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CHANGES IN FIBRE WALL STRUCTURE DURING DEFIBRATION

Tuulikki Lammi and Annikki Heikkurinen
The Finnish Pulp and Paper Research Institute (KCL)
P.O. BOX 70, FIN-02151 Espoo, Finland

ABSTRACT

Development of earlywood and latewood fibres was investigated to find out how morphologically different fibres undergo delamination. Fibre fractions rich in earlywood and latewood, were separated from mechanical pulps using a hydrocyclone and refined further in a wing defibrator. Changes in fibre structure due to defibration were studied using microscopy techniques that included measurement of fibre stiffness, fibre wall thickness and external fibre surface. Before refining, the latewood fibres were stiff and their external fibre walls were poorly developed. Refining reduced the stiffness of both fibre types. The stiffness of latewood fibres decreased to around that of unrefined earlywood fibres, and the external walls of latewood fibres became fibrillated. The wall thickness of both earlywood and latewood fibres was reduced only slightly. Although the tensile and tear indices of sheets made of latewood fibres were improved by refining, the tensile index of flexible latewood fibres was only half of that measured for unrefined earlywood fibres. This indicates that there are fibre properties other than stiffness which must be changed in order to get latewood fibres to bond and conform properly.

The same single fibres were used to determine fibre stiffness and cross-sectional fibre shape and from the results the relationship between fibre stiffness and cross-sectional fibre shape was examined. The differences in the flow rate required to deflect the fibre by same amount in stiffness measurement could not be explained by the cross-sectional shape of the fibres or the wall thickness. This means that the flow rate is highly dependent on the fibre structure, and that cross-sectional fibre shape cannot be used to predict fibre stiffness. This finding indicates that internal fibrillation occurs in the fibre walls during mechanical treatment of fibres. In the case of chemical fibres, internal fibrillation is the main effect of refining, although this has not yet been convincingly demonstrated in mechanically defibrated lignin-rich fibres.

INTRODUCTION

The challenge facing manufacturers of high-quality printing papers is to achieve excellent surface properties combined with high bulk. With modern paper machines and calendering techniques a lot can be done to develop the paper structure. However, in order to obtain the optimum paper structure both the fibre properties and the paper machine design must be adjusted properly.

Defibration affects not only the size of fibres but other properties too. During the defibration process, fibre properties change as a result of separation and further refining. The long fibres of mechanical pulps give the paper both desirable and undesirable properties. They improve bulk and stiffness but at same time reduce smoothness and opacity and increase fibre roughening. Long fibres also improve paper strength, which reduces the proportion of chemical pulp needed and hence improves the optical properties of the paper. The most common way to develop the bonding potential of long fibres is to treat them in a separate reject refiner. It is estimated that about 2/3 of the total refining energy is used in the development of fibre properties /1/.

The development of mechanical fibre structure during defibration is not yet properly understood. The existence of internal fibrillation /2-5/ has been verified in the case of chemical fibres, but so far no firm evidence has been presented to show that internal fibrillation occurs during mechanical defibration. It has been shown that during the defibration process, the fibre wall thickness decreases and the specific surface area of fibres increases /6-9/. Karnis /9/ has shown that fibre stiffness diminishes at the start of refining, but then remains constant. Only a little is known of how the layered fibre structure changes during defibration. According to Johnsen et al. /10/ only a few fibres with middle lamella are left after the first stage of refining. This indicates that the middle lamella is removed from the fibre surface in the early stage of refining, and that the outer layer of refined fibres is therefore the secondary wall.

The wall thickness of softwood fibres depends very much on the growing season. Thick-walled latewood fibres have been shown to cause surface problems in printing papers /11/. When different wood types were cyclically compressed, the latewood did not deform by the treatment /12/. This implies that the latewood absorbed less energy than the earlywood. Laurent et al. /13/ stated that after low-energy refining the surfaces of latewood fibres were more intact than those of earlywood fibres. The latewood content of the long fibre fraction has been shown to be dependent on the type of refining action: a single disc refiner removed latewood fibres from the long fibre fraction more efficiently than a double disc refiner /14/. The latewood content of the long fibre fraction has been found to fall during intensive reject refining /8,15/. Laamanen /16/ showed that there were more latewood fibres left in the long fibre fraction of groundwood than in pressure groundwood or thermomechanical pulp. However, it is not known how latewood fibres develop during defibration, despite the fact that their properties need to be developed in order to improve the surface properties of the paper with less calendering.

Based on the literature the following hypotheses can be put forward:

- The structure of mechanical fibres changes during the defibration process in a way that is characteristic of each fibre type, and these changes can be followed by measuring selected fibre properties.

