Determination of load-bearing element length in paper using zero/short span tensile testing

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ABSTRACT: This study presents an equation developed to estimate, from zero and short-span tensile tests, the average length of load-bearing elements (the distance between serious defects along a fiber length) within a sheet of paper. The equation was used to examine the effect of drying treatment on the average load-bearing element length in paper made from five furnishes: two radiata pine kraft pulps, a *Eucalyptus globulus* kraft pulp, a eucalypt neutral sulfite semichemical (NSSC) pulp, and a recycled pulp. Of the three sets of handsheets for each pulp, the first used never-dried pulps, the second used reslushed handsheets that had been air-dried under restraint, and the third set was made from reslushed handsheets that had been oven dried. For all five furnishes, the average length of load-bearing element was approximately equal to the optically measured arithmetic average fiber length and did not decrease after the fibers were dried. The results suggest that the reduction in the strength of paper made from previously dried fibers, compared to never-dried fibers, is not due to the introduction of serious defects during drying.

Application: This study helps explain the loss of sheet strength that occurs after paper is made from recycled fibers.

Defects in fibers include curl, kinks, crimps, microcompressions [1], and various types of folds and twists [2]. Defects affect both single fiber and sheet mechanical properties. Despite considerable effort, defects in fibers remain difficult to measure and their exact effects on sheet mechanical properties are hard to quantify using existing theories of the strength of paper. Of all the different types of defects in fibers, kinks, twists, and angular folds most strongly affect paper strength [2]. These are serious defects across which a fiber will not be able to bear a load. A fiber with a sharp kink in it will act as two independent segments within the sheet for the purposes of bearing a tensile load, reducing the effective fiber length and therefore the sheet strength.

Page and Seth [3] examined the reduction in the strength of paper made from previously dried fibers compared to paper made from never-dried fibers. They concluded that the strength loss in paper made from previously dried fibers was due to a combination of loss of shear bond strength and from defects induced in fibers during drying. The shear bond strength loss ranged from 0% to 46%, depending on the nature of the defects that were assumed to have occurred in the drying process [3]. The imprecision of the estimate arose because the authors could not quantify the nature and quantity of the defects in the sheet fibers.

A zero-span tensile test uses no gap between the jaws, while short-span tensile tests involve testing with a small gap (known as the span) between the jaws. Researchers have long used zero-span tests as a measure of average fiber strength [4]. Fiber defects can have a major influence on the zero and short-span strength. Perez and Kallmes [5] defined the probability, $\overline{f_c}$, that a fiber does not contribute to the zero-span test because of curl and concluded that, for a typical zero-span test, $\overline{f_c} \approx 0.4$. More recently, Mohlin and Alfredsson measured the change in zero-span strength with fiber defects [6]. An increase in the numbers of serious defects (kinks) significantly reduced the measured zero-span strength. This suggests that, given an adequate theoretical framework, we can potentially use zero- and short-span testing to quantify fiber defects within a sheet of paper.

The first theory of the zero-span test was by Van Den Akker *et al* [4]. They found that for a randomly oriented fiber network, the zero-span breaking length is $(3/8)Ib$, where I is the number of fibers that would have spanned between the jaws if all fibers had been aligned in the direction of the applied stress and b is the fiber breaking load. A theoretical expression for the short-span strength is due to Michie [7]. Later, Boucai [8] expressed the zero- and short-span breaking length of an unbonded network of fibers as $BL(G)=(3/8)FBL(1\text{-}1.13G/\bar{l})$ where G is the gap between the jaws, $BL(G)$ is the breaking length, FBL is the average fiber breaking length, and $\bar{l}$ is the average fiber length. Boucai stated that the equation was only valid for $G<0.35\bar{l}$ and gave no derivation of the equation. El-Hosseiny and Bennett [9] provided a relatively complete theory of zero- and short-span strength that considers the effects of distributions in the fiber length, elastic modulus, and tensile strength. However, these distribution functions must be known to use the theory quantitatively.

In the work that follows, I develop the theory of the zero- and short-span test to allow the average load-bearing element length within the sheet to be determined from zero- and short-span data. The term "load-bearing element" is used rather than "fiber" because fibers may contain kinks or other defects across which load cannot be transmitted. In such a case, it is the lengths between these serious defects (load-bearing element lengths) that are important in determining the mechanical properties of the sheet [1]. The theory is used to examine changes in load-bearing element length with drying treatment and to examine whether drying the fibers introduces serious defects.

