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REFINING CHARACTERISTICS OF SOFTWOOD FIBRE FRACTIONS

Kari Koskenhely,[1] *Ari Ämmälä,*[2] *Hanna Jokinen*[2]
and Hannu Paulapuro[1]

[1]Helsinki University of Technology, Laboratory of Paper Technology
[2]University of Oulu, Laboratory of Fibre and Particle Technology

ABSTRACT

The role of refining intensity and specific energy in refining of softwood kraft fibre fractions was studied. Several paper properties can be improved by selective refining of fractions. The tensile strength-dewatering resistance relationship benefits from low-intensity refining of the long-fibre fraction. The specific energy input determines the increase in fibre swelling which contributes to a higher sheet density and improved tensile strength. The apparent density-roughness relationship benefits from mild refining of the short-fibre fraction. Refining intensity has a strong effect on the magnitude of the gap between bar surfaces, on fibre shortening, and on the coarseness of fibres with high cell wall thickness. For the short-fibre fraction, which appeared to flocculate less, the maximum intensity causing "pad collapse" and more severe fibre shortening was lower than for the long-fibre fraction and feed pulp. The fraction-specific intensity and gap behaviour are believed to relate to the compressibility of flocs under the stress applied by bar surfaces – a phenomenon discussed in recent studies concerning the forces acting on fibre flocs.

INTRODUCTION

Chemical pulp fractionation combined with selective refining of the resulting fractions can improve the papermaking potential of fibres. The idea of this method is to separate the most suitable fibres for optimum mechanical treatment and for use in a specific paper product or layer of multiply paperboard. During the past ten years, fractionation of chemical pulp has been increasingly studied for the purpose mentioned above. Paavilainen [1] and Vomhoff and Grundström [2] used a hydrocyclone in fractionating bleached softwood kraft (SWK) and Sloane [3] used a pressure screen in processing kraft pulp. Jones et al. [4] studied the papermaking potential of early- and latewood fractions which were separated with the aid of centrifugal cleaners. In addition, several authors have studied mechanical pulp fractionation combined with refining of the resulting fractions, analysing the development of fibres and the properties of the fractions [5, 6, 7, 8]. These studies showed the potential of fractionation. For example, cell wall thickness (CWT) was found to be the most important fibre property for SWK reinforcement pulp, because CWT affects the flexibility and collapsibility of fibres, which subsequently affect paper strength [1]. Another study showed that the fractions after refining may have significantly different strength properties when compared at a given specific energy [2]. Despite these studies, only limited information can be found on how the different SWK fractions should be selectively refined to further improve the properties of paper produced from fractionated kraft pulp, and whether the behaviour of the fractions in refining differs. The term refiner behaviour refers to the magnitude of the gap and the ability of the fractions to tolerate the stress applied to the fibre flocs between the bar surfaces. Preliminary tests made before the present study indicated that the maximum refining intensity differed significantly for different screen-fractionated SWK fractions. Thus, it was assumed that more knowledge about the varied refining intensity and refiner gap might clarify the mechanisms behind the structural changes in fibres and the development of handsheet properties of fibre fractions.

In fractionation, the feed pulp is usually separated into a fine and a coarse fraction using a hydrocyclone or a pressure screen. The fractions produced by a hydrocyclone differ mainly in terms of CWT [1]. Pressure screening is the most efficient process to fractionate fibres by length [9, 10]. On the other hand, a change in fibre length and coarseness causes a change in flocculation, so that the number of contact points per fibre grows if fibre length increases or coarseness decreases. As a results, the floc network strength increases. At the contact points, several types of cohesive force exist: colloidal forces, mechanical surface linkage and elastic fibre bending. For example, fibre length, fibre stiffness and fibrillation affect the magnitude of these forces [11].

Fibre flocculation has an important role in low-consistency refining. It was identified long ago by Page et al. [12]. Also Banks [13] and Ebeling [14] succeeded in catching images of flocs between bars. Different gap widths for short- and long-fibre pulps have been reported by Watson and Phillips [15]. McKenzie and Prosser [16] have suggested that the design of the refining system should take into account the initial state of the pulp, and how it is affected by the refining process, in other words, whether the pulp is initially present as large flocs or whether its flocculating ability is significantly affected by the refining operation. Later, Hietanen [17] showed that the refiner gap increases when flocculation increases. The floc refining theory suggests that flocs are formed and broken up continuously under the shear forces originating from the rotating refiner fillings [18]. Consequently, fibres are refined as fibre flocs rather than individual fibres. The role of fibre flocs and forces acting on flocs in refining have been recently examined [19, 20, 21]. Atack [22] proposes that between refiner plates the magnitude of any pressure pulse is determined by the relevant thickness and compressibility of the agglomerate, and that it is associated mainly with the passage of the leading edge of a bar over its surface.