- Defibration increases fibre flexibility by making the fibre walls thinner and loosening the fibre wall structure. The latter indicates internal fibrillation, even in the case of mechanical fibres.

- Latewood fibres develop more slowly than earlywood fibres.

The purpose of this study is to test the above hypotheses, in other words to determine how earlywood and latewood fibres undergo delamination and to establish the reasons for the flexibility increase.

EXPERIMENTAL

The development of earlywood and latewood fibres was monitored using the pulps rich in earlywood and latewood, which were further refined in a wing defibrator. The same single fibres were used to determine fibre stiffness and the cross-sectional shape and from the results the relationship between fibre stiffness and cross-sectional shape was examined.

Pulps

Pulps rich in earlywood and latewood, were obtained from mill rejects by fractionating using a hydrocyclone /17/. Both groundwood (GW) and thermomechanical pulp (TMP) were used. After separation the latewood content of TMP varied from 5 to 25% and that of GW from 8 to 50%. The pulps were refined in a wing defibrator in order to develop the fibre structure without fibre cutting /18/, Fig. 1. In the pre-heating stage, the temperature of the defibrator was raised to 140 °C. After steaming, the consistency of the pulp was 40%. The refining itself was unpressurized, the speed of the wing was 750 rpm and the specific energy of refining (SEC) 3-4 MWh/t. The raw material of the pulps was Scandinavian spruce.

The relationship between cross-sectional fibre shape and fibre stiffness was studied using two TMP samples taken after different degrees of refining. The fibre properties of the coarser sample were compared with those of the more refined sample. The more refined sample was a mill reject which was refined further in a wing defibrator (SEC of the wing defibrator 4.2 MWh/t).

Methods

The pulps were tested for their fibre, pulp and handsheet properties, Table 1. Handsheets (60 g/m^2) were made from both combined long fibre fractions (McNett +14 and 14/28) and short fibre fractions (McNett 28/48 and McNett 48/200), no circulation water was used and sheets were dried against a polished plate. They were tested according to SCAN standards.

Fibre stiffness was calculated from the flow rate required to deflect the fibre 50 μm and from the fibre width /19-21/. Fibre dimensions were measured from the cross-sections /22/. In the light microscope examination fibres were classified into three groups (Not fibrillated, Fibrillated, and Broken). Simons stain /23,24/ was used to indicate differences in the compactness of the fibrillar structure. Latewood fibres were identified according to Mork's rule /25/, which classifies a fibre as latewood if its double wall thickness seen in the light microscope is greater than its lumen width. Here the latewood content is given as a percentage of the number of fibres counted.

The shape and wall thickness of single fibres were determined from optical cross-sections using with a confocal laser scanning microscope (CLSM) /26/. The fibres were stained with acridine orange before measurement. Cross-sectional images of the coarse sample were obtained in the dry state using a 100x oil objective. Water was removed from the fibres using freeze-drying and the dried fibres were embedded in resin. Cross-sectional images of the refined sample were obtained in the wet state using a 40x dry objective. The moment of inertia was calculated from ten cross-sections taken from the same fibre, assuming the cross-sectional fibre shape to be between an ellipse and a circle.

Table 1. Microscopy techniques used to characterize changes in fibre structure.

Property	Method	State of fibres	Fibres
Latewood content	Light microscopy /25/	wet	800
Fibre wall thickness	Light microscopy /22/	dried	200
Stiffness	Hydrodynamic measurement /19/	wet	50
Fibre structure	Light microscopy using Simons stain /23/	wet	800
External surface	Light microscopy	wet	800
Cross-sectional shape	CLSM /26/	dried and wet	

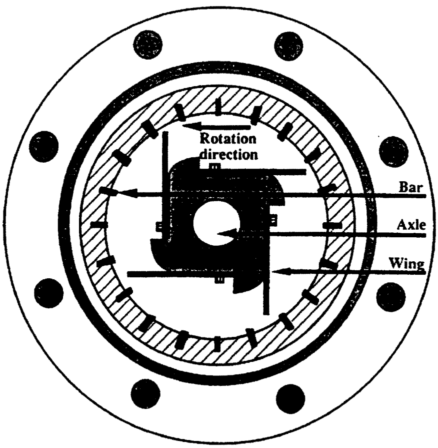

Fig. 1. Structure of a wing defibrator /18/. This is a batch type refiner in which the speed of the wings can be varied from 500 to 1500 rpm.

