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Determination of wet fiber strength

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ABSTRACT: A method for measuring the strength of wet pulp fibers, derived from the breaking stress of wet paper strips at a zero span and the number of fibers bearing the load, is presented. The measurement was carried out using thermomechanical and chemical pulps under various levels of refining. According to the results, the strength of individual fibers shows a significant correlation with the degree of treatment, whereas the traditional zero-span tensile method does not. The determined strength could be interpreted as a measure of the resistance of fibers to damage under mechanical treatment and the development of fibers in the refining process.

***Application*:** This technique can be applied to determine the resistance of pulp fibers to damage in the refining process as a means to control the operation of refiners in order to prevent severe degradation of pulp quality.

INTRODUCTION

The resistance of wet fibers to damage during mechanical treatment in refining process was proposed to be a basis for controlling the operation of refiners and for evaluating the development of pulp fibers. In this study, we focused on the strength of wet fibers, which is regarded as the most suitable criterion for this purpose.

There are two main approaches to determine fiber strength based on the breaking of pulp fibers. One is direct measurement of the breaking stress of individual fibers using special tensile devices [1, 2]. This method is unsuitable for testing numerous samples because it requires a large amount of work and great care in testing. In addition, the tensile strength of individual pulp fibers measured with this method reportedly varies in the range of 100-300 mN, which is an uncomfortable wide range of deviation [3, 4].

The other method involves measurement of the breaking force of a paper strip at a zero span [5]. This is a fast and economical method for assessing the strength of various types of papermaking pulp [6, 7]. However, there are many uncertainties related to the concept of zero-span tensile. Ambiguously, in the refining process, the zero-span tensile is found to both increase and decrease with the degree of refining [8, 9]. These ambiguous results are attributable to with several parameters, e.g., paper structure [1], fiber bonding [10-12], amount of fibers in the rupture zone [1, 11, 12], fiber length distribution [12, 13], and fiber deformation [14, 15]. The testing procedure is required to be modified to allow the zero-span tensile test to be applied for determining the strength of individual fibers. Nevertheless, the zero-span tensile strength was found to be strongly related to the genuine strength of individual fibers [16]. Gurnagual and Page [10] suggested that wet zero-span tensile strength could be used for measuring the resistance of wet fibers to mechanical action in the refining.

The objectives of the present study were to review the fundamental background and the ambiguous results of the zero-span tensile test, and to modify the testing method for determining the relative changes in fiber strength during the refining process.

THEORETICAL BACKGROUND

The zero-span tensile test measures the breaking force of a paper strip clamped between two jaws with zero-span length. According to Van der Akker et al. [1], the breaking force of the paper is associated with the strength of individual fibers, the number of fibers carrying the load, and the orientation of fibers in the rupture zone. In laboratory sheets, the paper structure is a random network. The fibers are laid down at the angle θ to the clamp line, as shown in Figure 1. It was estimated that the possibility of fibers crossing the clamp jaws would be $N \sin\theta \, d\theta/\pi$ [1], and the contribution of the force in the randomly oriented and inclined fibers to the observed load is approximately $\sin^3\theta$ of the breaking force of fibers [1]. The underlying relationship between the observed breaking stress of laboratory sheets and fiber strength could be written as:

$$ZS = F\sin^3\theta \cdot N\sin\theta\frac{d\theta}{\pi} \quad (1)$$

$$ZS = \frac{3}{8}FN \quad (2)$$

where ZS is the breaking stress of a paper sheet, F is the fiber strength (breaking force of fibers), and N is the number of fibers crossing the clamp jaw lying between θ and $\theta + d\theta$ [1].

According to equation (2), the average strength of individual fibers can be determined when the number of fibers in the rupture zone has been quantified. The number of fibers can be estimated by the relationship $N=WR/\omega$, where W is the sheet basis weight, R is the width of sheet tested, and ω is the weight per unit length of fibers [15, 17-19]. However, Perez and Kallmes [15] recommended that the number of fibers obtained from this estimation is not the actual fibers carrying the load. In reality, fibers are being deformed. Many curled fibers in the rupture zone remain unloaded during sheet straining. Based on the experimental evidence, the authors state that the actual fibers bearing the load are approximately 60% of the total fibers crossing the clamp jaws. According to Perez and Kallmes [15], equation (2) could be re-written as equation (3) and the strength of individual fibers calculated with the following equation (4).

$$ZS = (1 - f_c)\cdot\frac{3}{8}FN \quad (3)$$

$$F = \frac{1}{(1-f_c)}\cdot\frac{8}{3}\cdot\frac{ZS\omega}{WR} \quad (4)$$

where $(1\text{-}f_c)$ is probability of fibers crossing the clamp jaws and carrying the load, which is approximately 0.6 for laboratory sheets [15].