The objective of the present study was to find out whether the short-fibre (SF) and long-fibre (LF) fractions of pressure-screen-fractionated SWK and fine (FF) and coarse (CF) fractions of hydrocyclone-fractionated SWK should be refined at the same intensity as the feed pulp (SWK) or at a totally different intensity when looking for optimal paper properties. An effort was made to link the behaviour of the refiner gap caused by varied refining intensity and specific energy to the floc properties under compression, and to the observed structural changes in fibres.

MATERIALS AND METHODS

Pulps and analysis

A bleached softwood kraft pulp from a Finnish pulp mill was fractionated and selectively refined. The dry content of the pulp was 95 %. The pulp was a mixture of 44 % spruce (Picea abies) and 56 % pine (Pinus silvestris). Handsheets of 65 g/m^2 were produced from the feed pulp and from accept (SF and FF) and reject (LF and CF) fractions according to SCAN standards. Handsheet properties were measured according to SCAN standards, except Scott internal bond strength, which was measured according to the TAPPI T833 pm-94 standard. The SR value and pulp consistency were measured according to SCAN standards. Fibre length was measured with a Fiberlab apparatus designed by Metso Automation. The fibre saturation point (FSP), which indicates the total amount of water in the cell wall, was measured with the solute exclusion method [23]. In measuring the pore size distribution of the cell wall, the thermoporosimetry method was used [24]. FSP and thermoporosimetry were measured for the fibre fraction, with the P200 fines washed away in a Dynamic Drainage Jar. The same equipment equipped with a 200 mesh wire was used to measure the fines content of the hydrocyclone fractions. Unrefined fibre cross-sections were examined with an Environmental Scanning Electron Microscope from fibre cross-sections embedded in an epoxy-based resin, and cell wall thickness was measured using a Euclidean distance map, which measures the smallest distance of every point of the fibre skeleton to the fibre edge, giving the average cell wall thickness around the perimeter.

Fractionation

The pulp fractionations were performed at the University of Oulu. The aim of fractionation was to produce strong fractionation effects, i.e. large differences in fibre length between the accept and reject from screening, and in the earlywood / latewood contents from the hydrocyclone. In practice, this meant pronounced reject thickening behaviour in fractionation. Before the fractionations, dry pulp sheets were slushed with a retention time of 25 min in a Grubbens pulper at a consistency of 3 %. After fractionation, the dilute fractions were thickened using a bow screen and a belt wire thickener to a dry content of about 20%. During thickening, a small amount of primary fines was possibly lost, but the effect on the pulp was considered to be insignificant. After thickening, the pulp fractions were stored in a cold room at a temperature of 4°C. About 6 kg o.d. of each short-fibre, long-fibre, earlywood and latewood fraction was needed for the refining study.

Pressure screen fractionation

The pressure screen fractionation was carried out with a small pilot device, incorporating a 300-litre feed tank and a Metso FS-03 pressure screen. The diameter of the screen basket was 0.11 m with a screening area 0.03 m^2. The screen had a foil-type rotor with adjustable rotational speed. In order to achieve a reasonable fibre length difference in single-stage fractionation, the following screening conditions were chosen: a narrow slot width of 0.09 mm and a relatively smooth contouring of the screen plate with a profile height of 0.8 mm. A low feed consistency of 0.82% was used to achieve high reject thickening without blinding of the screen plate. The practical slot velocity for stable running was adjusted to 1.0 m/s with the foil tip speed of 16.5 m/s. The volumetric reject rate was kept constant at 25%. The pulp temperature was 28 °C. Because of the limited capacity of the screen fractionation process, several batches had to be run. The consistency and temperature of the feed pulp were measured and adjusted for every batch and operating parameters were kept equal.

Hydrocyclone fractionation

The hydrocyclone fractionation was performed using pilot-scale equipment, a feed tank of 12 m^3, and an industrial-scale GL&V Celleco Cleanpac 270 fractionating hydrocyclone. Inlet and outlet flow rates and pressure levels of both fractionation processes were controlled by adjusting the rotational speed of the feed pump and valves in the accept and reject lines. The volumetric flows and the pressure levels were monitored with magnetic flow meters and pressure gauges mounted in the feed, accept and reject pipes.