RESULTS

Changes in pulp and handsheet properties of earlywood and latewood fibres

Refining lowered the freeness of pulps rich in latewood faster than those rich in earlywood. The freeness of latewood TMP decreased by 436 ml while that of earlywood TMP decreased by only 55 ml. The same phenomenon was seen with GW. However, the fibre length, the proportions of the different McNett fibre fractions and the filtration resistance of short fibres were almost unchanged after refining.

The development of long fibres was investigated from handsheets made from combined McNett +14 and 14/28 fractions. The following properties of earlywood TMP handsheets made from long fibres changed during refining: density increased by 30%, tensile index by 60% and tear index by 68%. Similarly, the density of latewood TMP increased by 30%, tensile index 130% and tear index by 110%. Although the tensile and tear indices of latewood pulp improved during refining they were still lower than those of earlywood pulps. The density differences between handsheets of earlywood and latewood pulps were small. The light scattering coefficients of latewood pulps were significantly lower than those of earlywood pulps. Refining improved the light scattering properties of GW, but there was no improvement in tensile or tear index.

The tensile index of latewood short fibre fractions of TMP increased from 5 to 15 Nm/g. This indicates that during refining, particles with good bonding ability were formed from latewood fibres, although the filtration resistance of short fibres changed only a little.

Development of fibre properties

The latewood content of long fibre fractions was almost unaffected by refining, Figs. 2-3. Refining caused a slight reduction in the latewood content of TMP but a slight increase in that of GW. There was no difference between the latewood contents determined from the whole pulp or from the long fibre fraction, except in the case of earlywood GW. In the earlywood GW, most latewood fibres were present in the longest fibre fraction, the latewood content of McNett +14 being

29% and that of whole pulp 6%. GW shives contained mainly latewood fibres. Latewood GW contained 63% latewood shives and only 14% earlywood shives.

Fibre wall thickness and cross-sectional area were smallest in earlywood TMP and highest in latewood GW, Fig. 4. The fibre wall thickness of unrefined earlywood TMP was 3.8 μm and that of latewood GW 5.8 μm, latewood TMP and earlywood GW falling between the two. The wall thickness differences between the samples were retained after refining although the fibre walls were slightly thinner. The shape of the fibre wall thickness distributions also varied, the distribution of earlywood TMP being the narrowest, Fig. 5.

The differences in the latewood content of the long fibres were also seen as differences in the fibre width of samples, Fig. 6. Fibre width varied from 29 μm (latewood GW) to 38 μm (earlywood GW). The width of latewood GW fibres was reduced by refining while that of other samples remained the same.

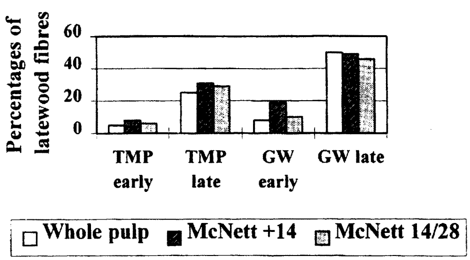

Fig. 2. Latewood content of different fibre fractions in earlywood and latewood pulps.

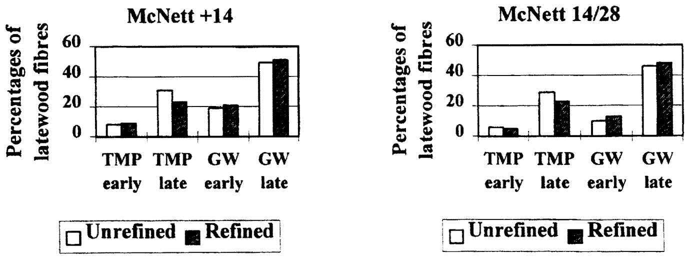

Fig. 3. Effect of refining on latewood content of earlywood and latewood pulps, McNett +14 and McNett 14/28 fractions.

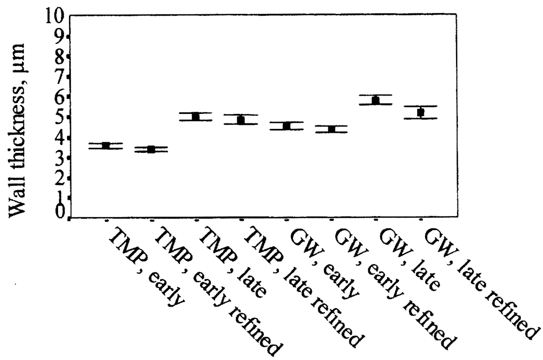

Fig. 4. Effect of refining on wall thickness of earlywood and latewood fibres, McNett 14/28.

