid for another pulp we studied. This further supports the contention that bonding ability, as measured by tensile strength, depends on both how likely the fibers are to collapse and come into contact with each other (bonding area), as well as to what extent fibers are fibrillated and interact with each other.

Image analysis

Studies of cross-sectional images of the P16/R30 fraction give further insights



7. It is possible to predict tensile strength of long fiber laboratory sheets from CRI and fibrillation for fiber length fractions P16/R30 and P30/R50 using the fiber geometry parameters external fibrillation and collapse resistance index CRI (CRI calculated from fiber width and fiber wall thickness).

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into how fibers are separated in the hydrocyclone. Examples are shown here of the highest and lowest bonding ability fibers in Pulp A (**Figs. 8a and 8b**). Stream 1 (8a) contains fibers with thinner fiber walls than Stream 5 (8b).

The measured distribution of fiber wall thickness was wide in all streams. However, as the micrograph images clearly show, fibers with the highest bonding in Stream 1 are more thinly walled.

Acoustic emission

To get a different view from that obtained by conventional handsheet testing of how fibers in the fractionated streams bond with each other, we analyzed the oriented handsheets for acoustic emission during tensile testing. Data for the feed, Stream 1 (fibers with highest bonding) and Stream 5 (fibers with lowest bonding) for Pulps A and B are shown in **Figs. 9a and 9b**.

For both pulps, Stream 1 exhibits the highest strength and Stream 5 the lowest, which is in line with previous findings. The AE measurement provides the number of hits, suggested to be the number of fiber bonds broken during tensile testing. This measurement can be associated with the measurement of fiber flexibility because the more flexible fibers have more opportunities to establish contacts with other fibers. The fibers with the highest bonding ability have a slower increase in the number of breaks over time, which might represent a sheet with greater toughness.

The data obtained from the AE measurements can thus be used to calculate W_c , a parameter correlating with fracture toughness of a handsheet (Equation 3).

$$W_c = \frac{\sigma_c}{2 * E} \quad 3$$

W_c is the load at 10% of the total number of acoustic events at fracture, divided by the product of specimen width and grammage of the paper [17]. E is the E - modulus calculated from the initial slope of the load - elongation curve.

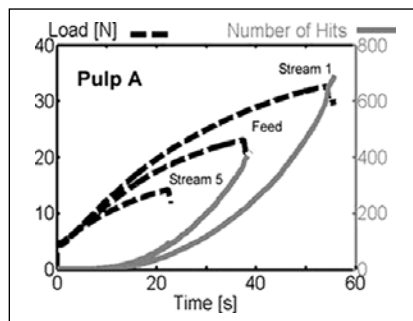
Bonding ability, as expressed in AE fracture toughness, has been evaluated and



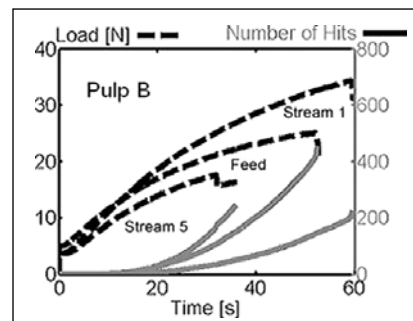
8a. Cross-sectional images of long fibers (P16/R30 fraction, Stream 1, Pulp A).



8b. Cross-sectional images of long fibers (P16/R30 fraction, Stream 5, Pulp A).



9a. Acoustic Emission curve, Pulp A, fraction P16/R30. Load and cumulative number of hits as a function of time.

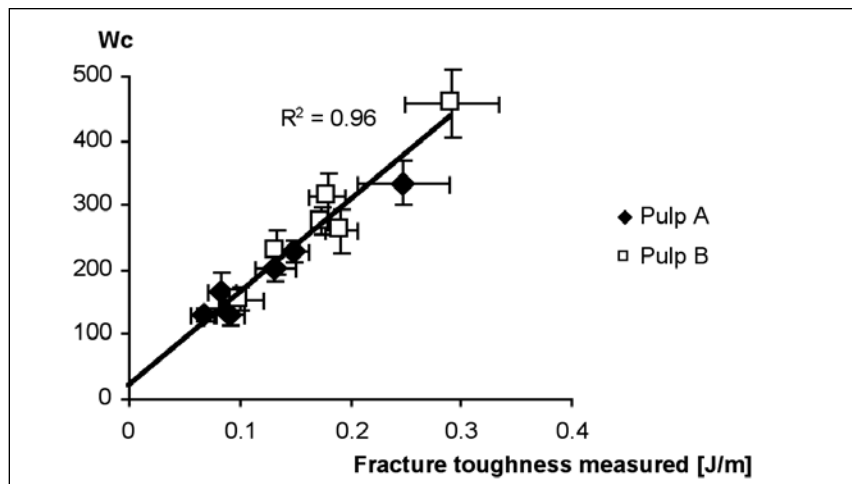


9b. Acoustic Emission curve, Pulp B, fraction P16/R30. Load and cumulative number of hits as a function of time.

