Source: Batchelor, W.J. (1999): Determination of Load-Bearing Element Length in Paper Using Zero/Short Span Tensile Testing. In "TAPPI International Paper Physics Conference" TAPPI, pp. 247-258.

DETERMINATION OF LOAD-BEARING ELEMENT LENGTH IN PAPER USING ZERO/SHORT SPAN TENSILE TESTING

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ABSTRACT

In this work, an equation is 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 each pulp, three sets of handsheets were made. The first set of handsheets was made from the never-dried pulps. The second set of handsheets was made by forming a set of handsheets and air drying them under restraint. The air-dried handsheets were then reslushed and made into handsheets. The third set was made by oven drying a set of handsheets, reslushing them and then forming handsheets. Zero and short span tensile strength measurements were made on the fifteen different sets of handsheets to allow the average length of load-bearing elements in each case to be calculated. For all five furnishes it was found that the average length of load-bearing element was approximately equal to the measured average fibre length, independent of the type of drying treatment used to produce the handsheets.

INTRODUCTION

Defects in Fibres and Effect on Sheet Mechanical Properties

Defects in fibres include curl, kinks, crimps and microcompressions [1] as well as various types of folds and twists [2]. Defects affect both single fibre mechanical properties [3] as well as sheet mechanical properties [2,4,5]. Despite considerable effort over many years, defects in fibres remain difficult to measure and their exact effects on sheet mechanical properties are hard to quantify using existing theories of the strength of paper.

As one example, in a recent paper Page and Seth [6] examined the reduction in the strength of paper made from previously dried fibres compared to paper made from never-dried fibres. They concluded that the loss of strength in paper made from previously dried fibres was due to a combination of loss of shear strength of the fibre-fibre bonds as well as from defects induced in the fibre by the drying process. However, it was not possible to determine the loss of shear bond strength given that the distribution and nature of the defects in the fibres, which had been induced by drying, could not be readily determined. Estimates ranging from 0 to 46% bond-strength loss were made, depending on the nature of the defects that were assumed to have occurred in the drying process [6].

Of all the different types of defects in fibres, kinks, twists and angular folds most strongly affect paper strength, as these are gross defects across which a fibre will not be able to bear a load. A fibre 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 fibre length and therefore the sheet strength. Mohlin et al [2] have shown that an increase from 0.3 to 2.0 in the number of kinks, twists and angular folds per fibre reduced the tensile strength of the sheet by approximately half. The defect numbers used by Mohlin et al were calculated from the optically measured morphology of the fibres in suspension. A potential problem with measurements like this is that the shapes of the fibres in suspension may be different to that of the dry fibres within the sheet, leading to incorrect estimates of the number and severity of defects in the fibres in the sheet. Obviously it would be preferable to measure fibre defects while they are in the paper sheet.

Zero/Short-Span Tests

Zero-span tensile tests involve performing a tensile test with as small a gap between the jaws as possible, while short-span tensile tests involve setting the jaws at a small distance apart (usually 0.1-0.6 mm). The gap between the jaws of the tester is known as the span.

Zero-span tests have long been used as a measure of the strength of the individual fibres [7]. One of the practical difficulties of using the zero span strength as a measurement of fibre strength is the existence of a residual span [8,9]. That is, even when the jaws are touching (zero gap), a finite distance in from the edge of a jaw is still required before sufficient clamping pressure is developed to prevent fibre pullout during the test. The result is that the true span between the jaws is always greater than the separation between the ends of the jaws. In practice the residual span has been set at a value of 0.2 mm and the true zero-span tensile strength can then determined by extrapolating measurements of zero and short-span strength versus span back to a span of –0.2 mm [10].

The first attempt to give a theoretical description of the zero-span test was by Van Den Akker *et al* [7]. They found that for a randomly oriented fibre network the zero span breaking length is $(3/8)Ib$, where I is the number of fibres that would have spanned between the two jaws if all of the fibres had been aligned in the direction of the applied stress and b is the breaking load of the individual fibres. The first attempt to derive an expression for the short-span strength is due to Michie [11] who found that the short span strength of a non-woven fabric is given by $(2Ib/\pi)\int_{\arcsin G/l}^{\pi/2}(\sin^4\alpha - (G/l)\sin^3\alpha)d\alpha$ where G is the gap between the jaws, l is the fibre length and α is the angle between the fibre and the jawline. In the derivation of the equation it is assumed that all of the fibres are straight with the same length, *l*. The expression derived by Van Den Akker *et al* is then a limiting case at $G = 0$.