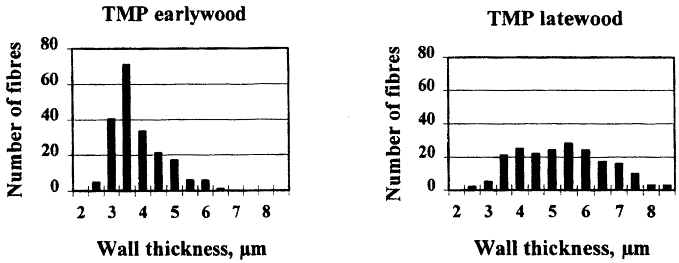

Fig. 5. Wall thickness distributions of unrefined earlywood and latewood TMP fibres, McNett 14/28.

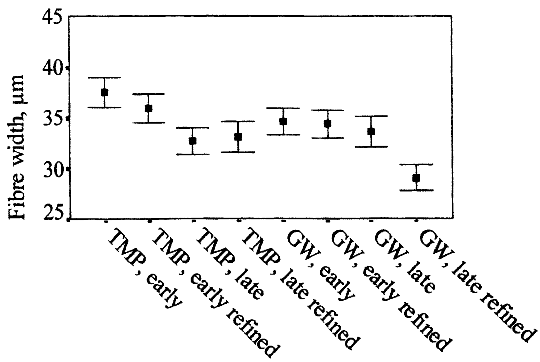

Fig. 6. Effect of refining on width of earlywood and latewood fibres, McNett 14/28.

Unrefined latewood fibres were about twice as stiff as earlywood fibres, Fig. 7. The stiffness of unrefined earlywood TMP fibres was around $20 \cdot 10^{-12}$ $1/Nm^2$ while that of unrefined latewood TMP fibres was $48 \cdot 10^{-12}$ $1/Nm^2$. This was seen for both TMP and GW. The stiffnesses of unrefined earlywood TMP and earlywood GW were the same. This also applies to the stiffnesses of unrefined latewood TMP and latewood GW. The stiffness of all fibre types was reduced by refining. The stiffness of latewood fibres fell to around the level of unrefined earlywood fibres. The flow rate required to deflect the fibre 50 μm in the stiffness measurement is presented in Fig. 8. With two minor exceptions, the order of the samples is the same in Figs. 7 and 8 indicating that the stiffness differences between the samples were not explained by the differences in fibre width. The flow rate distributions of latewood fibres were wider than those of earlywood fibres.

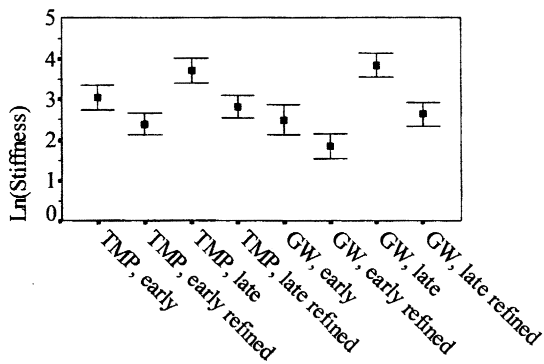

Fig.7. Effect of refining on stiffness of earlywood and latewood fibres, McNett 14/28.

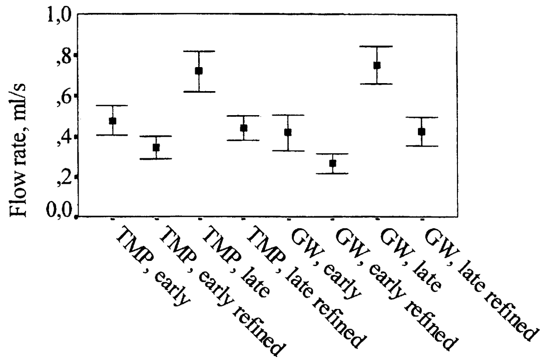

Fig. 8. Effect of refining on average flow rate required to deflect earlywood and latewood fibres by 50 µm in stiffness measurement, McNett 14/28.

The development of fibre structure and external fibre surface is shown in Table 3. Simons stain was used to detect changes in the fibre wall structure. It is assumed as the structure loosens, the yellow part of the stain penetrates into the fibre wall. Loosening is therefore indicated by an increase in number of yellow-stained fibres and a decrease in the number of blue-stained fibres. The yellow stain has a molecular size around 5 nm /27/. Refining loosened the fibrillar structure of all fibre types, but the number of blue-stained fibres remained high in the latewood pulps. It is not known whether the high content of blue-stained latewood fibres is due to the high compactness of the wall structure or to the optical effect caused by the thick fibre walls. Here, the number of colourless fibres in earlywood pulps was exceptionally high.

