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THE EFFECT OF REFINING ON WET FIBER FLEXIBILITY AND ITS RELATIONSHIP TO SHEET PROPERTIES

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ABSTRACT

The wet fiber flexibilities of several softwood and hardwood species were measured by Steadman's method (5). Softwoods showed a broader range of wet fiber flexibilities than hardwoods. Refining* decreased the spread as measured by the IQR and increased the median values. The wet fiber flexibility and its distribution was sensitive to the type of refiner, beating load and refiner consistency. Refining at high intensity by increasing the refiner load in a Valley Beater, resulted in the production of pulps with inferior strength properties. When the pulps were at constant WFF, those prepared under low intensity exhibited superior tensile strength. The main effect on the fibers beaten at high consistency was to sharply reduce their fiber length. Changing loads in the PFI mill had less of an impact on the WFF and paper properties. Refining with the low load resulted in maximizing fiber flexibility. However, the tensile strength was inferior. The tensile-density relationship did not change as a function of refining load in the PFI mill, indicating that the quality of refining did not change. The WRV was useful in understanding the relationship between fiber and sheet properties.

* The terms refining and beating are used interchangeably.

INTRODUCTION

The increase in fiber flexibility with refining is one of the most widely accepted concepts in papermaking and may be the primary reason for refining. The concept is built on some very good circumstantial evidence based on the effects of refining on other fiber and sheet properties (1-4). However, there is a limited amount of data which directly shows this relationship (5-8).

Clark (2), Higgins and de Young (9), Giertz (10) and Ebeling (11) have given good reviews on the effect of refining on fiber and paper properties. These reviews show that there are three main effects of refining on fibers; (a) fiber cutting or shortening, (b) external fibrillation and (c) internal fibrillation. Fiber cutting and external fibrillation lead to the formation of debris, or fines, and this accounts for the change in freeness of a refined pulp. Fiber cutting allows for more uniform sheet formation and can lead to higher sheet density (12). Cutting reduces the tearing and folding resistance of the resultant sheet (2). External fibrillation can enhance fiber-fiber bonding thereby increasing the tensile strength of paper sheets (2).

Perhaps the most important effect of refining is internal fibrillation. The term internal fibrillation refers to the breakdown of the fiber wall into separate lamellae (3). Internal fibrillation results in fiber swelling as water penetrates the fiber wall. Emerton proposed that the increase in paper strength as a result of refining was due to delamination which made the fibers more flexible (13). Stone and Scallan (4) showed that flexibility increases as the square of the number of lamellae formed in the fiber wall during pulping and refining processes. The presence of these lamellae was shown with SEM photomicrographs by McIntosh (14) and Page and DeGrace (3). Fibers prepared from the sulfite process separated into more lamellae than did those from kraft cooks (3) and it was concluded that the number of lamellae observed accounts for the increase in flexibility. Page (14,15) has shown that crimps, kinks, microcompression and curl play an important role in the beating process especially with dried pulps. Changes in these fiber characteristics affect the sheet mechanical properties.

A direct measure of the effect of refining on fiber flexibility has been attempted by several authors (5-7). Steadman (5-8) and others (6,7) showed that increases in flexibility with refining correlated with increases in apparent density and tensile strength. Using the method of Tam Doo and Kerekes (16), Hattula and Niemi (7) investigated the relationship of fiber flexibility of springwood and summerwood fractions, at various pulping yields, to sheet properties. Their work showed that flexibility increased with decreasing yield and with refining. The relationships of sheet density and tensile index to fiber flexibilities changed with pulp yield and refining. More recently Tam Doo and Kerekes (17) studied the effect of beating on fiber flexibility. Light beating in a PFI mill to 500 CSF decreased the stiffness 10-30% while at 300 CSF, the decrease was 50-70%. The results varied with the pulp type.