Boucai [8] expressed the zero and short span breaking length of an unbonded network of fibres as: $BL(G) = (3/8)FBL(1-1.13G/\bar{l})$ where $BL(G)$ is the breaking length, FBL is the average breaking length of an individual fibre and $\bar{l}$ is the average fibre length. Boucai stated that the equation was only valid for $G < 0.35\bar{l}$ and no derivation of the equation was given. However, an implicit assumption in this equation is that there are no fibres shorter than $0.35\bar{l}$, which may not be valid.

El-Hosseiny and Bennett [12] have provided a relatively complete theory of zero and short-span strength which considers the effect of distributions in the fibre length, elastic modulus and tensile strength. However, the distribution functions in these variables must be either known or assumed before any calculations can be made. Amongst the major results were that short span tensile strength is linearly dependent on the average tensile strength of the fibres while being almost independent of the average elastic modulus of the fibres. El-Hosseiny and Bennett also found that the tensile strength was significantly reduced as the standard deviation of either the elastic modulus or the tensile strength distribution increased.

Defects in the fibres can have a major influence on the measured zero-span strength. In 1965, Perez and Kallmes [13] considered the impact of both in and out of plane fibre curl on the zero-span test. They defined an average probability factor that a fibre does not contribute to the zero-span test because of fibre curl as $\overline{f_c}$. The value of $\overline{f_c}$ was then calculated from the ratio of the measured zero-span strength to the expected zero-span strength, as estimated from single fibre measurements. Perez and Kallmes concluded that for a zero-span tensile test of a typical handsheet $\overline{f_c}$ has an average value of 0.4. However, the existence of a residual span was not appreciated at the time and thus the measured zero-span tensile strengths would have been too low. In addition, as El-Hosseiny and Bennett later showed [12], measured zero-span values will invariably be lower than theoretical values calculated from a consideration of the average fibre length, strength and modulus alone. More recently, Mohlin and Alfredsson have measured the change in zero-span strength with fibre defects [6]. An increase in the numbers of gross defects (eg kinks) as well as an increase in curl were both found to significantly reduce the measured zero-span strength.

In the work that follows, a theoretical treatment of the zero and short/span test is developed to allow the average length of load-bearing elements within the sheet to be determined from zero and short-span test data. The term “load-bearing element” is used rather than “fibre” because, as discussed previously, fibres may contain kinks or other defects across which load cannot be transmitted. In such a case, it is the lengths of the load-bearing elements, which make up the fibre, that are important in determining the mechanical properties of the sheet [1]. The method will then used to examine changes in load-bearing element length with drying treatment.

ZERO/SHORT-SPAN TEST: THEORY.

We begin by defining the direction along which the tensile force is applied during the short-span test to be the y-axis, with the angle θ being defined with respect to this axis. If we consider a single, straight load-bearing element with length, l, and random orientation, θ, within the sheet of paper, then the probability of the load-bearing element crossing a single jaw line of width W_j may be approximated by

$$P_1 = \frac{l\cos\theta}{L_{sheet}}\frac{W_j}{W_{sheet}} \quad (1)$$

where L_{sheet} and W_{sheet} are the length and width of the sheet under test and it is assumed that W_j, L_{sheet} and W_{sheet} are very much greater than l. Now 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 of the load-bearing element being also gripped by both jaws is: $P_2 = 1 - \cos\theta \; G/l$. Here, G is the true span between the jaws, which is equal to the separation between the ends of the jaws plus the residual span, which is generally set to 0.2mm.

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

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

If the orientation of the fibres in the sheet is random then the probability density function for fibre orientation is $2/\pi$ and the average force generated by the load-bearing element, F_{av}, can be determined by multiplying Equation 2 by the probability $P_1 P_2$ that a fibre will be gripped by both jaws and averaging over the range of possible fibre orientations.

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

where $A(= L_{sheet}W_{sheet})$ is the area of the sheet and $\overline{f_c}$ is the fraction of fibres, gripped by both jaws, that do not bear load due to out-of-plane curl or other defects [13]. 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 this equation only the contributions to the measured load of fibres that are gripped by both jaws are considered. Therefore these equations only apply to wetted sheets, where there is minimal fibre-fibre bonding.