Equation (4) could be suitable for determining the strength of individual fibers. However, the coarseness of fibers used in this equation is an uncertain value because it is dependent on the method used to determine the length of distributed fibers. Using an optical image analyzer [20], the fiber length can be measured from the contoured length and projected length of fibers, as shown in Figure 1, and also the average length can be calculated in different ways, e.g., arithmetic average fiber length, length-weighted fiber length, and weight-weighted average fiber length. Moreover, the distribution of fiber length was found to be a significant influence on the results of this testing [12, 13]. Therefore, an appropriate method for measuring fiber length, corresponding to the mathematical methodology, needs to be specified.

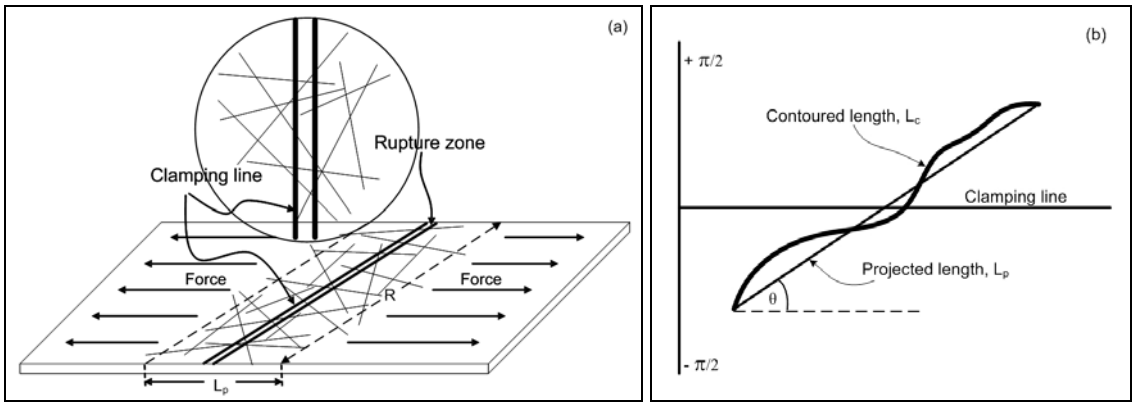

Figure 1. A model of the rupture zone of fibers under the clamp jaws of the zero-span tester.

Based on the statistical geometry of the complex fiber network, the modeling of the network and the distribution of fibers crossing the scanning line basically relies on the projected length of fibers (Figure 1b) [17]. The average length of load-bearing elements in measuring zero-span tensile strength was found to approximately equal the measured arithmetic average fiber length [21]. On the basis of this information, a new method using appropriate parameters, instead of fiber coarseness, is proposed for determining the strength of individual fibers.

In the proposed new method, the estimated number of rupture fibers, called active fibers, is determined based on the unprocessed data obtained from an optical analyzer and statistical analysis. Figure 1 shows the modeling of the rupture zone of a testing strip for determining the active fibers. It was assumed that all active fibers can be gripped completely within their length. The boundary of the active area is thus proposed to be limited by the projected length of fibers calculated based on the arithmetic average and the width of the paper strip clamped by the tester jaws. After setting the rupture zone, the number of whole fibers contained in this area is calculated according to equation (5). Here, the probability of fibers crossing the clamp jaws and carrying the load is estimated based on the statistical approach modified from the model of fibers crossing the scan line [17, 22], the findings of Van der Akker et al [1], as well as the effect of fiber deformation related to unloading fibers, which is represented by the probability of fiber carrying the load from Perez and Kallmes [15]. The active fibers are thus approximated by equation (6).

$$N_T = nAW \tag{5}$$

$$N' = (1 - f_c) \cdot N_T \sin\theta \frac{d\theta}{\pi} \tag{6}$$

where N_T is the total number of fibers contained in the rupture zone, n is the number of fibers per unit weight obtained by using an optical analyzer, A is the active area obtained by the projected length of fibers (L_p) times the width of the sheet tested (the width of tester jaws), W is the dry basis weight of the testing strip, and N' is the number of fiber bearing the load.