ZERO-/SHORT-SPAN TEST: THEORY

We begin by defining the angle, θ as 0° along the loading direction. If we consider a single, straight load-bearing element with length, l, and random orientation, θ, within a sheet of paper, then the probability of the load-bearing element crossing a single jaw line of width W_j is approximately

$$P_1 = \frac{l\cos\theta}{L_s}\frac{W_j}{W_s} \tag{1}$$

where L_s and W_s are the length and width of the test sheet and it is assumed that W_j, L_s, $W_s >> l$. If we consider a second jaw placed at a span, G, from the first, then if the load-bearing element has been gripped by the first jaw, the probability that both jaws grip the load-bearing element is $P_2=1-(1/\cos\theta)G/l$.

If the separation between the jaws has increased by ΔG during the test, then the overall strain on the test section is $\varepsilon=\Delta G/G$, and the strain, ε_f, in a fiber oriented at θ and gripped by both jaws is $\varepsilon_f=\varepsilon\cos^2\theta$, provided ε is small. Therefore, the force in this load-bearing element is $F_f=EC\varepsilon\cos^2\theta$ where E is the fiber wall Young's modulus and C is the fiber wall cross-sectional area. The component of this force in the test direction is

$$F_f=EC\varepsilon\cos^3\theta \tag{2}$$

If the fibers are randomly oriented, then the fiber-orientation probability density function is $2/\pi$ and the average force on a load-bearing element, F_{av}, can be determined by multiplying Eq. 2 by the probability P_1P_2 that a fiber will be gripped by both jaws and averaging over the range of possible fiber orientations to yield

$$F_{av} = (1-\overline{f_c})EC\varepsilon\frac{lW_j}{A}\frac{2}{\pi}\int_0^{\cos^{-1}(G/l)}\left(\cos^4\theta - \frac{G}{l}\cos^3\theta\right)d\theta \tag{3}$$

where A ($=L_sW_s$) is the area of the sheet and $\overline{f_c}$ is the fraction of fibers, gripped by both jaws, that do not bear load due to out-of-plane curl or other defects [5]. The upper limit of integration occurs because for angles beyond this value, the load-bearing element can never bridge the gap between the jaws. In the derivation of Eq. 3, only the contribution of fibers gripped by both jaws are considered. Accordingly, these equations only apply to wetted sheets, where there is minimal fiber-fiber bonding. Therefore, this theory is directly applicable to the measurements on the rewetted sheets presented later in this paper.

Integrating Eq. 3 yields

$$F_{av} = (1-\overline{f_c})EC\varepsilon\frac{lW_j}{A}\frac{2}{\pi}\left[-\frac{1}{12}\left(\frac{G}{l}\right)^3\sqrt{1-\left(\frac{G}{l}\right)^2}+\frac{3}{8}\arccos\frac{G}{l}-\frac{7}{24}\frac{G}{l}\sqrt{1-\left(\frac{G}{l}\right)^2}\right] \tag{4}$$

A first-order Taylor series expansion in powers of G/l is accurate for $G<0.7l$ and yields

$$F_{av} = (1-\overline{f_c})\varepsilon\frac{W_j}{A}\frac{3}{8}EC\left[l-\frac{32}{9\pi}G\right] \tag{5}$$

where the factor $32/9\pi$ is numerically equal to 1.13 and this equation is similar to that given by Boucai [8].

If there are $I(G)$ load-bearing elements that satisfy the condition $l>32G/9\pi$, then the total force at a given strain, $F(\varepsilon, G)$, is given by

$$F(\varepsilon,G) = (1-\overline{f_c})\varepsilon\frac{W_j}{A}\frac{3}{8}\sum_{k=1}^{k=I(G)}E_kC_k\left[l_k-\frac{32}{9\pi}G\right] \tag{6}$$

where the index, k, denotes each of the $I(G)$ distinct load-bearing elements, each with different Young's modulus and length. This can then be rewritten as

$$F(\varepsilon,G) = I(G)(1-\overline{f_c})\,\varepsilon\frac{W_j}{A}\frac{3}{8}\left[\overline{ECl}\Big|_G - \frac{32}{9\pi}\overline{EC}\Big|_G G\right] \tag{7}$$

where $\overline{ECl}\big|_G$ is the average value of ECl for the set of $I(G)$ fibers. We cannot use this equation to predict the sheet strength in a zero-/short-span test, because sheet-breaking strain and $\overline{f_c}$ are unknown. However, as will be shown, we can extract considerable useful information.