After integrating equation 3 we obtain

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

We consider only the case where G is small compared to l. Using a Taylor series expansion in powers of G/l and ignoring second order and higher terms yields

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

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

Thus, 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 the following sum, where the index, k, has been used to denote the $I(G)$ distinct load-bearing elements, each with different Young's modulus and length.

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

This can then be written in the form

$$F(\varepsilon,G)=I(G)(1-\overline{f_c})\,\varepsilon\frac{W_j}{A}\frac{3}{8}\left[\overline{E(G)C(G)l(G)}-\frac{32}{9\pi}\overline{E(G)C(G)}G\right] \quad (7)$$

where the overstrikes denote the average values of the products for the set of *I(G)* fibres.

This equation cannot be used to predict the breaking length of a sheet in a zero/short-span test, since both the strain at which the sheet will break, ε_{frac}, and the fraction of fibres which do not contribute to the load, $\overline{f_c}$, are unknown. However, as will be shown, there is still considerable information that can be usefully extracted.

If we consider the case of *G*=0 then *I(0)* is the total number of load-bearing elements within the sheet which is given by

$$I(0)=\frac{BA}{\omega\overline{l(o)}} \quad (8)$$

where *B* is the sheet grammage, ω is the average coarseness of the fibres and $\overline{l(0)}$ is the arithmetic average length of load-bearing elements within the sheet.

By making the key assumption that for the individual load-bearing elements, the value of EC is largely independent of the length of the load-bearing element, the following approximation can be made.

$$\overline{E(0)C(0)l(0)}\approx\overline{E(0)C(0)}\,\overline{l(0)} \quad (9)$$

Substitution of Equations 8 and 9 into Equation 7 and setting *G*=0 yields

$$F(\varepsilon,0)=\frac{3}{8}\frac{B}{\omega}(1-\overline{f_c})\,\varepsilon W_j\,\overline{E(0)C(0)} \quad (10)$$

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

$$\left.\frac{dF(\varepsilon,G)}{dG}\right|_{G=0}=-\frac{3}{8}\frac{32}{9\pi}\frac{B}{\omega\overline{l(0)}}(1-\overline{f_c})\varepsilon W_j\,\overline{E(0)C(0)} \quad (11)$$

where it has been assumed that $\overline{E(G)C(G)}$ and $I(G)$ are independent of *G* when $G<<\overline{l(0)}$.

Therefore the estimated arithmetic average length of load-bearing elements in the sheet, $\overline{l(0)}$ is given by

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

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*, it is possible to determine the arithmetic average length of the load-bearing elements within the sheet. This is a very interesting result as no method of estimating the average length of load-bearing elements within the sheet of paper has previously been presented.

The assumption that is most likely to be in error in the preceding derivation is Equation 9, which states that for all of the $I(0)$ fibres in the sheet, the fibre length, l, does not depend on EC. This assumption is likely to be deficient as longer fibres will tend to have a larger cross-sectional area. This is even more pronounced for mixes of softwood and hardwood fibres. To estimate the error involved Equation 9 we assign an error factor, K, such that K is given by $\overline{E(0)C(0)}\,\overline{l(0)} = K\overline{E(0)C(0)l(0)}$ and a value for K of 1.0 indicates no error in Equation 9. The true average load-bearing element length, $\overline{l(0)}_{true}$, is then related to the length of load-bearing element estimated from Equation 12 by $\overline{l(0)}_{true} = K\overline{l(0)}$.

To obtain an idea of the magnitude of K, two furnishes with artificial distributions of fibre properties were constructed and used to calculate K. Each furnish was assumed to have a bimodal distribution of fibres, with each fibre type having a single characteristic length, *l* and relative value of *EC*. The results are shown in Table 1. For the first of these distributions (hardwood pulp with early and latewood fractions), *K* is 0.97, implying that there is only minimal error involved in using Equation 12. The second distribution (mixed softwood and hardwood) produced a lower value of *K* of 0.8. Thus for this sort of mixed furnish, the arithmetic length of load-bearing elements predicted by Equation 12 would have significantly overestimated the true load-bearing element length. In general, K will always be less than 1.0 for any furnish where longer fibres have larger values of EC.

Table 1 Example values of *K*.