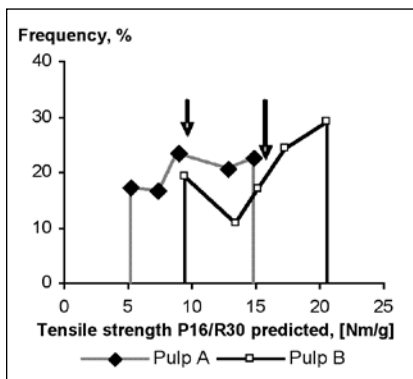
shows a trend similar to fracture toughness measured as J-integral. The correlation between fracture toughness measured as J-integral and W_c from the AE measurements was very good (**Fig. 10**).

From the results of AE measurements, it also appears that the Pulp B fibers are stronger than the Pulp A fibers, as they sustain the load for a longer period before rupture. Figs. 9a and 9b also show that the load at break is quite similar for Pulp A and Pulp B fibers but

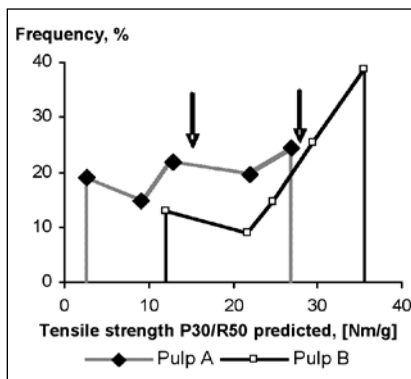
the difference in the number of breaks between Pulp A and Pulp B is significant. The Stream 1 Pulp B fibers have only about one third of the fiber bond breaks compared to the Stream 1 Pulp A fibers. This could suggest that the Pulp B fibers have stronger specific bonds than the Pulp A fibers. Similar conclusions can be drawn when calculating the ratio of the load after 20 seconds of elongation and the number of breaks detected during 20 seconds. It is



10. Correlation between fracture toughness measured traditionally and W_c , a parameter correlating with fracture toughness, from acoustic emission measurements. Tested on oriented, calendered handsheets produced from fiber length fraction P16/R30.



11a. Bonding ability distribution of P16/R30 fraction. Arrows indicate value of feed.



11b. Bonding ability distribution of P30/R50 fraction. Arrows indicate value of feed. As seen in Figs. 11a and 11b, these two pulps exhibit different distributions with respect to bonding ability. Pulp B has a higher proportion of fibers with higher bonding ability, as well as a higher level of bond strength of these fibers. The predicted tensile strength values come from the prediction seen in Fig. 7.

possible that fibers shown to have a high bonding ability measured by other methods also exhibit stronger fiber bonds.

Discussion

We have shown that hydrocyclones separate fibers according to their bonding ability and we applied different methods of measuring fiber bonding ability to evaluate this. All the methods correlate well with each other, and the results of the hydrocyclone fractionations provide valuable knowledge of which parameters contribute to fiber bonding ability. Also, it was possible to illustrate

the distribution of fiber bonding ability for the fibers in Pulps A and B; but this laboratory method is time-consuming. The objective now is to develop a more rapid method for characterizing fibers in mechanical pulps with respect to bonding ability distribution.

We found the possibility in this study to calculate the bonding ability of long-

fiber fractions from optical measurements of fiber width, fiber wall thickness and external fiber fibrillation using Fiber-Lab™. This work appears very promising. Knowing the split of the fibers by weight in each hydrocyclone stream and the calculated value of the tensile strength of each stream, it is possible to plot the bonding distribution in a way similar to that used for illustrating fiber length distribution (Figs. 11a, 11b).

CONCLUSIONS

In our work on developing a method for characterizing fibers with respect to their distribution in bonding ability we found that:

1. The hydrocyclones used in this study separate fibers according to their bonding ability, and the degree of external fibrillation and collapse resistance index of the fibers calculated from optical measurements are sufficient to predict quite accurately the tensile strength of long fiber handsheets.
2. It is possible to predict the parameter W_c of handsheets, correlating

INSIGHTS FROM THE AUTHORS

The bonding properties of fibers are becoming an increasingly important concern as demands on paper strength, paper surface, and process energy consumption steadily increase. We chose this topic in the belief that looking only at averages of fiber bonding ability is unlikely to reveal the whole truth about the fibers.

Olof and Rita Ferritsius have studied fundamental fiber properties from a mill point of view for more than two decades, and this study is a continuation of their work. Forgacs' view of mechanical fiber characterization has been a leading light and Ulla-Britt Mohlin has performed valuable research in evaluating laboratory sheets as a measure of fiber bonding ability. The concept of looking at distributions of fiber bonding ability, however, is new.

Defining fiber bonding ability has been tricky, and that was a difficult area of our research. In the mechanical pulping world, fiber bonding ability is a term used to describe the structure of a sheet rather than the chemical bond strength. An interesting and surprising finding from our research is that it is possible to predict tensile index of long-fiber laboratory sheets from the optically measured fiber properties of collapse resistance index and external fibrillation. This will be of increasing importance with increasing demands on long-fiber quality.



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Ferritsius



Shagaev

Mills can benefit from our study through the possibility of characterizing fiber bonding ability in more accurate ways, which may enhance the design of more quality- and energy-efficient mechanical pulp processes. The next step is to develop a faster and process-closer method of measuring the distribution of fiber bonding ability.

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well with fracture toughness, based on acoustic emission measurements.

3. It is possible to describe the distribution in fiber bonding ability for mechanical pulps. However, a more rapid method should be developed.

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