A novel method of measuring WFF was described at the 1984 Fundamental Research Conference (5). Briefly, the technique involves the placement of a very thin, wet fiber network over a series of parallel fine stainless steel wires placed on top of a glass slide. In this way, fibers will cross the stainless steel wires and will be out of contact with the glass for a certain distance. This distance is measured optically; the shorter the distance, the more flexible the fiber. This method of determining WFF has certain inherent advantages: (a) Over 300 fibers may be measured in a reasonable length of time, which gives a greater reliability to this test; (b) All fibers, whether damaged, curled, or short, are measured; (c) The measurement is less subjective than most single-fiber tests; (d) The procedure follows closely the preparation of handsheets.

In this paper we examine the effect of beating and some of its variables on wet fiber flexibility (WFF) using this newly developed technique. We then attempt to relate WFF to other fiber and sheet properties.

RESULTS AND DISCUSSION

The Distribution of WFF in a Fiber Sample

The heterogeneous nature of the structure of natural fibers has long been recognized. In measuring the flexibility of a fiber population, it has been found that the standard deviation is very high (5,16). Figure 1 shows that softwood fibers exhibit a bimodal distribution reflecting the great differences in flexibility for summerwood and springwood fibers which is not apparent for hardwood species shown in Figure 2. The distribution can be characterized in different ways. The range is a measure of the distribution of the whole sample. However, this measurement can be strongly influenced by the WFF values of just a few fibers in the population. A better measure of the distribution of WFF in a sample is the interquartile range (IQR) which is a measure of the spread of the middle half of the population.

Table 1 lists the IQR for a number of unrefined pulps. The data shows that softwood fibers exhibit a broader distribution in WFF than hardwoods reflecting the summerwood-springwood differences for these pulps. Summerwood-springwood determinations were made by visual observation of the images on the video screen. The summerwood fractions show a broader distribution than the springwood fractions and this may be due to the greater variation in collapsibility for the summerwood population. It was observed that while most of the springwood fibers were totally collapsed, the summerwood fibers exhibited varying degrees of collapse. The greater collapsibility of the springwood fibers accounts for their higher WFF.

The Effect of Refining on the WFF Distribution

Table 2 lists the changes in the IQR and WFF for a western red cedar dry lap beaten in a Valley Beater. The data shows that not only is the WFF of the fibers increased but that refining also produces a more homogeneous mixture of fibers with respect to WFF as indicated by the decrease in the IQR for the population and subpopulation of springwood and summerwood. Changing the beating conditions affects the change in both the WFF and distribution. Table 3 shows the effect of beating on WFF with a high and low load in the

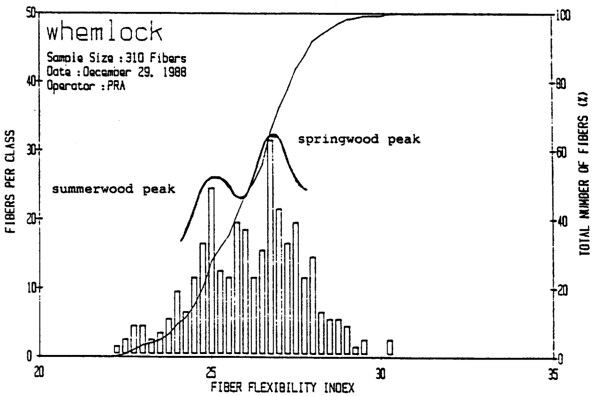

Fig 1 Histogram showing the distribution of WFF for an unrefined UBK western hemlock pulp

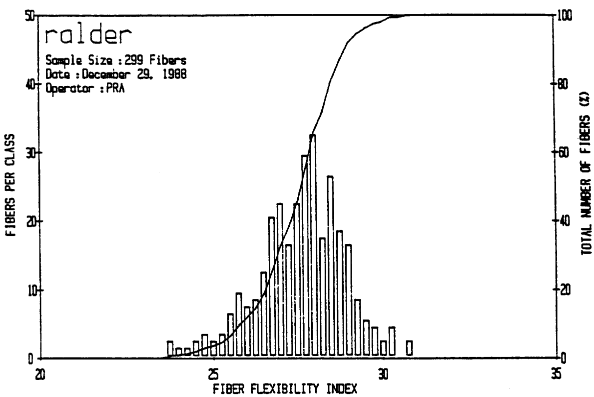

Fig 2 Histogram showing the distribution of WFF for an unrefined BK red alder pulp