Furnish	Relative number of fibres	*EC*	*L*	$\overline{E(0)C(0)l(0)}$	$\overline{E(0)C(0)}\,\overline{l(0)}$	*K*
Hardwood	0.5	1.0	0.6	0.9	0.875	0.972
	0.5	1.5	0.8			
Hardwood & softwood	0.8	1.0	0.5	1.2	0.96	0.8
	0.2	2.0	2.0			

EXPERIMENTAL

The experimental work was conducted in two stages. In the first stage, AMCOR Research and Technology Centre supplied three commercial pulps. The pulps were an unbleached radiata pine softwood kraft (called radiata pine kraft #1), an unbleached NSSC eucalypt (mixed species) pulp and an unbleached recycled pulp. They had been produced in various mills operated by AMCOR. All pulps had been stored in wet-lap form, near 0^{o}C and the fibres of the first two pulps had never previously been dried.

Handsheets were made in a British Handsheet machine under standard conditions, except that the samples were not refined in the PFI mill. For each furnish, three sets of handsheets were made. The first set of handsheets, were made and then air-dried under restraint (in the presentation of the results, these are called Never/Air Dried). After drying the sheets were then 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).

Fibre length measurements on the wet starting pulps were made a Kajaani FS 200. For the waste and the pine kraft #1 pulps measurements were also made on samples taken from the two reslushed pulps. An Instron Universal Tester was used to measure the tensile strength of samples.

The zero and short-span measurements were made on rewetted samples using a Pulmac zero and short span tester. Measurements were made at spans of 0.0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 mm. Some of these spans were available as a setting built into the machine, while the rest of the spans used were obtained by inserting a feeler gauge of the required thickness between the adjustable jaw spacer and its stop block. 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.

The second set of measurements were made on two additional pulps, a second unbleached radiata pine kraft (labelled radiata pine kraft #2) and a *eucalyptus globulus* kraft pulp. The second radiata pine kraft pulp was collected directly from a brown stock washer at a Kappa number of 45 and a shives content of 5%, before being stored at a consistency of 12%. All sets of handsheets used in subsequent testing were then made within a week of collection. The *eucalyptus globulus* pulp had been pulped in a laboratory digester and then oxygen bleached to a kappa number of 17.9, before being kept under refrigeration for a year at ~20% consistency and then used to make handsheets.

Physical testing on the second set of pulps was performed in a similar manner to that for the first set of pulps, except that zero and short span measurements were only made at spans of 0.0, 0.1, 0.2, 0.4 and 0.6 mm.

RESULTS AND DISCUSSION

Mechanical Property Measurements

The results of the zero/short span measurements for the five furnishes are shown in Figures 1-5. Each of these figures shows three curves, one each for the Never/Air Dried, Air/Air Dried and Oven/Air Dried sets of handsheets. In each of Figures 1-5, a residual span of 0.2mm has been added to the spans at which the measurements were made. Thus measurements made with the jaws closed (0 mm nominal span) are shown as being made at a 0.2mm true span.

Figure 6 shows the tensile index measurement for the five different pulps and the three methods of preparing the handsheets.

The results in 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). Differences between the three curves are smallest in Figure 1, which shows the data for the NSSC eucalypt pulp. This is not surprising, as this is a chemi-mechanical pulp, which should exhibit very little hornification upon drying. There is also very little difference between the curves for the eucalypt kraft pulp (Figure 2). The data in Figure 3 (waste furnish) show that the Never/Air Dried sheets were weaker than the Air/Air Dried sheets at all spans, with the Oven/Air Dried sheets generally being having intermediate strength. This result is somewhat difficult to understand, given that it would be expected that oven drying the fibres should further hornify and weaken them, thereby reducing the zero/short span strengths of the handsheets made from these fibres.

The pine results show different trends for the two pulps. For pine kraft #1, it can be seen that the Never/Air Dried sheets generally had the lowest zero/short span strength. This is a surprising result given that fibre strength is expected to deteriorate with each additional and/or harsher drying cycle. This is also in contrast to the measurements on pine/kraft #2, where very little difference can be seen in the measured zero/short span strength for the air-dried once and the air-dried twice sheets, but the oven-dried sheets produced uniformly lower zero/short span strengths.

A partial explanation for the differences between the two sets of pine kraft data may be that pine kraft #1 had undergone some hornification while in storage. Evidence for this comes from Figure 6 which shows the sheet tensile strength, for the five different furnishes and the three different methods of preparing the handsheets. In Figure 6 all of the furnishes, except Pine Kraft #1, show a common trend with the Never/Air Dried sheets the strongest and the Oven/Air Dried sheets the weakest. In the case of pine kraft #1, both the Never/Air Dried sheets and the Air/Air Dried sheets show identical tensile strengths, indicating that the pine kraft #1 had aged during storage.