The hydrocyclone fractionation was conducted in two stages, directing the reject of the first stage to the second stage. At the second stage, the hydrocyclone accept was circulated back to the feed tank, while continuously removing reject, i.e. the coarse fraction (CF), until the chosen mass reject rate was achieved. The accept of the first stage formed the fine fraction (FF). Low feed consistencies, 0.24% in the first stage and 0.26% in the second stage, were used to ensure a strong enough fractionation effect. The pressure drop in the first stage was 260 kPa and in the second 285 kPa. Volumetric reject rates were constant at 6% and 4%, and the correspondent mass reject rates were 30% and 25%. The pulp temperature in both stages was 23 °C.

Refining

A Voith LR 40 laboratory refiner with disc configuration was used to treat the fibres. The operating principle of the refiner has been described by Sepke, Pott and Melzer [25] and by Wultch and Flucher [26]. The specific edge load (SEL) theory [26, 27] was applied to control refining intensity. Plate fillings of 3.6-4.4-4.7–30° were used. Specific energy was calculated from the net power, from the pulp mass left in the system and from the refining time. The actual refining parameters are given in Appendices 1 and 2. The rotation speed of the rotor filling was 2000 rpm, with the stator filling moving and closing the refiner gap. Its position was recorded, and the position value was used to indicate changes in the gap width. The absolute gap was not known. Before the actual refining series, the maximum intensity for the SF, LF, and SWK fractions was mapped. The mapping was executed in 0.5 J/m steps, since the amount of fractionated pulp was limited. The accepted maximum intensity was one step downwards from the intensity at which the motor load of the refiner started fluctuating. The fractionation and refining of pressure screen-fractionated pulp was executed first and the hydrocyclone-fractionated pulp was produced and refined about 6 months later. Before the hydrocyclone series, the fillings were reconditioned with a mixture of pulp and 320 mesh silicon carbide powder.

To describe the fibre flocculation numerically, the crowding factor (N) of the pulps was calculated based on Equation (1), put forward by Kerekes and Schell [28]. For pulp fibre suspensions it is often convenient to use mass consistency, C_m, fibre length, L, and fibre coarseness, ω, to compute N. C_m is expressed in %, L in m and ω in kg/m. N was calculated both for unrefined fractions and for refined test points using the measured values presented in Appendices 1 and 2.

$$N \approx \frac{5C_m L^2}{\omega} \tag{1}$$

RESULTS AND DISCUSSION

Fractionation

Pressure screen fractionation

In pressure screen fractionation, the volumetric reject rate was 25% and the mass reject rate 63%. Thus, the reject thickening factor was 2.5, indicating strong fractionation. The SF fraction had an average fibre length of 2.01 mm, while the LF fraction had a fibre length of 2.45 mm, as shown in Table 1. The fractionation result was reasonable, taking into account the quite narrow fibre length distribution of the original pulp. The corresponding fibre length difference could also be used in industrial fractionation with pressure screens. For capacity reasons, however, elevated feed consistencies would be needed, which results in multi-stage fractionation. As illustrated in Table 1, the CWT and the latewood content of the SF fraction were lower than those of the LF fraction and SKW. Typically, fibre length and coarseness correlate, so that longer fibres are coarser [29]. A part of the fractionation result may originate from the tendency of slotted screen plates to classify fibres of equal length according to their flexibility.

Table 1 Properties of unrefined feed pulp, SF fraction, LF fraction, FF fraction and CF fraction.

Fraction	Fibre length lw (mm)	Coarse-ness (mg/m)	FiberLab CWT (μm)	ESEM CWT (μm)	ESEM Diameter, (μm)	Early wood (%)	Late wood (%)	Inter-mediate (%)
Pressure-screen F.								
Feed pulp, (SWK_Ps)	2.27	0.158	5.90	2.32	32.96	80	20	2
Short-fibre-fraction (SF)	2.01	0.153	5.60	2.22	33.15	85	15	3
Long-fibre-fraction (LF)	2.45	0.171	6.30	2.57	32.39	78	22	2
Hydro-cyclone F.								
Feed pulp, (SWK_Hc)	2.30	0.159	6.30	2.30	32.65	83	17	0
Fine-fraction (FF)	2.23	0.158	5.95	2.34	31.83	83	17	0
Coarse-fraction (CF)	2.33	0.196	6.40	2.42	32.21	74	26	0