If G=0 then $I(0)$ is the total number of load-bearing elements within the sheet, which is given by

$$I(0) = \frac{BA}{\omega\bar{l}\big|_0} \tag{8}$$

where B is the sheet grammage, ω is the average coarseness of the fibers, and $\bar{l}\big|_0$ is the arithmetic average length of load-bearing elements within the sheet.

If, for the individual load-bearing elements, the value of EC is largely independent of the length of the load-bearing element, we can make the following approximation:

$$\overline{ECl}\Big|_0 \approx \overline{EC}\Big|_0\,\bar{l}\Big|_0 \tag{9}$$

Substitution of Eqs. 8 and 9 into Eq. 7 and setting G=0 yields

$$F(\varepsilon,0) = \frac{3}{8}\frac{B}{\omega}(1-\overline{f_c})\,\varepsilon W_j\,\overline{EC}\Big|_0 \tag{10}$$

and the derivative of $F(\varepsilon, G)$ with respect to G at G=0 is

$$\left.\frac{dF(\varepsilon,G)}{dG}\right|_{G=0} = -\frac{3}{8}\frac{32}{9\pi}\frac{B}{\omega\bar{l}\big|_0}(1-\overline{f_c})\varepsilon W_j\,\overline{EC}\Big|_0 \tag{11}$$

where it has been assumed that $\overline{EC}\big|_0$ and $I(0)$ are independent of G when $G<<\bar{l}\big|_0$.

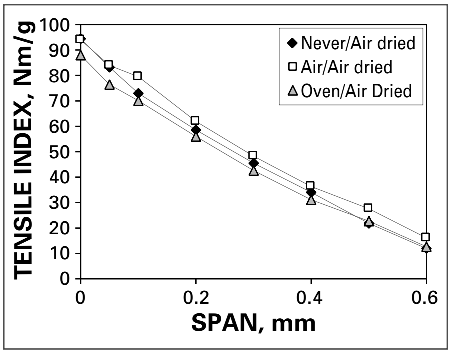
Therefore, the arithmetic average length of load-bearing elements in the sheet, $\bar{l}\big|_0$ is given by

$$\bar{l}\Big|_0 = -\frac{32}{9\pi}\frac{F(\varepsilon_{frac},0)}{\left.\frac{dF(\varepsilon_{frac},G)}{dG}\right|_{G=0}} \tag{12}$$

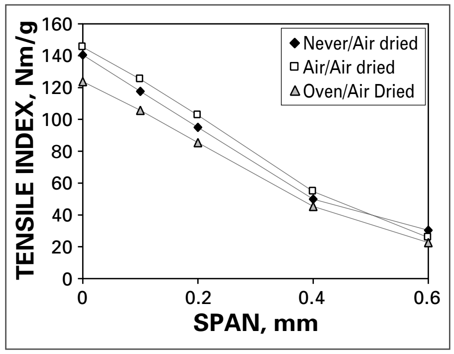
where ε_{frac} is the strain at which fracture occurs. Thus, by measuring the breaking load as a function of the span between the jaws, G, we can determine the average length of the load-bearing elements within the sheet of paper. This is an interesting result, as no method of doing this has previously been presented.

EXPERIMENTAL

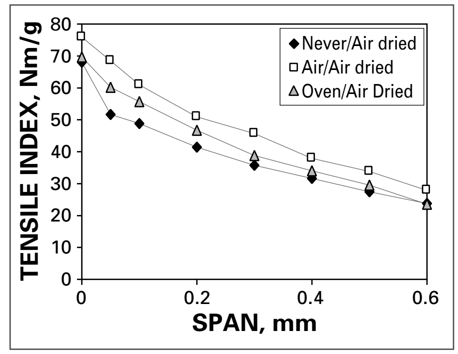
Five pulps were tested to evaluate the theory. Amcor Research and Technology Centre supplied four commercial pulps from Amcor mills: two unbleached radiata pine softwood kraft pulps (called radiata pine kraft No. 1 and No. 2), an unbleached, neutral sulfite semichemical



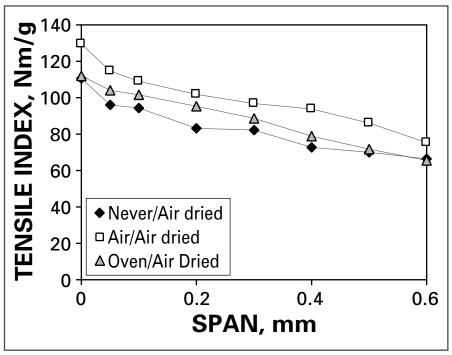
1. Tensile index vs. span for eucalypt NSSC handsheets prepared from never-dried, air-dried, and oven-dried pulps.