Fiber type*	IQR	WFF Index
Lodgepole pine (BK)	1.74	28.29
springwood	1.51	28.57
summerwood	1.98	27.73
Douglas fir (UBK)	2.23	26.45
springwood	1.61	27.30
summerwood	1.78	25.60
Western red cedar (BK,dry)	2.49	28.04
springwood	1.40	28.80
summerwood	1.83	26.19
Red alder (BK)	1.63	27.82
Red alder (UBK)	1.55	27.41
White birch (UBK)	1.44	26.82
Aspen (UBK)	1.37	27.00
Northern red oak (UBK)	1.54	26.78

* Never dried pulps unless otherwise noted.

Table 1. IQR of the WFF Index Distribution for Unrefined Fibers

Fiber type	CSF, ml	IQR	WFF Index
whole pulp (unref.)	700	2.49	28.04
springwood		1.40	28.80
summerwood		1.83	26.19
whole pulp	550	1.93	28.34
springwood		1.49	28.92
summerwood		1.58	27.23
whole pulp	450	1.61	28.46
springwood		1.28	28.96
summerwood		1.17	27.59
whole pulp	310	1.41	28.75
springwood		1.27	29.20
summerwood		1.29	28.19

Table 2. The Effect of Beating on the Distribution of the WFF Index for a Bleached Kraft Western Red Cedar Dry-Lap Pulp

CSF, ml	Beating time, minutes	WFF index	IQR	Average fiber length, mm
700	0	28.04	2.49	2.30
High load	(11.0 kg)			
550	15	28.36	1.73	1.81
450	23	28.41	1.66	1.55
310	30	28.34	1.78	1.32
Low load	(5.5 kg)			
550	30	28.34	1.93	2.10
450	45	28.46	1.61	2.07
310	65	28.75	1.41	1.88

Table 3. The Effect of Beating Load in the Valley Beater on WFF, WFF Distribution and Fiber Length

Valley Beater. It can be seen that beating with the higher load produced a more heterogeneous pulp (greater IQR) of lower WFF when compared at constant CSF and that refining at high load greatly reduced fiber length.

Changing the refining consistency in a PFI mill resulted in great differences in the distribution and development of WFF for a summerwood-rich fraction of a bleached kraft southern pine pulp. The summerwood-rich fraction was obtained by collecting the centricleaner rejects of the whole pulp. They were then refined in 30 gram batches at 10% or 20% consistencies in the PFI mill. Samples were collected at 3000, 6000 and 9000 revolutions. WFF measurements were made on these pulps and the data are presented in Table 4. It can be seen that high consistency refining increases the IQR of the distribution indicating a very uneven fiber treatment most likely due to greater flocculation. At 10% consistency, a more uniform fiber treatment was obtained and the IQR is decreased as refining continues. The lower consistency ultimately produces pulps of higher, more uniform WFF. It is interesting to note that at 6000 revolutions, the WFF decreases at both 10% and 20% consistency before increasing again. Somewhat similar results were obtained by Tam Doo and Kerekes (7). The origin of this effect remains unknown.

PFI revs.	10% WFF index	10% IQR	20% WFF Index	20% IQR
0	27.15	1.89	26.63	1.84
3000	28.68	1.50	28.12	1.62
6000	28.49	1.72	27.97	2.19
9000	29.30	1.35	28.21	2.57

Table 4. The Effect of PFI Refining Consistency on WFF and Distribution of a Summerwood-Rich Fraction of BK Southern Pine

The Effect of Refining Intensity on WFF

Modern theories of refining action focus on the amount of applied energy and how the energy is transferred to the fibers. It is now generally accepted that the refining action takes place on the leading edges of the bars of the refiner plates and that the fibers are refined as flocs rather than as single fibers. The Specific Edge Load (SEL) theory (30) measures the applied energy in terms of W•s/m. The value is determined by calculating the net power used to refine the pulp (W•s) and calculating the total length of bar edges on the refiner plates (m). The theory has been modified, as documented by Claudio-da-Silva (18), to describe the refining process in terms of number of impacts and severity of impacts per fiber. No matter how the analysis is done, the result is the same. Low intensity refining, which is characterized by many gentle impacts on the fibers, will result in superior paper properties when compared to high intensity refining at the same total applied energy (18-22). This is accomplished by preserving fiber length, fiber strength and increasing fibrillation, both internal and external. High intensity impacts cut and damage fibers and do not maximize the papermaking potential of pulps (21). With this in mind, experiments were conducted to show how different refining intensities affect the development of WFF.