Then, replacing the possibility of fibers crossing the clamp jaws in equation (1), $N \sin\theta \, d\theta/\pi$ by the new estimated number of fiber bearing the load obtained by equations (5) and (6) gives the breaking stress of the sheet tested at zero span, which is according to equation (7).

$$ZS = (1 - f_c) \cdot F \sin^3\theta \cdot nAW \sin\theta \frac{d\theta}{\pi} \tag{7}$$

In summary, the strength of individual fibers, derived from the breaking stress of a sheet of paper, the number of rupture fibers, and the orientation factor, is given by:

$$F = k \cdot \frac{ZS}{nAW} \tag{8}$$

where k is 4.44 [Appendix] derived from the combinations of the orientation factor and possibility of fibers carrying the load.

EXPERIMENTAL

Thermomechanical pulp (TMP) made from Norway spruce (*Picea abies L. Karst.*) and bleached kraft softwood pulp (BKSW) were used as raw materials. The TMP pulp was produced under various levels of specific energy consumption, ranging from 0.8 to 2.4 MWh/t, in the pilot plant of the Finnish Pulp and Paper Research Institute (KCL). The BKSW pulp, obtained from a Finnish pulp mill, was refined using a Voith laboratory LR40 refiner [23]. The refiner was operated at a refining consistency of 4%, a refining intensity of 2 J/m, and a specific refining energy consumption of 100, 200, and 300 kWh/t.

The test pulps were fractionated using a Bauer McNett classifier, and the TMP pulp fractions were collected from 30-mesh and 50-mesh screens. The BKSW pulp fractions were collected from 50-mesh and 200-mesh screens. The number of fibers at a given dry weight, fiber length and fiber coarseness were measured using the KajaaniFiberLab apparatus [20] according to TAPPI standard T 271. Laboratory sheets of fractionated pulp were prepared according to ISO 5269 without drying. The zero-span tensile test of wet sheets was carried out according to ISO 15361-2. The average strength of wet fibers was calculated based on equations (4) and (8).

RESULTS

Thermomechanical pulp

The average strength of the wet long-fiber fraction was found to be approximately 100-200 mN, as shown in Table 1 and Figure 2. This range is close to the breaking force of wood fibers measured by the straining of a single fiber [2, 3]. Zero-span tensile strength was found to be about 80-90 Nm/g with no distinct differences between the R30 and R50 fiber fractions, as shown in Figure 3. The average strength obtained

with the modified technique (8) showed good correlation with the degree of refining, whereas the zero-span tensile showed no significant correlation. Increasing levels of refining caused the wet strength and coarseness of fibers to decrease, whereas the number of fibers at a given dry weight increased. Refining of TMP pulp from CSF of 600 to 100 ml caused a reduction in fiber strength of approximately 30-40 %, as shown in Figure 4.

Figure 5 shows a comparison of fiber strength calculated based on equations (4) and (8). The results obtained from both equations are equal in terms of the relative changes in wet fiber strength. At a given coarseness, the calculation based on equation (8) yields higher strength values, evidently because the length of fibers obtained relied on different fiber image detections. In equation (8), the measurement of fiber length is based on the projected length relating to the statistical geometry of the fiber network, while in the equation (4) the calculation of fiber coarseness is based on the contoured length. However, both equations could be used to examine the relative changes in fibers with the degree of refining.

Figure 6 shows the images of TMP fibers under various levels of refining taken using the scanning electron microscope. At a high level of refining, the fibers are delaminated, fibrillated and peeled off, which was proposed to indicate the damage of fibers. We believed that these effects caused the reduction of fiber coarseness, and consequently decreased strength of fibers.