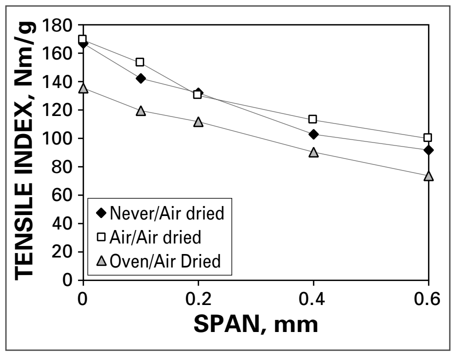
2. Tensile index vs. span for Eucalyptus globulus kraft handsheets prepared from never-dried, air-dried, and oven-dried pulps.



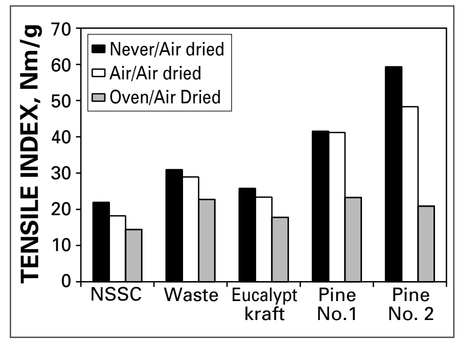
3. Tensile index vs. span for waste paper handsheets prepared from never-dried, air-dried, and oven-dried pulps.



4. Tensile index vs.span for radiata pine kraft No. 1 handsheets prepared from never-dried, air-dried, and oven-dried pulps.



5. Tensile index vs. span for radiata pine kraft No. 2 handsheets prepared from air-dried once, air-dried twice, and oven-dried pulps.



6. Sheet tensile index measured from handsheets prepared from never-dried, air-dried, and oven-dried pulps for the five different furnishes.

(NSSC) eucalypt (mixed species) pulp, and an unbleached recycled pulp. A *Eucalyptus globulus* pulp was also used. This had been pulped in a laboratory digester and then oxygen bleached to a kappa number of 17.9. All pulps except radiata pine kraft No. 2 had been stored near 0°C. Radiata pine kraft pulp No. 2 was collected directly from a brown stock washer at a kappa number of 45. All handsheets used in subsequent testing were then made within a week of collection.

We used a British Handsheet machine to make 60 g/m^2 handsheets under standard conditions, except that the samples were not refined in a PFI mill. We made three sets of handsheets for each furnish. The first set of handsheets, was made and then air-dried under restraint (in the results, these are called never/air dried). After drying the sheets were used for testing. The second set of handsheets was air dried under restraint before being reslushed, formed into handsheets again, and air dried under restraint again (called air/air dried). The last set of handsheets was allowed to dry unrestrained in an oven, before being reslushed and formed into handsheets to be air dried under restraint (called oven/air dried).

Fiber length measurements on the wet starting pulps were made using a Kajaani FS 200. For the waste and the pine kraft No. 1 pulps, fiber length measurements were also made on samples taken from the two reslushed pulps. An Instron Universal Tester was used to measure tensile strength. The zero- and short-span measurements were made on rewetted samples using a Pulmac zero- and short-span tester. The zero- and short-span measurements were generally made according to AS/NZS 1301.459rp:1998, except that the pulps were not refined in a PFI mill before testing.

RESULTS AND DISCUSSION

Figures 1-5 show the results of the zero-/short-span measurements for the five furnishes. Each figure shows three curves, one each for the never/air dried, air/air dried, and oven/air dried sets of handsheets. Figures 1-5 show little difference between the zero- and short-span strengths for the handsheets prepared by the different methods (never/air dried, air/air dried, and oven/air dried). This is consistent with literature indicating that drying has little effect on the zero-span strength [10, 11]. Differences between the three curves are smallest in Fig. 1, which shows the data for the NSSC eucalypt pulp. There is also very little difference between the curves for the eucalypt kraft pulp (Fig. 2). Figure 3 (waste furnish) shows that the never-/air-dried sheets were weaker than the air-/air-dried sheets at all spans, with the oven-/air-dried sheets generally having intermediate strength. The pine results show different trends for the two pulps. For radiata pine kraft No. 1 (Fig. 4), the never-/air-dried sheets generally had the lowest zero-/short-span strength. This is also in contrast to the measurements on radiata pine kraft No. 2 (Fig. 5), where very little difference can be seen in the zero-/short-span strength for the never-/air-dried and the air-/air-dried sheets, but the oven-/air-dried sheets had uniformly lower zero-/short-span strengths.