Refining clearly increased the external fibrillation of latewood fibres, but no changes were seen on the surfaces of earlywood fibres. The GW pulps contained more broken earlywood fibres than the other pulps, even before refining.

Sample	TMP Earlywood		TMP Latewood	Earlywood	GW Latewood		GW	
SEC, MWh/t	**-**	**4.1**	**-**	**4.3**	**-**	**3.0**	**-**	**3.4**
Latewood content, %	5	5	25	25	8	8	50	50
Pulp properties								
Freeness, ml	360	305	694	258	102	62	632	173
PFI shives, %	0.1	0.9	6.7	4.5	3.0	3.7	32.5	28.7
Fibre length, mm	1.88	1.82	1.31	1.24	1.02	0.96	0.78	0.70
McNett +14	22.8	27.9	1.3	1.7	10.4	6.2	1.2	1.0
14/28	40.8	33.5	28.4	26.5	24.8	22.7	14.2	12.8
28/48	16.7	15.2	39.7	35.8	17.3	18.4	28.9	30.4
48/200	11.8	12.3	28.4	26.5	24.8	22.7	14.2	12.8
-200	8.2	11.1	2.3	8.5	23.3	24.9	22.4	17.0
Filtration resistance, $m^2/g \bullet 10^{-8}$								
McNett 28/48	-	28	-	7	24	35	-	-
McNett 48/200	229	213	17	82	110	117	17	26
Handsheet properties, combined long fibre fractions McNett +14 & 14/28								
Density, kg/m^3	258	334	203	263	265	280	-	202
Tensile index, Nm/g	13.3	21.3	2.79	6.48	11.8	12.2	-	0.78
Tear index, mNm^2/g	5.7	9.6	1.1	2.3	4.6	5.3	-	0.32
Light scatt., m^2/kg	30.1	31.1	21.5	23.4	23.4	30.9	-	14.1
Opacity, %	87.8	92.0	82.6	88.8	88.2	91.9	-	82.7
Handsheet properties, combined short fibre fractions McNett 28/48 & 48/200								
Density, kg/m^3	475	539	242	315	478	483	256	294
Tensile index, Nm/g	51.8	51.9	5.1	15.3	43.7	38.6	2.5	5
Tear index, mNm^2/g	5.8	4.9	1.1	2.4	4.4	3.8	0.6	1
Light scatt., m^2/kg	49.7	47.7	30	35.1	63.6	63.2	29.1	31.2
Opacity, %	94.9	96.6	89.3	94.2	96.5	97.8	91.5	95.0

Table 2. Development of pulp and handsheet properties of earlywood and latewood fibres during refining.

Sample	TMP Earlywood		TMP Latewood		GW Earlywood		GW Latewood	
SEC, MWh/t	-	4.1	-	4.3	-	3.0	-	3.4
Simons stain, %								
Blue	28	18	48	45	28	17	61	48
Blue-greenish	29	25	24	20	28	37	20	28
Yellow	30	38	20	25	23	31	11	18
Colourless	13	19	9	10	21	15	8	6
Fibrillation, %								
Not fibrillated	52	49	51	41	32	30	51	37
Fibrillated	29	32	38	53	32	32	34	57
Broken	19	19	11	6	36	39	15	6

Table 3. Development of internal and external fibre structure of earlywood and latewood fibres in refining.

Relationship between stiffness and cross-sectional shape

Fibre stiffness is a function of the fibre's modulus of elasticity and moment of inertia. The moment of inertia in turn, is a function of cross-sectional fibre shape, in particular fibre thickness, whereas the modulus of elasticity is related to the material and the structure of fibre wall. In order to examine the relationship between fibre stiffness and cross-sectional fibre shape, both properties were measured from the same fibre. First the flow rate was measured using the stiffness measurement, and optical cross-sections were then imaged using the same fibre.

The repeatability of fibre deflection in the stiffness measurement was tested in order to see whether deflection causes changes in the fibre structure, Fig. 9. The deflection curves obtained for the fibres were identical, indicating that the deflection used did not affect the structure of fibres.

The flow rate for the coarse sample was 0.9 ml/s and that for the refined sample 0.5 ml/s, Table 4. High flow rates were obtained for coarse fibres with a high moment of inertia and those with a low moment of inertia, Fig. 10. In the case of the refined sample, low flow rates were obtained for fibres with very different cross-sectional fibre shapes. The same phenomenon was seen with flow rate and fibre wall thickness, Fig. 11. This indicates that the deflection ability of fibres is related to the fibre structure which can be changed during refining. This leads to the conclusion that fibre stiffness cannot be predicted from the cross-sectional fibre shape.