Load-Bearing Element Length Estimation
To determine the average length of load-bearing element using Equation 12, the true zero-span strength and the slope of the zero-span versus span curve at zero span must be determined. The major difficulty in doing this is that while measurements were taken at spans in the range 0-0.6 mm, the existence of a residual span of 0.2-mm gives a true range of spans, at which measurements were made, of 0.2-0.8 mm. Thus to use equation 12, the existing strength versus span data must be extrapolated to a true span of 0.0 mm, which is an extension on the measured range of spans of 33%.

A number of methods were trialled to fit the data so that the average length of load-bearing elements could be estimated. The results for the load-bearing element length determined using three of them are shown in Table 2, while Table 3 gives a comparison between the load-bearing element lengths estimated in Table 2 and the average fibre lengths determined optically in a Kajaani FS 200.

Given the limited number of data points it was decided to only use linear or quadratic functions to perform the fits. The theory developed in this paper suggests that the fitting should be undertaken differently for the short and long fibre furnishes. For the long fibre pulps (pine kraft #1 and #2) where $\overline{l(0)} >> G$, then it can be assumed that $\overline{E(G)C(G)}$, $\overline{l(G)}$ and $I(G)$ are independent of G. This implies from Equation 7 that the zero/short span strength will be linearly dependent on G. Furthermore, if the assumption that $\overline{l(0)} >> G$ is not valid, then the second order and higher terms in the Taylor series expansion of Equation 4 cannot be neglected. In Table 2, the data for two linear fits are shown, one a linear fit of the full set of data and the other a linear fit to a restricted set of data (true spans: 0.2-0.4mm- measurements at nominal spans from 0.0 to 0.2 mm). This last fit is likely to provide the most accurate fit as the assumptions given above are not viable at larger spans. For the short fibre pulps, $\overline{E(G)C(G)}$, $\overline{l(G)}$ and $I(G)$ are not independent of *G,* making the dependence of the zero/short span strength on G difficult to predict without knowledge of the distribution of fibre properties. Therefore for the short fibre pulps a quadratic function was chosen, which was generally sufficient to accurately represent the data across its range. The load-bearing element lengths used for comparison from the optical fibre length data are highlighted with a grey background in Table 2 and the corresponding values in Table 3 are similarly highlighted.

Table 2 Load-bearing element length (mm) determined from different methods of fitting.

	Never/Air Dried			**Air/Air Dried**			**Air/Oven Dried**		
	Quadratic	Linear (0-0.4mm)	Linear	Quadratic	Linear (0.0-0.4mm)	Linear	Quadratic	Linear (0-0.4mm)	Linear
Euc NSSC	0.61	0.82	0.97	0.74	0.90	1.02	0.69	0.86	0.99
Euc 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 #1	1.00	1.19	1.97	1.33	1.32	2.02	1.75	1.82	1.88
Pine #2	0.89	1.29	1.69	1.26	1.21	1.83	1.24	1.50	1.71

Table 3 shows the average length of load-bearing element determined, as described above, from fitting the zero/short span data and using Equation 12. These averages are compared with optical measurements of fibre length from a Kajaani FS 200. Both the arithmetic fibre length and the length weighted fibre length are given for comparison. The optical fibre length data given in italics were not actually measured. Instead it was assumed that the fibre lengths measured for the never-dried starting pulps were the same for the pulps after air and oven drying. This is a reasonable assumption given that for the waste pulp and pine kraft # 1, the fibre length was measured optically for all three pulps and very little difference was found.

In examining Table 3, it can be seen that there is a generally a close match between the measured arithmetic fibre length and the average length of load-bearing element. In 11 out 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 fibre length measured optically. The worst match was for the Oven/Air Dried pine kraft #1 sheets where the estimated load-bearing element length was 1.82 mm while the arithmetic average fibre length was 1.18 mm. Furthermore, when the average length of load-bearing element is examined for different pulp drying treatments, there is no trend between the treatments, which suggests that the drying treatments have not produced any changes in the average length of load-bearing elements within the sheet. 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.

Thus in Table 3, no reduction is observed in the estimated 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 the gross defects, such as kinks, being set into fibres, therefore reducing the load-bearing element length. A number of other possible explanations for the strength loss observed upon drying have been proposed [6]. These include a reduction in fibre-fibre shear bond strength upon drying or the production during the drying process of defects such as micro-compressions, which affect the fibre mechanical properties without changing the load-bearing element length. It is clear that these alternative explanations will have to be investigated before the cause or causes of the reduction in sheet strength upon drying can be clarified.