A partial explanation for the differences between the two sets of pine kraft data may be that radiata pine kraft No. 1 had deteriorated while in storage. Evidence for this comes from **Fig. 6**, which shows the sheet tensile strength for the five furnishes and the three methods of preparing the handsheets. In Fig. 6, all of the furnishes (except radiata pine kraft No. 1) show a common trend with the never-/air-dried sheets the strongest

	NEVER/AIR DRIED			AIR/AIR DRIED			AIR/OVEN DRIED		
	Quadratic	Linear, 0-0.4 mm	Linear	Quadratic	Linear, 0.0-0.4 mm	Linear	Quadratic	Linear, 0-0.4 mm	Linear
Eucalypt NSSC	0.61	0.82	0.97	0.74	0.90	1.02	0.69	0.86	0.99
Eucalypt kraft	0.67	0.92	1.04	0.79	1.00	1.02	0.74	0.96	1.02
Waste	0.63	0.82	1.26	0.73	0.90	1.26	0.75	0.92	1.23
Pine No. 1	1.00	1.19	1.97	1.33	1.32	2.02	1.75	1.82	1.88
Pine No. 2	0.89	1.29	1.69	1.26	1.21	1.83	1.24	1.50	1.71

I. Load-bearing element length (mm) determined from different methods of fitting for a residual span of 0.2mm.

	NEVER/AIR DRIED			AIR/AIR DRIED			OVEN/AIR DRIED		
	Arithmetic, FS 200	Load-bearing element length, fit	Length weighted, FS 200	Arithmetic, FS 200	Load-bearing element length, fit	Length weighted, FS 200	Arithmetic, FS 200	Load-bearing element length, fit	Length weighted, FS 200
Eucalypt NSSC	0.63	0.61	0.81	*0.63*	0.74	*0.81*	*0.63*	0.69	*0.81*
Eucalypt kraft	0.57	0.67	0.71	*0.57*	0.79	*0.71*	*0.57*	0.74	*0.71*
Waste	0.61	0.63	1.14	0.63	0.73	1.17	0.59	0.75	1.10
Pine No. 1	1.23	1.19	2.19	1.27	1.32	2.21	1.18	1.82	2.15
Pine No. 2	1.56	1.29	2.43	*1.56*	1.21	*2.43*	*1.56*	1.50	*2.43*

II. Comparison between load-bearing element length and optically measured fiber lengths. Values in italics were not measured but have been assumed to be identical to those measured optically for the never-dried pulps.

and the oven-/air-dried sheets the weakest, which is consistent with general observations in the literature. In the case of radiata pine kraft No. 1, both the never-/air-dried sheets and the air-/air-dried sheets show identical tensile strengths, possibly indicating that the radiata pine kraft No. 1 had hornified during storage.

To determine the average length of load-bearing element using Eq. 12, the zero-span strength and the slope of the strength versus span curve at zero span must be determined. This is complicated by the presence of an unknown residual span, which must be added to all of the spans. The residual span is the distance in from the jaw edge required to fully hold the fiber and will depend on clamping pressure, the paper-jaw coefficient of friction, the sheet density, and the force at which the sample breaks. In the absence of an accurate way to measure the residual span, load-bearing element lengths were calculated using the residual span of 0.2 mm, as proposed by Boucai [12] and Cowan [13].