Hydrocyclone fractionation

The volumetric reject rates of the hydrocyclone fractionation stages were 6 % and 4%. The mass reject rates were 30% and 25% and reject thickening factors 5.5 and 6.3, indicating strong fractionation. The total mass reject rate of the two-stage system was 14.5% of the original feed pulp. As shown in Table 1, the coarseness, CWT and latewood content of the CF were higher than those of the FF. The mean fibre lengths of the CF and FF are close to each other. This is an expected result, as a hydrocyclone has been found to fractionate fibres based on their density when fractionating unrefined pulp and based on the specific surface when fractionating refined pulp, and fibre length is in a secondary role in the separation [30].

Structural changes in fibres and related handsheet properties

Fibre shortening,

The fibre shortening for a specific fraction was most severe at the highest intensity. For SF the critical refining intensity enhancing fibre shortening was 2.4 J/m, and for all the other fractions 3.7 J/m, as illustrated in Figure 1.

Fibre breaking by tensile-type stress has been proposed as the mechanism behind fibre shortening. Page [31] has stated that fibre flocs are trapped and compressed between bar surfaces, that fibre shortening is due to the high

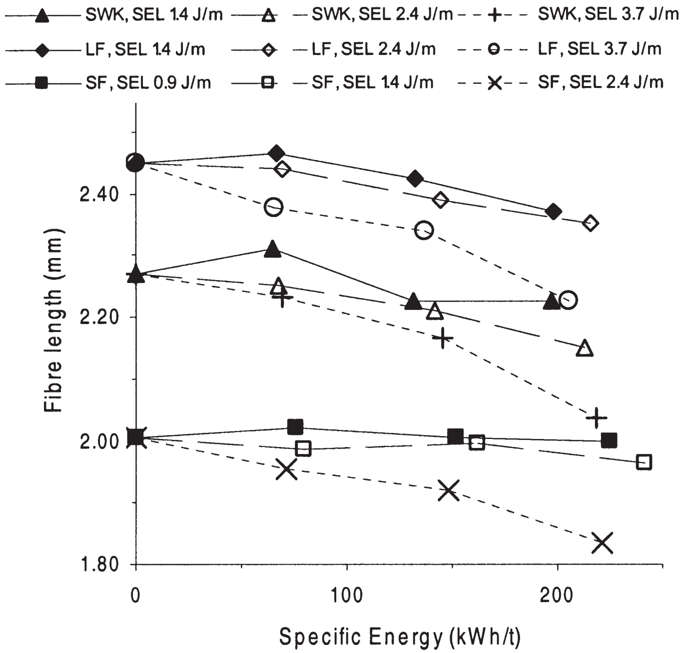

Figure 1 Effect of specific energy and intensity on average fibre length of pressure screen fractions.

tension of fibres in the centre of the floc caused by shear forces, and that this tension may exceed the fibre strength. Kerekes and Olson [32] have concluded that fibre rupture is a single-event phenomenon rather than a fatigue process. Stephansen [33] has suggested that cutting is due to squeezing of fibres between the bars, and that the actual bar edge is not sharp enough to actually cut the fibres. Stephansen [34] confirmed this by replacing the leading edge by vulcanized rubber; fibres appeared to accumulate on the rubber edge but they were increasingly broken between the narrower metal section of the bars and the bedplate. However, he also found that increasing speed of the laminar pulp flow which hits the edge decreases the amount of fibrage. It appears that the role of the actual bar edge in trapping the end of the fibre or the fibre floc and in causing tension stress still remains partly unclear. Mckenzie and Prosser [16] showed that merely moving a fibre floc back and forth between two microscope slides under pressure may shorten the fibres. On the other hand, studies of abrasive filling surfaces have shown increased fibre shortening. In order to avoid excessive fibre shortening, the role of the bar microprofile, i.e. bar edge roundness and roughness, in fibre shortening should be studied further.

Fibre swelling

The specific energy proved to be the parameter explaining the opening of the pores of the fibre cell wall for all fractions. An increase in specific energy increased the amount of pores whose size was above approximately 50 nm, and the total amount of water held in the cell wall also correlated with specific energy. Interestingly, the type of fraction or refining intensity applied did not affect the opening of micropores nor the level of total fibre swelling. An example is given in Figure 2 which shows the pore size distribution of pressure screen fractions refined at 2.4 J/m intensity.