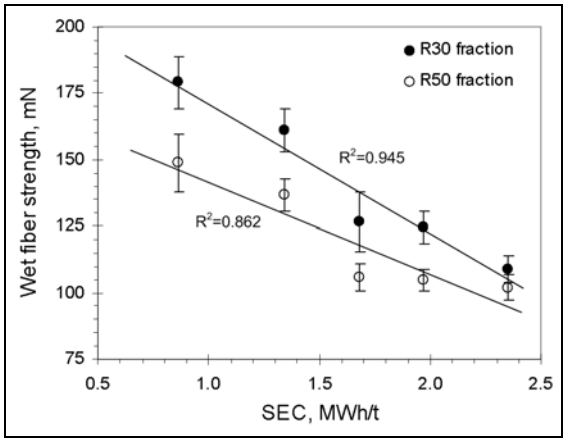

Figure 2. Strength of wet TMP fibers calculated according to equation (8) as a function of specific energy consumption.

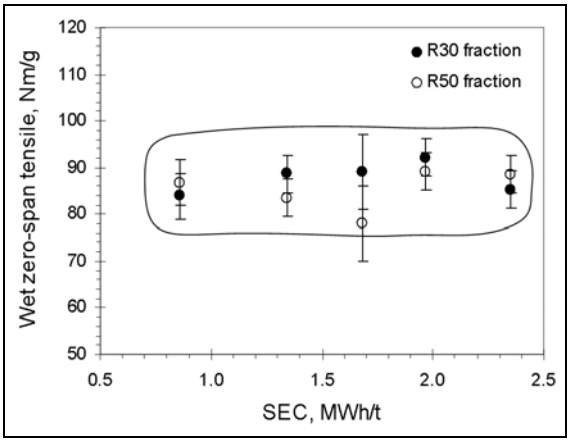

Figure 3. Zero-span tensile of wet TMP fibers as a function of specific energy consumption.

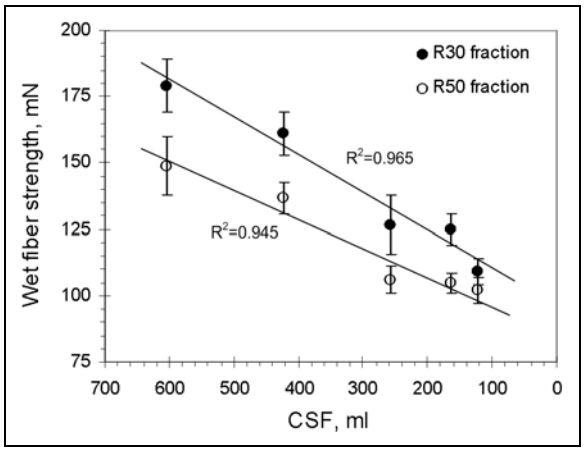

Figure 4. Strength of wet TMP fibers calculated based on equation (8) as a function of pulp freeness.

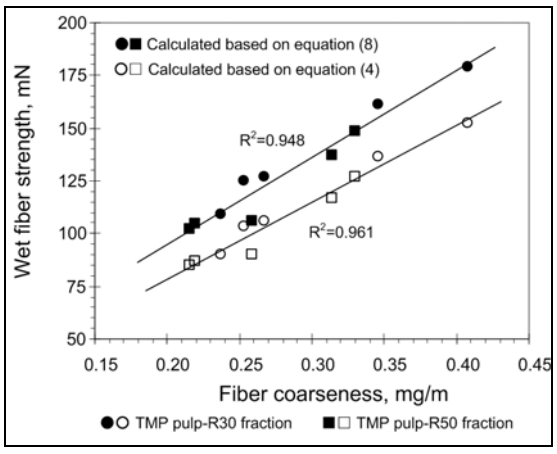

Figure 5. Comparison between the strength of wet TMP fibers obtained from equations (4) and (8).