Pulps were refined in a Valley Beater and a PFI Mill. While these refiners do not lend themselves to application of theories such as SEL by varying the refining load, statements concerning the nature of the refining impacts can be made and related to WFF and sheet strength. The Valley Beater was operated with the standard 5.5 kg load (VB_lo) and with twice the standard load (VB_hi). Pulps were refined at 1.63% consistency to approximately 550, 450 and 300 CSF. For the pulps refined in the PFI Mill, the standard 17 kg load (PFI_hi) and a 9 kg load (PFI_lo) were used. Pulps were refined at 10% consistency in 30 gram batches to the same freeness levels as for the Valley Beater pulps. The pulp used in all trials was a bleached kraft, western red cedar from dry lap.

Figure 3 shows the change in WFF index as a function of CSF for the pulps refined under four different conditions. Refining in the PFI Mill at high load results in an initial sharp increase in WFF then levels off as refining continues. The high load for the Valley Beater increases the WFF from the unbeaten state to the first beater point but then remains constant with further beating. Refining at the low load for both the Valley Beater and PFI Mill shows a steady increase in WFF throughout the refining curve. As expected, a more gentle refining action ultimately results in higher flexibility, especially for the pulps refined in the Valley Beater.

Since data on net applied energy is not available as a means of comparison, the refining effect is best analyzed with respect to some property of the paper sheet, for example fines-free tensile index. Figure 4 shows the relationship of fines-free tensile index to WFF. The highest tensile values are obtained with the standard operating conditions for the Valley Beater (VB_lo) and the PFI Mill (PFI_hi). The other conditions when compared at constant WFF produce sheets of inferior tensile strength. The tensile strength of the VB_hi pulps increases even though the WFF value is constant.

The data presented here, all for the same fiber type, shows that the WFF-tensile relationship is highly dependent on the refining conditions and at the same WFF widely different tensile values can be produced. While to a great extent the WFF is controlled by internal fibrillation, the scatter in the tensile values indicates that additional factors are involved. Differences in fiber length and fines-content can be discounted since fiber length data is similar, with the exception of the VB_hi pulps, and all sheets were prepared fines-free. It may be that differences in external fibrillation, removal of

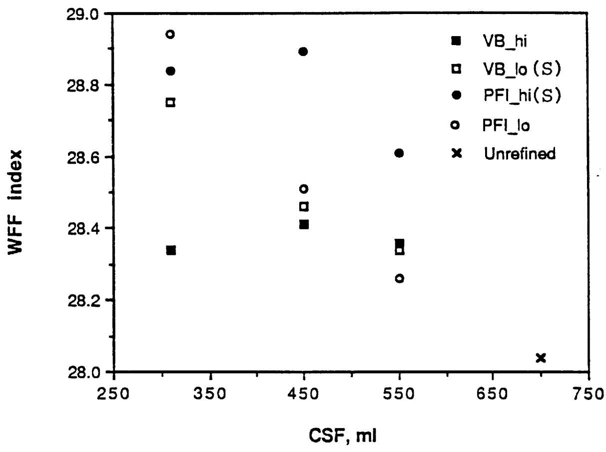

Fig 3 The relationship of WFF index to CSF for a bleached kraft western red cedar dry-lap pulp beaten by various methods