The most intense increase in swelling occurred at the beginning of refining,

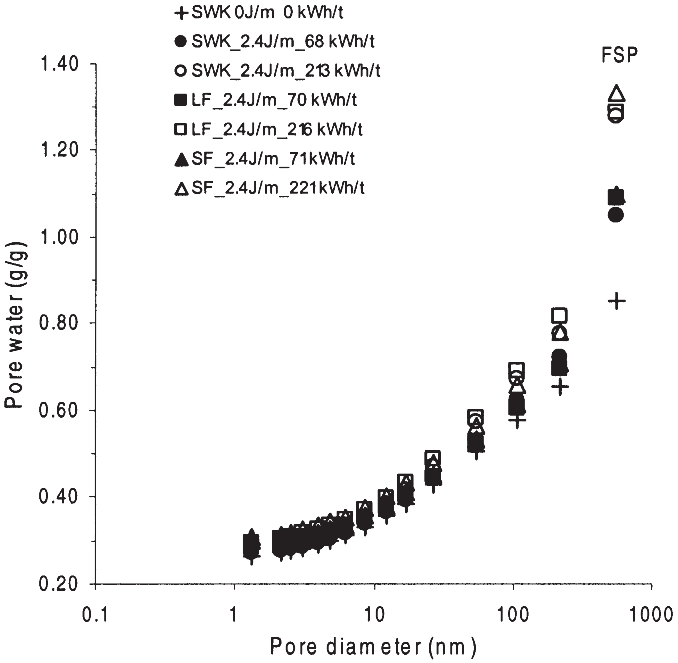

Figure 2 Characteristics of pore size distribution and fibre saturation point of pressure screen-fractionated pulp. Fractions refined at 2.4 J/m intensity.

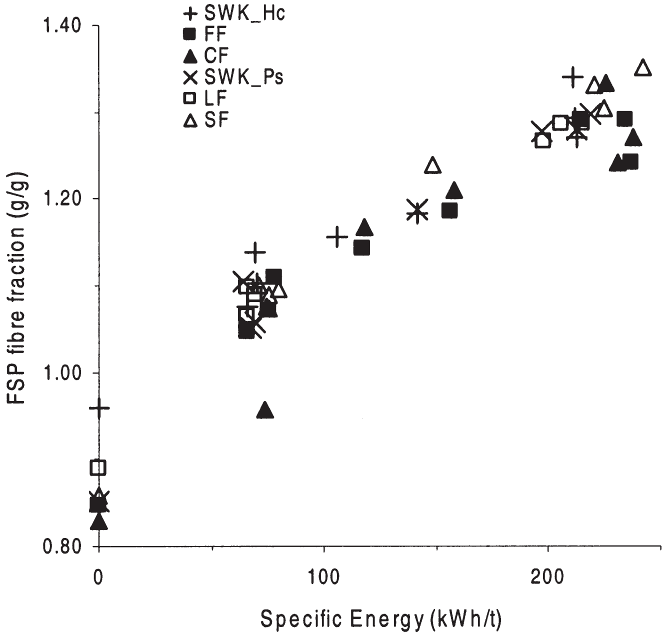

Figure 3 FSP versus specific energy of all the fractions. The symbol SWK_Hc refers to the feed pulp for the hydrocyclone fractionation and SWK_Ps to the feed pulp for the pressure screen fractionation.

and later the slope angle of the swelling curve measured by FSP decreased slightly. Figure 3 shows the fibre saturation point versus specific energy for all fractions refined at different intensities. Nanko et al. [35] called the former phase initiation and the progress of S1 and S2 delamination. When refining energy is increased further, external fibrillation continues, and presumably part of the fines that are generated as external fibrils are loosened from the fibre frame. In a study conducted by Stone et al. [36], kraft fibre walls were found to swell slightly at the start of refining and then remain constant.

Fibre swelling is important for the development of sheet density and tensile strength. On the other hand, specific energy is a combination of the number of impacts and their intensity [37, 38]. In view of this, increased swelling and tensile strength are achieved most energy-efficiently at the highest possible intensity and with a low number of impacts. However, increased refining intensity may be detrimental to fibre length, which impairs strength. For the mechanical treatment made in a low-consistency refiner with symmetric bars and grooves the dilemma remains whether the number of impacts could be increased energy-efficiently. Increasing pheripheral speed would be a theoretical option, but in this case the no-load power would increase too.