Sample	Coarse	Refined
Flow rate, ml/s	0.9	0.5
Fibre wall thickness, μm	3.9	4.1
Moment of inertia, μm^4	18200	16900
Fibre perimeter, μm	111	106

Table 4. Average properties of coarse TMP fibres compared with those of refined TMP fibres, McNett +14.

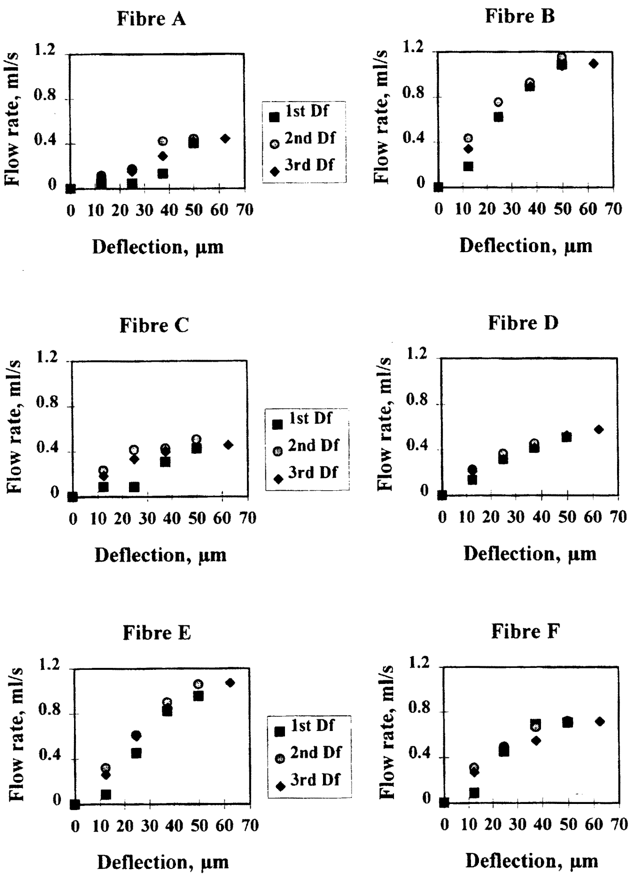

Fig. 9. Deflection curves of refined thermomechanical fibres, McNett +14. 1st Df represents the first deflection, 2nd Df = the second deflection and 3rd Df = the third deflection.

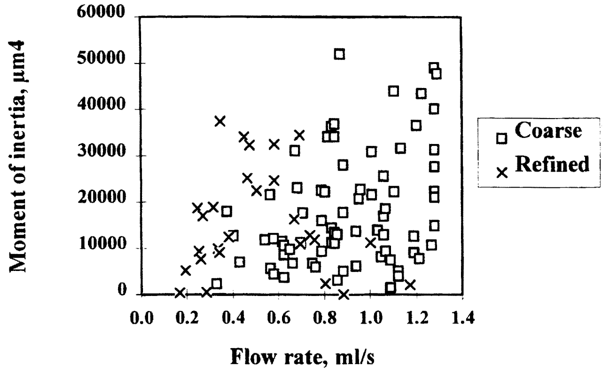

Fig. 10. Moment of inertia as a function of flow rate measured from coarse and refined fibres, McNett +14.

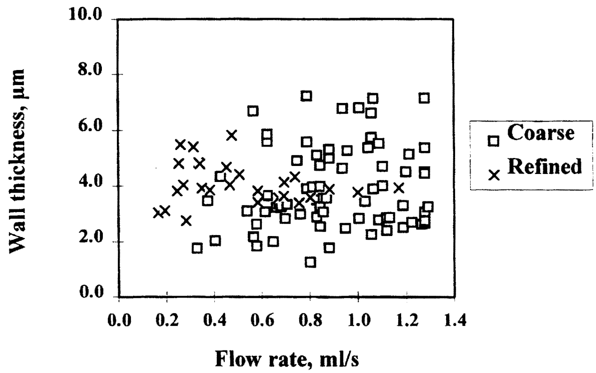

Fig. 11. Wall thickness as a function of flow rate measured from coarse and refined fibres, McNett +14.

DISCUSSION

The hypothesis that the structure of mechanical fibres changes during the defibration process in a way that is characteristic of each fibre type allowing these changes to be followed by measuring the properties of fibres, is valid. The refining used in this investigation developed the properties of fibres, as the fibre length and wall thickness remained the same. The changes in fibre structure were observed as an increase in fibre flexibility, a loosening of the fibre structure and fibrillation of the fibre surface.