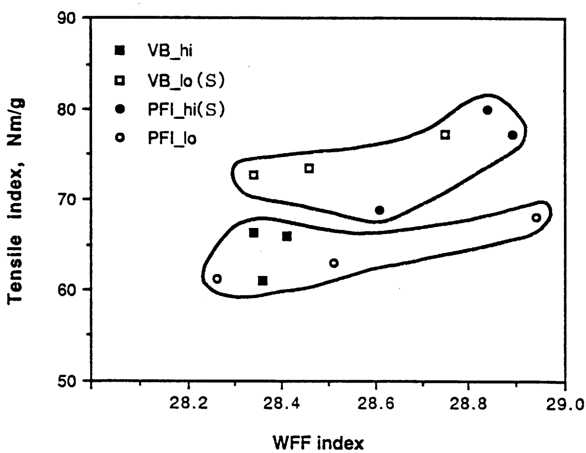

Fig 4 The effect of refining intensity on the relationship of tensile index to WFF index for fines-free handsheets prepared from a BK western red cedar dry-lap pulp

curl kinks, crimps or introduction of microcompressions play some role in determining the tensile values. The PFI Mill at the high load provides a harsher treatment for the fibers and could be expected to result in more external fibrillation. With the high load on the Valley Beater, WFF is hardly changed, indicating that very little fiber fibrillation occurs under this condition. In contrast, the beating with the low load appears to fibrillate the fibers and greatly increases the WFF. Clark (2) strongly advocated the concept of external fibrillation enhancing paper strength. However, others have argued against a major role for external fibrillation in determining paper strength (23).

Figure 5 shows a plot of tear vs. tensile values for the differently heated pulps. The data clearly shows that the pulps beaten in the Valley Beater under high load conditions are inferior to all the others. The low tear values indicate fiber damage and severe fiber cutting as shown in Table 5. It is also interesting to note that the fiber length for the PFI mill for the standard conditions are lower than for the standard conditions for the Valley Beater. The other data all falls on the same line indicating that the refining process for these conditions has a similar effect on the fibers.

	average fiber length, mm			
	Valley Beater		PFI Mill	
CSF, ml	HIGH	LOW(S)	HIGH(S)	LOW
700 (unref.)	2.30	2.30	2.30	2.30
550	1.81	2.10	1.94	2.11
450	1.55	2.07	1.93	1.85
310	1.32	1.88	1.74	1.88

(S) indicates standard conditions.

Fiber length analysis done on a Kajaani FS-200 analyzer courtesy of Kajaani Electronics, Ltd.

Table 5. The Effect of Refining Load on Fiber Length

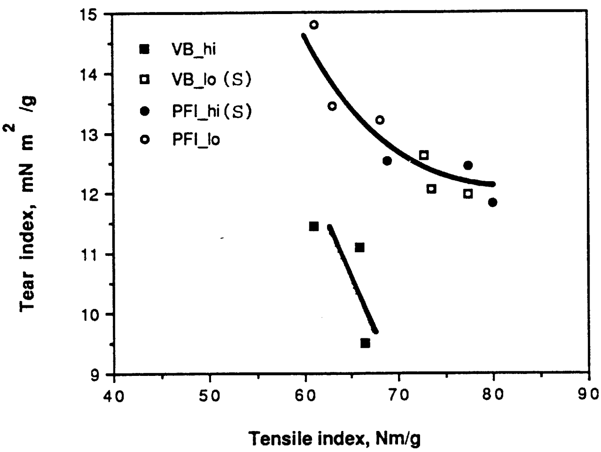

Fig 5 The effect of refining intensity on the relationship of tear index to tensile index for fines-free handsheets prepared from a BK western red cedar dry-lap pulp

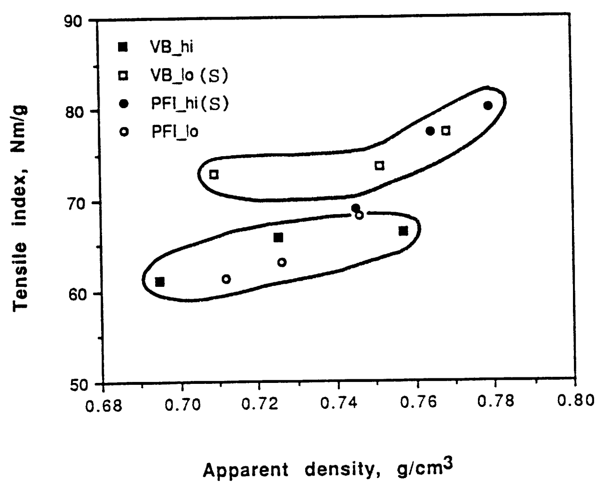

Fig 6 The effect of refining intensity on the relationship of tensile index to apparent density for fines-free handsheets prepared from a BK western red cedar