Other structural changes: coarseness reduction, fines formation, and Shopper Riegler of pulp

The CF fraction displayed a greater tendency to form fines than FF. Most of the fines values were measured at 2.4 J/m, and only for hydrocyclone fractions. Fines values measured at 3.7 J/m did not indicate a greater tendency to form fines. Increased specific energy increased the fines amount of CF, FF and SWK at over 100 kWh/t specific energy. The results are in accord with those given in Paavilainen's [1] study, though the accuracy of the fines measurements of this study was comparatively rough. According to Paavilainen [1], an increase in cell wall thickness makes the fibres more susceptible to fines formation, external fibrillation and fibre shortening.

Fibre coarseness decreased strongly when CF was refined at a high intensity of 3.7 J/m. Interestingly, FF refined at low intensity and high specific energy gave the lowest coarseness value of all the points, but this was not reflected as increased fines or increased Scott internal bond strength. All in all, intensity did not affect coarseness systematically as it affected fibre length; instead coarseness was mainly reduced by specific energy. At high specific energy, low-intensity refining at 1.4 J/m produced a slightly lower Shopper Riegler value for LF, CF and FF.

Impact of fibre structural changes on handsheet properties

Refining increases fibre swelling, which further increases sheet density, which appears best to explain the tensile strength of all the fractions. Figure 4 illustrates tensile strength versus sheet density for all the fractions. In addition to swelling of fibres due specific energy, the development of handsheet density appeared to depend partly on some other mechanism, since at the same FSP the CF fraction gave slightly lower density. The greater cell wall thickness and fibre stiffness of CF possibly affected the conformability of fibres when the sheet was formed, though stiffness was not actually measured.

Both the tear strength of an unrefined fraction and the maximum tear of refined fractions depended on the type of fraction used. Both SF and FF had high unrefined tear, but when a low specific energy of 75 kWh was applied, the maximum tear did not increase to the level of LF and CF, which gave the

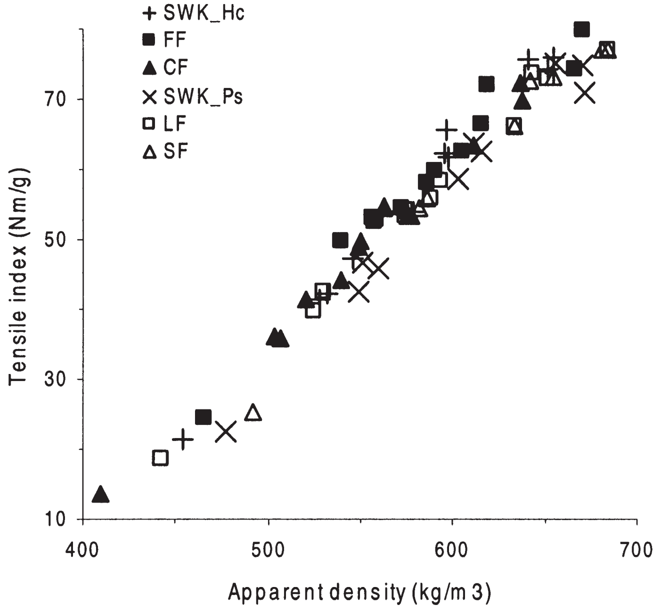

Figure 4 Tensile strength versus apparent density.

highest tear values. Whether the maximum tear of SF and FF may have developed already below 75 kWh/t could not be concluded. Simultaneously, SF and FF had lower coarseness than LL and CF, but the zero-span tensile strength of FF did not differ from the zero-span strength of CF. Paavilanen [1] concluded that a coarse fraction gives a higher tear than a fine fraction. Jones et al. [4] found the same type of result; at a given freeness, a latewood fraction gave higher tear strength.

Increased fibre shortening was detected at the highest refining intensity. However, higher intensity affected tear only at a high specific energy, and only for LF, CF and SWK fractions. In addition, CF showed lower maximum tear when it was refined at the highest intensity. Simultaneously, the CF fraction also experienced the strongest coarseness reduction, which was also reflected as reduced zero span tensile strength at higher specific energy. Seth and Page [39] have reported that among fibres with similar strength, coarser fibres produce sheets with higher tearing resistance, and that in a poorly-bonded sheet tearing resistance depends more on fibre length than on fibre strength.