Our hypothesis was that latewood fibres develop more slowly than earlywood fibres. We assumed that the high fibre stiffness and intact fibre walls of latewood fibres were the main reasons for the low bonding ability of unrefined latewood fibres. The result showed that the latewood fibres were stiffer than the earlywood fibres at the same specific energy consumption. Refining reduced the stiffness of latewood fibres to around that of earlywood fibres, while microscope examination showed that their external surface had become fibrillated. However, the tensile and tear indices of sheets made from these refined flexible latewood fibres were still lower than those of sheets made from unrefined earlywood fibres. Thus, in the case of latewood fibres there appears to be properties other than fibre flexibility and degree of external fibrillation which must be developed in order to get the fibres to conform and bond properly. One of these properties is evidently high wall thickness, which results in high fibre thickness. Thick-walled latewood fibres could have been assumed to give the paper some desirable properties such as bulk. However, this was not the case in this investigation. The densities of unrefined earlywood and refined latewood TMP were similar although their tensile and tear indices were completely different.

Refined fibres were more easily deflected than unrefined fibres by the water flow during stiffness measurement. Their greater flexibility was due to changes in the wall structure. When the relationship between cross-sectional fibre shape and flexibility was compared using the same single fibre no clear relationship was found between the cross sectional fibre shape and flow rate required to deflect the fibre or between fibre wall thickness and the fibre flexibility either. As stiffness is a function of both modulus of elasticity and moment of inertia, the results indicate that refining caused the decrease in the modulus of elasticity and that there exists internal fibrillation even in the case of mechanical fibres.

The wing defibrator used here is a laboratory refiner and its principle of operation differs from that of the pilot and mill-scale refiners. In earlier studies /8,15/ the latewood content and wall thickness of long fibres were found to decrease during intensive reject refining. The fact that fibre wall thickness and the content of latewood fibres in the long fibre fractions changed very little indicates that the refining action was more gentle than in industrial refiners. However, this refiner can be used to investigate the mechanism of refining. In earlier studies refining has been observed to make the fibre walls thinner and the fibres more flexible. Hence, it was not known whether fibre flexibility can be increased without some peeling of the fibre walls. In this study the flexibility of long fibres increased although their wall thickness remained the same. Thus the results suggest that the increase in fibre flexibility is a true refining effect that is also obtained in industrial refiners in addition to the peeling of fibre walls.

CONCLUSION

Refining changed the fibre structure, but not the size of fibres. An increase in fibre flexibility is an important refining effect. The decrease in fibre stiffness was due to changes in fibre structure and no decrease in wall thickness was required. The measurements obtained suggest that internal fibrillation also occurs in mechanically defibrated lignin-rich fibres.

The separate refining of pulps rich in earlywood and latewood, developed the properties of both pulps. The most significant changes were observed in fibre stiffness and in the external surface of latewood fibres. Refining lowered the stiffness of latewood fibres to the level of unrefined earlywood fibres but had only a minor effect on wall thickness; hence the differences in fibre wall thickness remained after refining. As the fibres became more flexible the tensile and tear indices increased. However, the tensile index of flexible latewood fibres was only half of that of unrefined earlywood fibres. This indicates that there are fibre properties other than stiffness or external fibrillation which must be changed in order to get latewood fibres to bond properly. It is assumed that the intensity of refining was too low to develop the properties of latewood fibres optimally. This should be further investigated.

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Transcription of Discussion

Changes in Fibre Wall Structure during Defibration

Tuulikki Lammi, Consultant, KCL, Finland

Ho Fan Jang, Scientist, Paprican, Canada

I have two questions. First, how did you measure the external fibrillations of the wall? Second, how did you obtain fibre cross-sectional images from which you calculated the moment of inertia. Were the fibres in a wet state?

Tuulikki Lammi

It is how many fibrils along the fibre which determines whether it is fibrillated or not.

Ho Fan Jang

So this is a direct observation then?

Editors note: Gary Baum answered this question and said that it is a qualitative light microscopic method.

Tuulikki Lammi

Yes. The cross section was measured by freeze drying and also in the wet state because you can measure mechanical fibres in wet state with the CLSM. They were of course stained beforehand in order to produce enough fluorescence.

Ho Fan Jang

You have also measured fibre coarseness from the images of the fibres? Were they freeze dried?

Tuulikki Lammi

Yes.

Dr Gary Baum, Vice President - Research, IPST, USA

A point of clarification, did you measure the moment of inertia for each cross section or did you use an average cross section?