Table 3 Comparison between load-bearing element length and optically measured fibre lengths. Values in italics for the arithmetic and length weighted fibre lengths were not measured but have been assumed to be identical to those measured for the never-dried pulps

	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)
Euc NSSC	0.63	0.61	0.81	*0.63*	0.74	*0.81*	*0.63*	0.69	*0.81*
Euc 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 #1	1.23	1.19	2.19	1.27	1.32	2.21	1.18	1.82	2.15
Pine #2	1.56	1.29	2.43	*1.56*	1.21	*2.43*	*1.56*	1.50	2.43

CONCLUSIONS

An equation was 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 it was found that the average length of load-bearing element was approximately equal to the measured arithmetic average fibre length, independent of the type of drying treatment used to produce the handsheets.

ACKNOWLEDGEMENTS

I gratefully acknowledge many useful discussions with Daniel Ouellet of Paprican and Russell Allan of the Amcor Research and Technology Centre. Some of the pulps were supplied by and the handsheets made at the Amcor Research and Technology Centre. The assistance of Glenda Spencer in making the handsheets is gratefully acknowledged. The assistance of Michael Briggs and Geoff Ennis in performing the experiments is also gratefully acknowledged. Funding from the Federal Government of Australia through the Cooperative Research Centre for Hardwood Fibre and Paper Science is gratefully acknowledged

Source: Batchelor, W.J. (1999): Determination of Load-Bearing Element Length in Paper Using Zero/Short Span Tensile Testing. In "TAPPI International Paper Physics Conference" TAPPI, pp. 247-258.

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Source: Batchelor, W.J. (1999): Determination of Load-Bearing Element Length in Paper Using Zero/Short Span Tensile Testing. In "TAPPI International Paper Physics Conference" TAPPI, pp. 247-258.

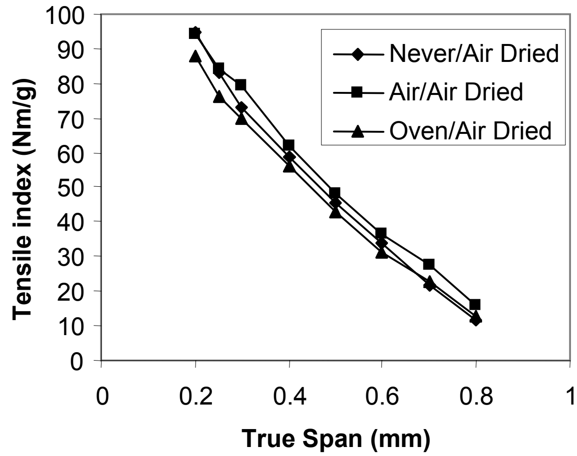

Figure 1 Tensile index vs. gap for eucalypt NSSC handsheets prepared from never dried, air dried and oven dried pulps.

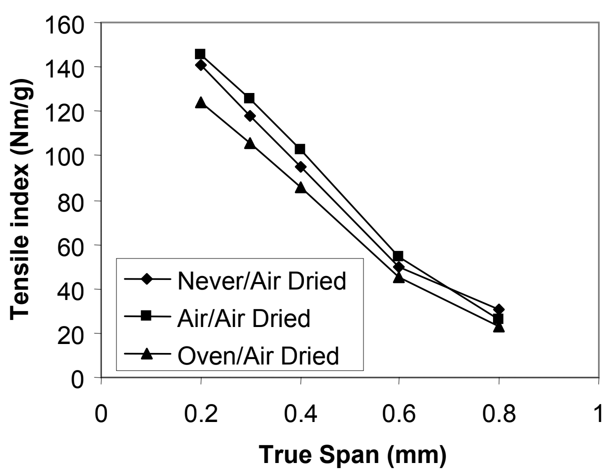

Figure 2 Tensile index vs. gap for eucalypt globulus kraft handsheets prepared from never dried, air dried and oven dried pulps.

Source: Batchelor, W.J. (1999): Determination of Load-Bearing Element Length in Paper Using Zero/Short Span Tensile Testing. In "TAPPI International Paper Physics Conference" TAPPI, pp. 247-258.