Figure 6 shows the relationship of tensile index to apparent density for fines-free sheets. The data show certain similarities to the data presented in Figure 4. It can be seen that the standard refining conditions for both the Valley Beater (VB_lo) and PFI Mill (PFI_hi) develop higher tensile values when compared to the other refining methods at constant density levels. A closer look at the data for the PFI Mill only, in Figure 7 reveals a linear relationship of tensile index to apparent density. This indicates there is little difference in the way the refining process affects the fibers for the two loading levels of this refiner. Sheet apparent density is a linear function of the amount of energy applied during refining (2) and, for the PFI mill, varying the load only changes the amount of energy applied and not the refining mechanism. This may be due to the high refining consistencies (10%) used for the PFI Mill which decreases the severity of impacts on individual fibers, or due to the difference in the refining action of this refiner compared to a Valley Beater or disc refiner. For the PFI mill, refining takes place as fiber flocs are rubbed against the smooth surface of the refining chamber while in disc mills or beaters, the refining action takes place at the edges of passing bars (24). Changing the refining load on the Valley Beater changes the refining mechanism from one involving fibrillation (VB_lo) to one which predominantly crushes and cuts fibers (VB_hi). When compared at constant sheet density, the low load produces pulps which form sheets of superior tensile strength (Figure 6).

Refining, WFF and Sheet Apparent Density

Steadman has shown that for any given fiber type the increase in fines-free apparent density as a function of refining correlates with increases in WFF (5). The data in Figure 6 showed that changing the load on the Valley Beater changed the tensile-density relationship. Figure 8 shows that changing the refining load also changes the WFF-density relationship. High load, high intensity beating increases the sheet density without changing WFF. Beating under the standard conditions (lower intensity) results in a gradual increase in both WFF and apparent density, and as shown in Figure 6, superior tensile strength for the paper sheet. The increase in density under the high load conditions is most

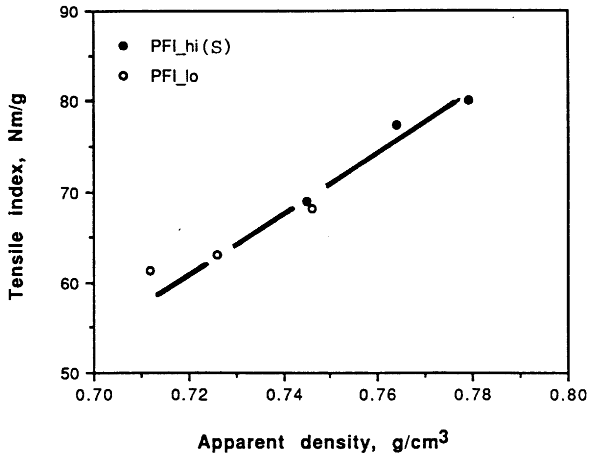

Fig 7 The effect of refining intensity in the PFI mill on the relationship of tensile index to apparent density for fines-free handsheets prepared from a BK western red cedar dry-lap pulp

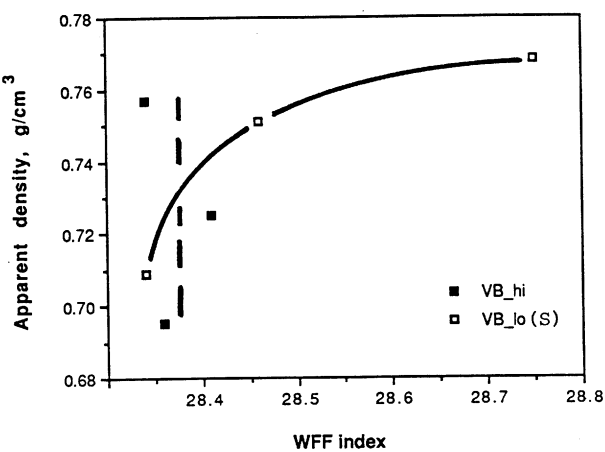

Fig 8 The effect of refining intensity in a Valley Beater on the relationship of fines-free sheet apparent density to WFF index for handsheets prepared from a BK western red cedar dry-lap pulp