Handsheet properties indicating papermaking potential

Figure 5 shows the tensile index versus SR for pressure screen fractions. When a low amount of specific energy (66–80 kWh/t) was applied to the LF fraction at a low intensity of 1.4 J/m, tensile strength increased the most. The tensile strength of the LF fraction increased from 19 to 54 Nm/g, whereas the tensile strength of the SF fraction increased from 25 to 54 Nm/g, even when a little more energy was applied. In addition, the dewatering resistance of the 198 kWh/t refined LF fraction reached about the same level as that of the 162 kWh/t refined SF fraction. It should be noted that the SR of the unrefined LF fraction was the lowest; for unrefined pulp the difference between LF and SWK was 1.5 units. At low-intensity refining of hydrocyclone fractions, the dewatering resistance-tensile strength relationship was not significantly affected by the type of fraction, but mainly by specific energy.

The CF fraction needed a higher energy input both to increase SR and tensile strength. At the same specific energy, the tensile strength of CF was lower than that of FF, but the density and tensile strength of the coarse fraction could be improved by increasing the specific energy input. At the

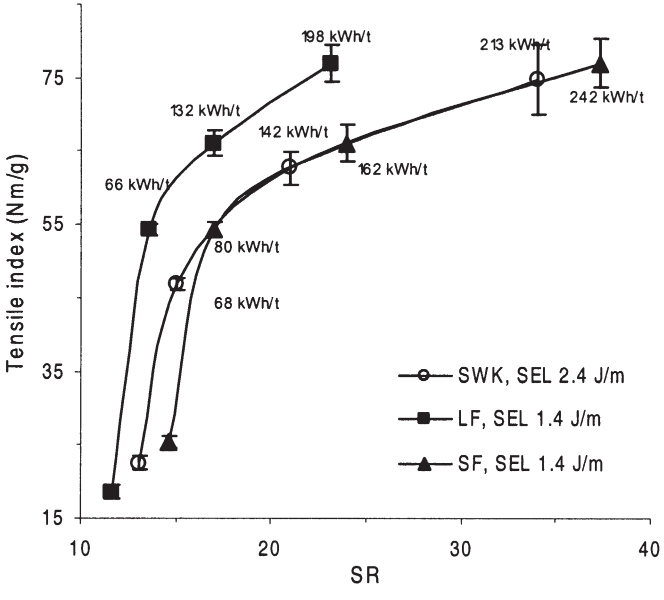

Figure 5 Characteristics of dewatering resistance (SR) – tensile index combination of pressure-screen fractions. The best intensity for the specific fraction was selected.

same tensile strength, the light scattering coefficients of FF and SWK were higher than that of CF. In a study by Vomhoff and Grundström [2], similar behaviour is reported. At a given strength level, the light scattering of the fine fraction is higher, which is favourable for the optical properties of the sheet. Paavilainen [1] explains the difference in light scattering between coarse and fine fractions by the different number of fibres in a sheet of a specific grammage. The number of coarse fibres is lower and there are fewer scattering surfaces.

Figure 6 shows apparent density versus roughness of pressure-screen fractions. At a given density, the roughness of the untreated and mildly refined SF fraction was lower than the roughness of the two other fractions. When the amount of refining of SWK was increased, its roughness approached the values of the SF fraction. Since refining the pulp further will increase the dewatering resistance and the risk of bulk loss, it would be advisable to refine