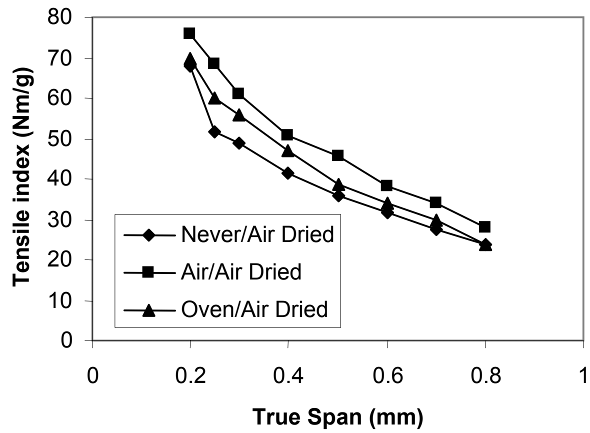

Figure 3 Tensile index vs. gap for waste paper handsheets prepared from never dried, air dried and oven dried pulps.

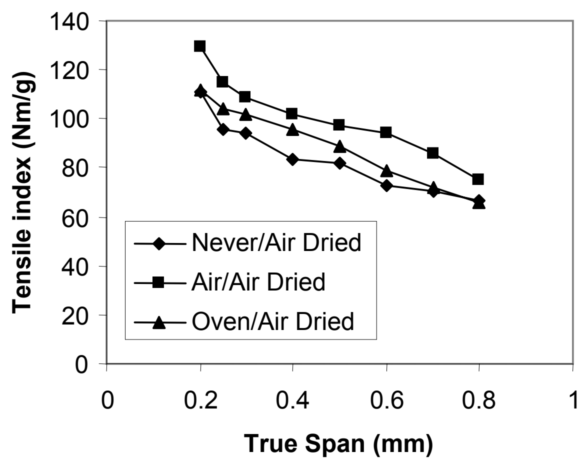

Figure 4 Tensile index vs. gap for radiata pine kraft # 1 handsheets prepared from never dried, air dried and oven dried pulps.

Source: Batchelor, W.J. (1999): Determination of Load-Bearing Element Length in Paper Using Zero/Short Span Tensile Testing. In "TAPPI International Paper Physics Conference" TAPPI, pp. 247-258.

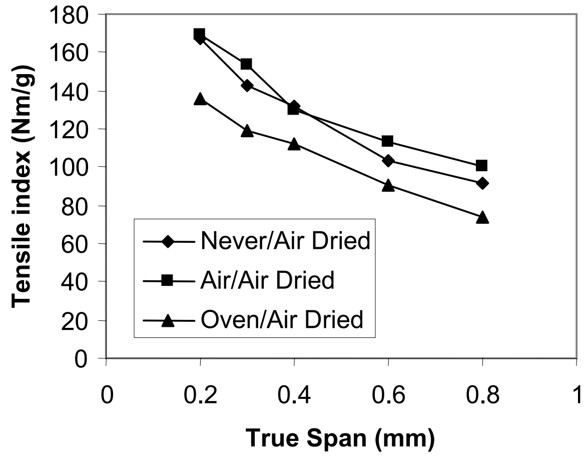

Figure 5 Tensile index vs. gap for radiata pine kraft # 2 handsheets prepared from air dried once, air dried twice and oven dried pulps.

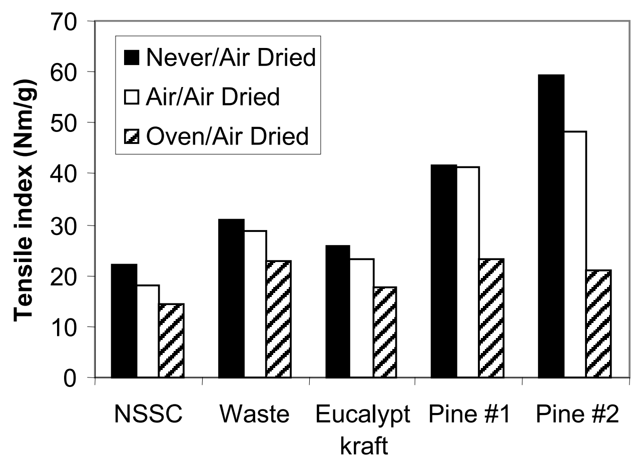

Figure 6 Tensile index measured from hand-sheets prepared from never dried, air dried and oven dried pulps for the five different furnishes.