Tuulikki Lammi

It was an average of moments of all cross-sections according to FEM.

Stuart Loewen, Associate, LSZ Paper Tech Inc, Canada

Did you assume that the fibre was actually symmetric in terms of moment of inertia and impact on bending stiffness calculations?

Tuulikki Lammi

The two ellipses were defined and they went through the centre of gravity.

Mukhtar Hussain, Senior Consultant, Omni Continental, Canada

Fig 4 in your paper showed that TMP late wood has the same wall thickness as SGW early wood.

Tuulikki Lammi

They are from quite different defibration processes so you can see the actual effect of defibration conditions and these groundwood early wood fibres have thick fibre walls compared to the TMP earlywood.

Mukhtar Hussain

Are you implying that SGW will give pulp with larger wall thickness

Tuulikki Lammi

Yes. For this study we have only taken the whole fibres of long fibre fraction. In ground wood there are lots of split fibres with sections of wall missing and the weight of the fibre can be less than that of TMP fibre. We measured cross sections of only whole fibres.

Mukhtar Hussain

My understanding is that SGW should have better fibrillation and reduced wall thickness. - is this the case?

Tuulikki Lammi

We have been looking only at the long fibre fraction. TMP and ground wood have very different kinds of fibre fractions in the pulps. We were just concentrating on the long fibres

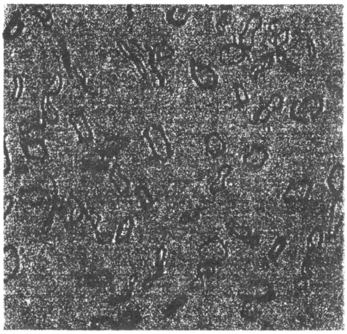
Mukhtar Hussain

So you are saying that this result only applies to the long fibre? If you take the whole pulp the results will be the opposite?

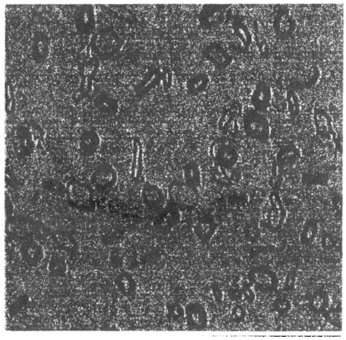
Tuulikki Lammi

Yes it could be.

Editors note Gary Baum requested new Figure from Tuulikki Lammi (see below)



TMP, earlywood-rich



TMP, latewood-rich

Cross sections of fibres made of unrefined earlywood-rich and latewood-rich TMP samples, Mcnett 14/28. Length of line = 100 μm

Mark Kortschot, Associate Professor, University of Toronto, Canada

I think there are two possibilities for the change in moment of inertia which you show. Either the wall was internally fibrillated or is it possible that when the fibres are actually deforming in the flow field that the tube collapses and so the moment of inertia is reduced and then the tube recovers once the fibres are removed from the flow?

Tuulikki Lammi

Yes, that is possible.

Borje Wahlstrom, President, Borje Wahlstrom Inc, USA

Why did you choose to do the refining at low intensity? There is a lot of work that shows that if you want to decrease wall thickness and flexibilize the fibres high intensity refining is the way to do it.

Tuulikki Lammi

With low intensity refining we could see that we could increase the flexibility without decreasing the wall thickness but these are two separate effects and this is why we chose low intensity refining.

Borje Wahlstrom

So it was not looking for the best method, it was finding out what the mechanisms were?

Tuulikki Lammi

Yes.

Thad C Maloney, Research Scientist, Helsinki University of Technology, Finland

Do you feel that the fibre flexibility might be related to the delamination of the cell wall and do you have a way to study this?

Tuulikki Lammi

Yes - it is related to the delamination of the cell wall but we do not have any measurements of the mechanical fibres to show this.

Gary Baum

Can you use your CLSM to do this?

Tuulikki Lammi

Yes - but it is harder to see than with mechanical fibres because it is on such a smaller scale. You can see delamination of chemical fibres with CLSM but not that of mechanical fibres, because it is on a smaller scale.

Dr Richard Bown, Director, ECC, UK

You showed a graph of light scattering coefficient which showed an increase in light scattering when you refined the pulp. You could look at light scattering as a function of wave length which would give you some indication of the size of the scattering elements. Does that not give you some indication of what is changing in these fibres?

Tuulikki Lammi

Yes. it tells us how this external surface is changing but it is also related to the bonding.

Richard Bown

I think it may also support your idea of internal delamination which would lead to an increase in light scattering coefficient due to elements of a size similar to that of the fibre laminates.