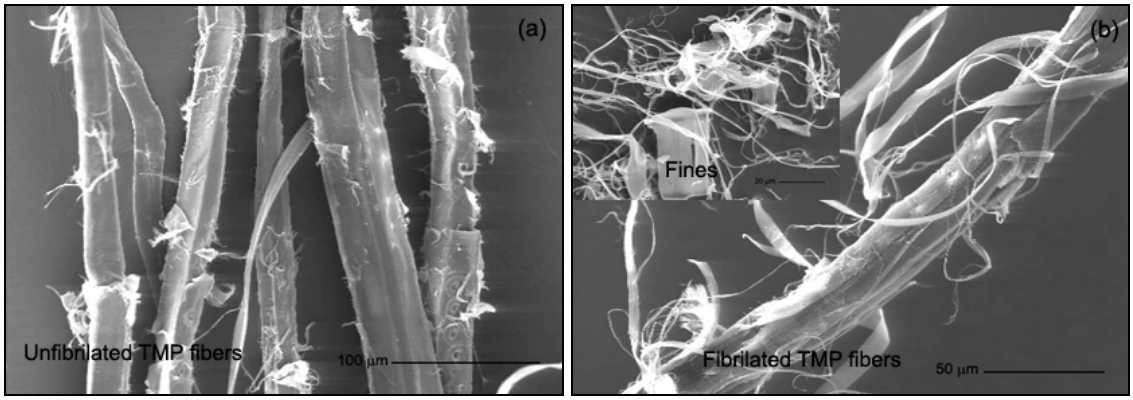

Figure 6. TMP pulp fibers under different levels of refining: (a) SEC 0.86 MWh/t and (b) SEC 2.35 MWh/t.

Table 1. TMP and BKSW fiber properties (R50 fraction) under various levels of refining. The strength of wet fibers was calculated according to equation (8).

Samples	SEC (MWh/t)	CSF* (ml)	Fiber length** (mm)	Fiber coarseness (mg/m)	Number of fibers (fibers/mg)	Wet zero-span tensile (Nm/g)	Wet fiber strength (mN)
TMP pulp							
1	0.86	605	1.43	0.330	1813	86.7	149
2	1.34	422	1.48	0.314	1836	83.5	137
3	1.68	257	1.33	0.259	2461	78.1	106
4	1.97	163	1.29	0.219	2930	89.1	105
5	2.35	122	1.25	0.216	3084	88.5	102
BKSW pulp							
1	0.00	717	1.68	0.179	2723	128.6	135
2	0.10	605	1.76	0.180	2679	147.5	150
3	0.20	448	1.65	0.210	2433	144.6	173
4	0.30	270	1.57	0.269	2012	144.8	220

* CSF measured with whole pulp; ** Arithmetic average fiber length measured from the projected length.

Bleached kraft softwood pulp

The strength of wet-fractionated pulp, R50 and R200 fractions, was found to increase with increasing specific refining energy, as shown in Figure 7, while the zero-span tensile showed no significant changes (Figure 8). In terms of the strength of the whole pulp determined based on equation (8) and zero-span tensile test, there were no distinct changes in the line with degree of refining, as shown in Figure 7 and 8.

The coarseness of fractionated pulp was found to increase with an increasing degree of refining, while the number of fibers at a given dry weight decreased, as shown in Table 1. These results show that at high degrees of refining, a relatively lower number of fractionated fibers per unit weight is obtained, even though the fiber lengths are shorter indicated that the fractionated BKSW fibers were coarser under the refining process. Figure 9 shows the distributions of cell wall thickness of fractionated fibers (R50 and R200) under various degrees of refining. It shows that the refined chemical pulp contained higher percentage of thick fibers than unrefined pulp. According to these results, it could be confirmed that in low consistency refining, the shorter and coarser fibers were produced.

Figure 10 shows a comparison of fiber strength between BKSW and TMP pulps at a given fiber coarseness. BKSW pulp was found to have higher strength than TMP pulp. This result is in agreement with the hypothesis that the strength of fibers relates to the ratio of cellulose content in the pulp fibers. A higher proportion of cellulose provides better strength [24].

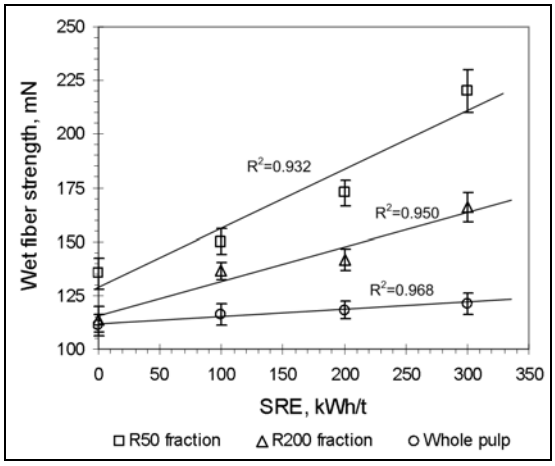

Figure 7. Strength of wet BKSW fibers obtained from equation (8) as a function of specific energy consumption.