likely due to changes in fiber length. Table 5 shows that the average fiber length for the VB_hi pulps was greatly reduced. The shorter fibers should give a higher packing density when pressed into a sheet. This was confirmed in an experiment where moist paper sheets were cut into thin strips to reduce the average fiber length. Measurements of fines-free WRV and fines-free density for these pulps showed that indeed reducing fiber length can increase sheet density as well as WRV. The data are presented in Table 6.

Treatment	Avg. fiber length, mm	WRV g H_2O/g fiber	Apparent density g/cm^3
uncut	2.99	0.77	0.58
once cut	2.24	0.89	0.62
twice cut	1.67	0.91	0.63

Sixty g/m^2 handsheets were pressed to approximately 50% solids and then cut into thin strips 1-2 mm in width (once cut). Some of the strips were then reformed into handsheets and cut again (twice cut).

Table 6. The Effect of Fiber Cutting on Fiber Length, Fines-Free Sheet Apparent Density for an Unrefined, BK Western Red Cedar Dry-Lap Pulp

The water retention value (WRV) can also be used to characterize the beating response. Figure 9 plots fines-free apparent density against fines-free WRV. When compared at a constant WRV, the apparent densities of the VB_lo sheets are higher than that for the VB_hi sheets. This indicates two mechanisms for water retention. The first, for the VB_lo pulps, is a function of fiber structure. These fibers are more delaminated and fibrillated, with a higher specific surface area which increases the WRV and ultimately sheet density. For the pulps refined at high loads, the WRV changes due to changes in fiber length (Table 5) which influence the water-holding capacity of the fiber pad. Shorter fibers form

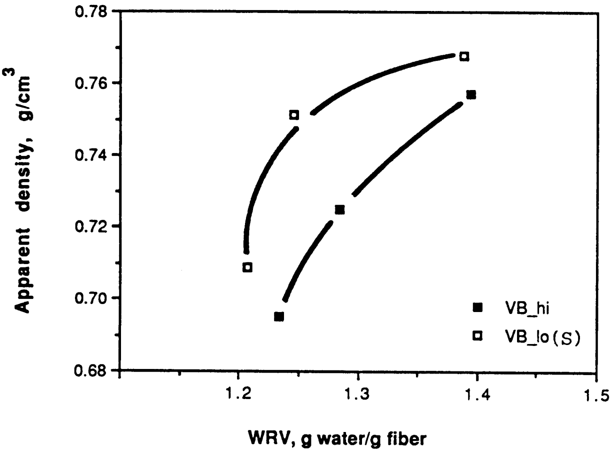

Fig 9 The effect of refining intensity in a Valley Beater on the relationship of fines-free sheet apparent density to fines-free WRV for handsheets prepared from a BK western red cedar dry-lap pulp

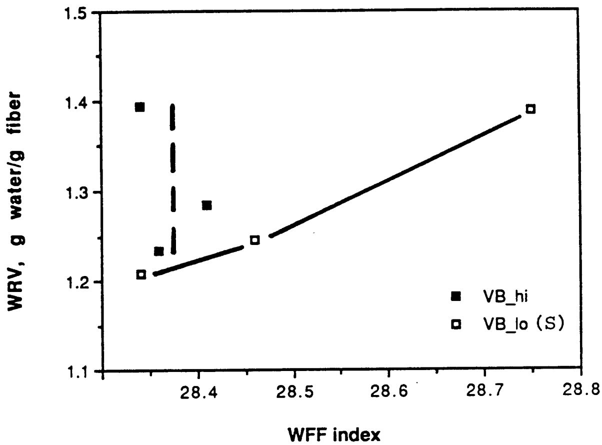

Fig 10 The effect of refining intensity in a Valley Beater on the relationship of fines-free WRV to WFF index for a BK western red cedar dry-lap pulp

more uniform, finely structured pads which hold more interfiber water. However, the sheet density is lower since the fibers have not been fibrillated or delaminated.