If the residual span is 0.2 mm, then this must be added to all of the spans, giving a range of spans of 0.2-0.8 mm. It is then necessary to extrapolate the data to a span of zero, in order to use Eq. 12. **Table I** shows the load-bearing element lengths determined using three of several methods investigated for fitting the data. Given the limited number of data points, I decided to use only linear or quadratic functions to perform the fits. The theory developed in this paper suggests that the fitting should differ for the short and long fiber furnishes. For the long fiber pulps (radiata pine kraft No. 1 and No. 2) where $\bar{l}|_0 >> G$, we assume that $\overline{EC}|_G$, $\bar{l}|_G$, and $I(G)$ are independent of G. This implies from Eq. 7 that the zero- and short-span strength will be linearly dependent on G. Table I shows the data for two linear fits, one a linear fit of the full set of data and the other a linear fit to a restricted set of data (spans: 0.2-0.4 mm measurements at nominal spans from 0.0-0.2 mm). This last fit is likely to provide the most accurate fit, as the above assumptions are not true at larger spans. For the short fiber pulps, $\overline{EC}|_G$, $\bar{l}|_G$, and $I(G)$ are not independent of G at any span, making the dependence of the zero- and short-span strength on G difficult to predict without knowledge of the distribution of fiber properties. Therefore, a quadratic function was chosen for the short fiber pulps, which was generally sufficient to accurately represent the data across its range.

Table II compares the load-bearing element lengths from Table I with fiber lengths measured by a Kajaani FS 200. The load-bearing element lengths used for comparison with the optical fiber length data are highlighted with a gray background in Table I. The corresponding values in Table II are similarly highlighted. Both the arithmetic fiber length and the length-weighted fiber length are given for comparison. The data in Table II generally show a reasonable match between the measured arithmetic fiber length and the average length of load-bearing element. In 11 of the 15 data sets measured here, the average load-bearing element length calculated from fitting the zero-/short-span data agreed to within 0.2 mm with arithmetic fiber length measured optically. The best match between the measured arithmetic fiber length and the average load-bearing element length occurs for the never-/air-dried samples. The worst match was for the oven-/air-dried pine kraft No. 1 sheets where the estimated load-bearing element length was 1.82 mm and the arithmetic average fiber length was 1.18 mm. Furthermore, when the average load-bearing element length is examined for different pulp drying treatments, there is no reduction in load-bearing element length with increasing severity of drying treatment. Indeed, for all five furnishes, the average load-bearing element length calculated from the fits is somewhat higher for the oven-/air-dried sheets than for the never-/air-dried sheets. It is not clear why an increasingly severe drying treatment would have caused the load-bearing element length to increase. Remember that these results were obtained on rewetted papers. There remains the question as to the applicability of the results to dry paper, as moisture often weakens fibers [14]. However, as the load-bearing element length is determined from a strength ratio (Eq. 12), any change in fiber strength with wetting will have no effect on the calculated load-bearing element length, because all zero- and short-span strengths will be reduced proportionally.

Thus, no reduction is observed in Tables I and II in load-bearing element length with drying treatment. This implies that the loss of sheet strength commonly observed the first time a pulp is dried is not due to serious defects, such as kinks, being set into fibers, therefore reducing the load-bearing element length. This is consistent with results [15] suggesting that the major cause of the strength loss in drying is a reduction in the fiber-fiber shear bond strength. Another possible contributor to strength loss upon drying [3] is the production of minor defects such as microcompressions, which affect the fiber mechanical properties without changing the load-bearing element length.

CONCLUSIONS

This study described an equation developed to allow the average length of load-bearing elements within a sheet of paper to be estimated from zero and short-span tensile tests. This was used to examine the effect of drying treatment on the average length of load-bearing element in five furnishes: two radiata pine kraft pulps, a eucalyptus globulus kraft pulp, a eucalypt NSSC pulp, and a recycled pulp. For all five furnishes, the average length of load-bearing element was approximately equal to the measured arithmetic average fiber length for the never-/air-dried pulps. The average length of load-bearing elements increased as the harshness of the drying treatment intensified. The results imply that the reduction of strength of sheets made from previously dried compared to never-dried pulps is not due to the introduction of serious defects, such as kinks, into the fibers during drying.

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INSIGHTS FROM THE AUTHOR

The idea for this study developed as I was researching paper strength and looking at how the changes in fiber properties caused by refining affect strength. The zero-span strength is used in equations for paper strength. I became interested in how the measured zero-span strength relates to the properties of the fibers.

My previous work focused mainly on low-consistency refining. Following this work, the emphasis of my research shifted more towards fiber and sheet mechanical properties.

One of the most difficult aspects of this work was trying to take into consideration distributions in fiber properties during work on the theory.

I had expected that one of the causes of strength loss on drying would be the introduction into the fibers of large defects such as kinks and twists. The research presented here shows that this is not true.

Although mills may not directly benefit from this research at the moment, the information presented here is one more step toward understanding the loss of sheet strength that occurs after paper is made from recycled fibers.

As a next step, I worked on a method to measure fiber stress-strain properties using zero- and short-span tensile tests.

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