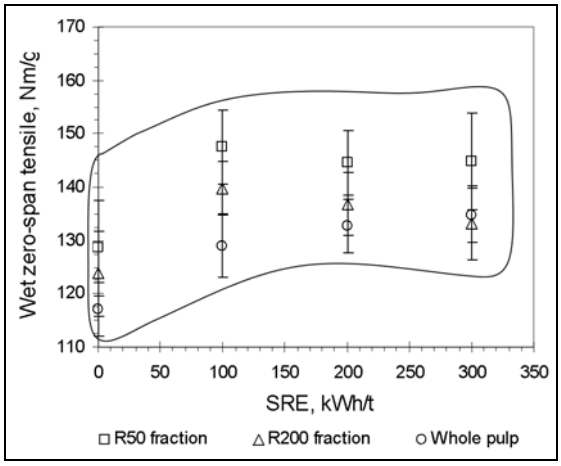

Figure 8. Zero-span tensile of wet BKSW fibers as a function of specific energy consumption.

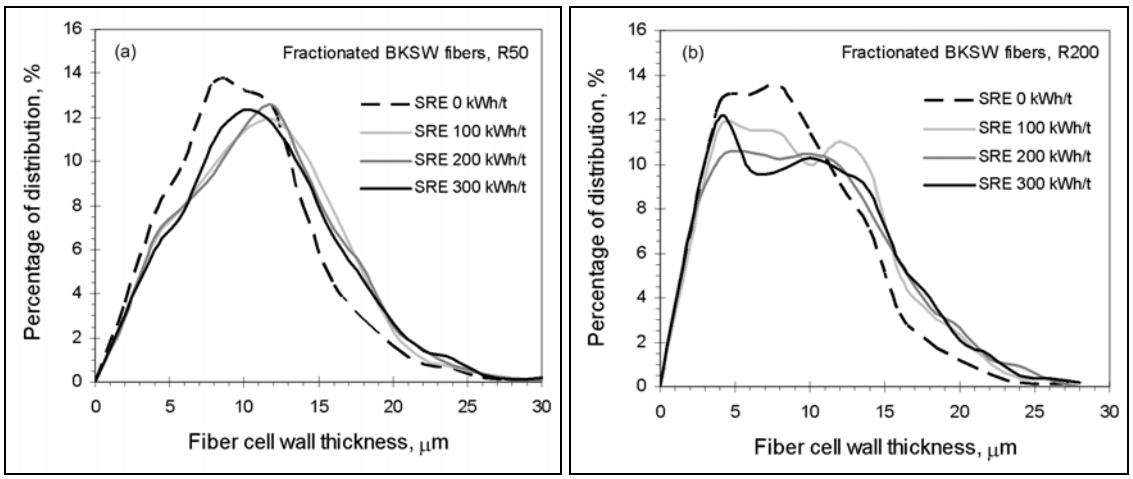

Figure 9. Cell wall thickness distribution of fractionated BKSW fibers: (a) R50 and (b) R200, measured using the KajaaniFiberLab.

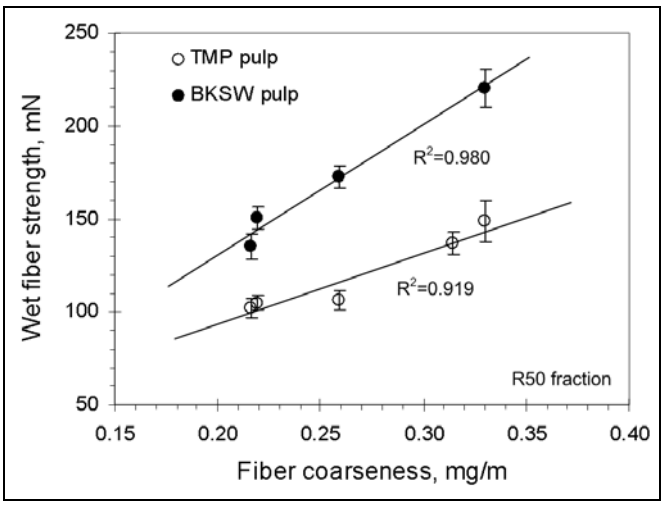

Figure 10. Wet strength of fractionated TMP and BKSW pulp fibers retained on 50-mesh screen under various levels of refining as a function of fiber coarseness.