The difference in the mechanisms of water retention for the two refining conditions can be illustrated by plotting the relationship of WRV to WFF and this is shown in Figure 10. It can be seen that the increase in WRV for the VB_hi pulps is dependent of WFF. This provides additional evidence that the WRV is changing due to changes in fiber length and not fibrillation or delamination. The unchanged WFF is one reason for the inferior sheet density and tensile strength of sheets produced from these pulps. For the VB_lo pulps, refining increases both the WRV and WFF. The linear increase in WRV and WFF for these refining conditions is due to changes in fibrillation and delamination but other factors may be involved as well (15). It is these changes in fiber structure which are responsible for the superior paper properties of the pulps refined at the lower load.

The differences in the relationships of apparent density and WRV to WFF for the pulps produced in the PFI mill under different loads were not as great. The higher load produced pulps which formed sheets of higher density when compared at similar WRV and WFF presumably due to increased external fibrillation. The WRV for the high load pulps was only slightly higher than that for the low load pulps.

FINAL REMARKS

The WFF test developed by Steadman (5) gives a distribution of wet fiber flexibilities in a pulp sample. Because there is no selection of fibers in the test, the values are more representative than those obtained by other methods. The fibers may be damaged, kinked, crimped or curled. Subdividing the WFF of a softwood pulp into an early and latewood fraction determining the spread in WFF and the response of WFF on refining under a variety of refining conditions makes this novel fiber measurement of value in studying the behavior of stock in commercial refiners. This suggestion is supported by the consistent picture between WFF, refiner action and paper properties.

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Transcription of Discussion

THE EFFECT OF REFINING ON WET FIBRE FLEXIBILITY AND ITS RELATIONSHIP TO SHEET PROPERTIES

P. Abitz and P. Luner

Addendum

The interquartile range IQR referred to in Tables 1-4 and in the test is defined as:

$$\frac{IQR}{median}$$

and should be understood in this context: i.e. a measure of the degree of dispersion of the wet fibre flexibility values.

Dr. N. Gurnagul PPRIC

In your plot of wet fibre flexibility versus freeness for highly loaded beaters when you have a drop in freeness you also have a decrease in wet fibre flexibility - can you explain this?

P. Luner

We had a lower development at higher loads. The development of freeness went up initially and then levelled off compared to other conditions of beating.
In instances where this did occur and was outside the range of experimental error, we feel that the results are due to the unexpected behaviour of fibres under the conditions of pulp and slide preparation. This is manifested in anomalous span lengths and/or fibre widths. Tam Doo and Kerekes at PAPRICAN have made similar observations.

Dr. H. Nanko Japan Pulp & Paper Research Institute

I would like to ask you two questions - I do not understand the

meaning of the measurement of wet fibre flexibility because a flexible fibre is not always conformable. I think we should measure the conformability of the fibres.
And the second question is - the value of the wet fibre flexibility index is not changed very much with beating in Table 4. With PFI revolutions zero under these conditions, the wet fibre flexibility is 27 and at revolutions of 9,000 it is 29, this indicates that it is not a very sensitive measure. What do you think about this?

P. Luner

One has to convert the logs to the numbers. I must apologise for using logs, this is why I included the slide showing the numerical values of the wet fibre flexibility. In the case of refining the Western Red Cedar there is over a twofold change in the flexibility values; this is considerable. In terms of the type of test we are using you can call it conformability or flexibility. If you take a pure mechanical approach there is a difference between conformability and stiffness. We are using the test as an index of flexibility. You may choose to call it conformability or the propensity to conform and I would accept either of these terms for our test.

G. Baum, James River

Do the fibres adhere to the stainless steel wires?

P. Luner

I don't know if they adhere but we have done different things to the wires with no difference in the test result but I should mention that if you change the nature of the glass surface there are differences.

G. Baum

Have you tried glass "wires"? The pulp fibres should adhere to the glass.

P. Luner

We haven't tried glass wires but we have tried plastic wires but there are a lot of variables in the test.