DISCUSSION

According to the results, the zero-span tensile test gives an unclear measure of fiber strength under various degrees of refining. At a given basis weight, test sheets could be assumed to contain different numbers of fibers, depending on the coarseness and length of fibers corresponding to the degree of refining. The paper sheets might have high coarseness with a low number of fibers, or low coarseness with a high number of fibers. This might balance the breaking force of paper sheets in the test series. When the number of fibers is taken into account in determining the strength of fibers based on equation (4) and (8), logical results correlating with the degree of refining both for chemical and mechanical pulps are obtained.

With mechanical pulp, this method allows differentiation of fiber strength under different levels of mechanical treatment. Apparently, the wet strength and the coarseness of fibers decrease in line with the degree of treatment. In accordance with the fundamentals of mechanical pulping, during the treatment, pulp fibers are disrupted and peeled off, resulting in reduced coarseness and strength [25, 26]. Therefore, this technique is could be use to analyze the strength of individual fibers, which can be interpreted as their resistance to damage in the refining process.

The results of the BKSW pulp refining tests are contradictory to those obtained with TMP pulp. The strength and coarseness of fractionated fibers change in the opposite direction in relation to the degree of treatment. At a high level of refining, the fractionated pulp has higher coarseness and strength. These results could be explained that in chemical pulp refining, the fibers were shortened and fibrillated. The external fibrillation still attached to the fibers [28]. According to the morphology of softwood fibers, tracheid fibers (prosenchyma cells) consist of thinner fibers and coarser fibers with flattened or tapered edges [27]. We believed that severe damage and shortening firstly take place with thinner fibers and along the tapered edges (thinner parts) of coarser fibers. Thus, coarser parts of tracheid fibers are retained at high levels of treatment (Table 1 and Figure 9). Based on the results, we propose that in chemical pulp refining, the determination of fiber strength is a more suitable to analyze the development of pulp fibers properties than their resistance to mechanical action because the average strength of individual fibers increasing along the degree of refining as shown in Figure 7.

CONCLUSIONS

The results showed that the number of fibers has a significant effect on the balance of the zero-span tensile strength of paper sheets. The simplified zero-span tensile technique, which takes into account the number of active fibers in the rupture zone, provides a meaningful indicator of how the strength of fibers is modified under various degrees of mechanical treatment. This technique can be applied to determine the resistance of fibers to damage during refining in mechanical pulping, and to evaluate the development of chemical pulps under different refining conditions.

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APPENDIX

Zero-span tensile introduced by Van der Akker et al. [1].

$$ZS = F\sin^3\theta \cdot N\sin\theta\frac{d\theta}{\pi}, \qquad F = \frac{8}{3}\cdot\frac{ZS}{N}$$

Modified zero-span tensile obtained using the combinations of the orientation factor and possibility of fibers carrying the load introduced by Van der Akker et al. [1] and Perez and Kallmes [15], as well as taking into account the estimated numbers of fibers in the rupture zone according to equation (5).

$$ZS = (1-f_c)\cdot F\sin^3\theta \cdot nAW\sin\theta\frac{d\theta}{\pi}$$

$$F = \frac{1}{(1-f_c)\cdot(\sin^4\theta\frac{d\theta}{\pi})}\cdot\frac{ZS}{nAW}$$

$$F = \left[\frac{1}{0.6}\cdot\frac{8}{3}\right]\cdot\frac{ZS}{nAW}$$

$$F = k\cdot\frac{ZS}{nAW}, \quad k = 4.44$$

INSIGHTS FROM THE AUTHORS

A research project concerning the use of grit treatment in the refining process has been carried out at the Helsinki University of Technology. According to the experiments, the breaking down of the fiber cell walls during refining might case severe degradation of fiber strength. In order to control this damage, the resistance of wet fibers to damage in refining, correlating with the degree of treatment, is needed to be determined. An appropriate method to determine the relative changes in fiber strength during refining is lacking. Therefore, in this study, fiber strength testing methods based on the zero-span tensile test were reviewed and modified for this purpose.

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