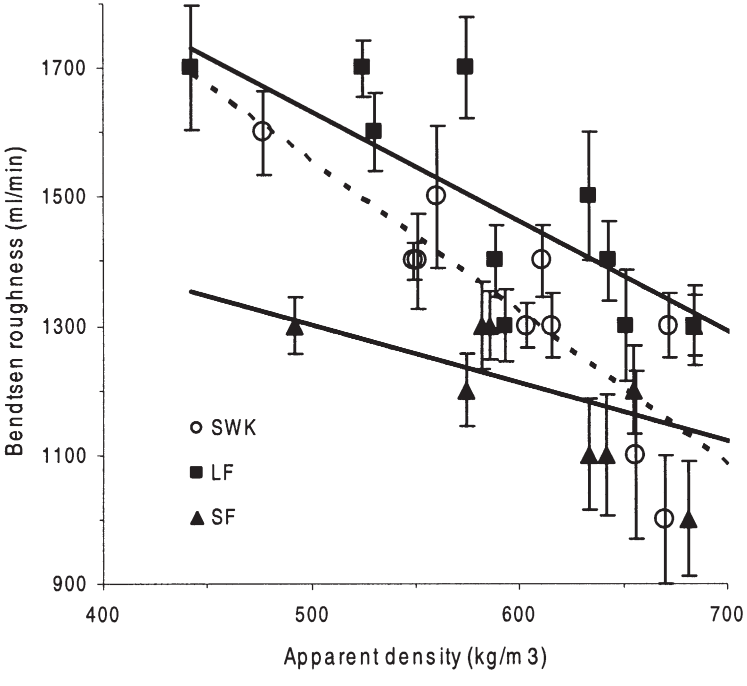

Figure 6 Characteristics of density-Bendtsen roughness combination of pressure-screen fractions.

the SF fraction only mildly, and thus maintain a low dewatering resistance and yet obtain sufficient smoothness. In addition, a mild specific energy input results in a significant strength improvement. A short-fibre-type component could be utilised to improve the surface smoothness for example of a layer of multiply paperboard. When the Bendtsen roughness and permeability of handsheets produced from hydrocyclone fractions were compared at a given density, no improvement in these properties was detected between the different fractions.

Refiner behaviour

Impact of refining intensity on gap

Figure 7 illustrates how the position of the stator changed when refining intensity and specific energy for pressure screen fractions were varied. At a given intensity, the gap of SF was narrowest. At an intensity of 1.4 J/m, the average gap was 66 μm narrower for the SF fraction than for SWK, and for

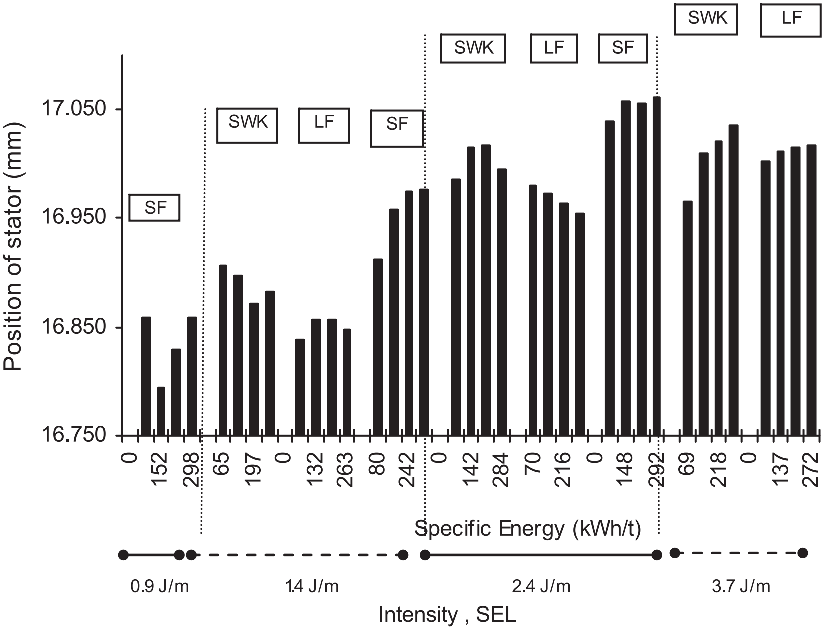

Figure 7 Changes in gap width (position of stator) for pressure-screen fractions refined under varying intensity and specific energy.

the LF fraction the average gap was 106 μm wider than for the SF fraction. At a refining intensity of 2.4 J/m, the corresponding differences were 50 and 86 μm.

After fractionation, the pressure screen fractions differed mainly by fibre length, but a slight increase in coarseness and CWT for LF was detected. The average fibre length for LF was 2.45 mm, for SF 2.01 mm, and for SWK 2.27 mm. The correspondent coarseness values were 0.171 mg/m, 0.153 mg/m, and 0.158 mg/m. The cell wall thickness for LF was 2.57 μm, for SF 2.22 μm, and for SWK 2.32 μm mm, as shown in Table 1. Moreover, the consistency of pressure screen pulp varied because of pulper leakage. All these parameters affect flocculation. A visual assessment of the SF pulp and the calculated N = 543 for unrefined pulp samples suggested a lower tendency to flocculate for the SF fraction. In Figure 8 the stator position is plotted against the crowding factor. The treatment of SF occurs in a narrower gap range at both intensities. Thus, the level of flocculation indicated by the crowding factor might be an appropriate indicator of major differences in the gap for fractions

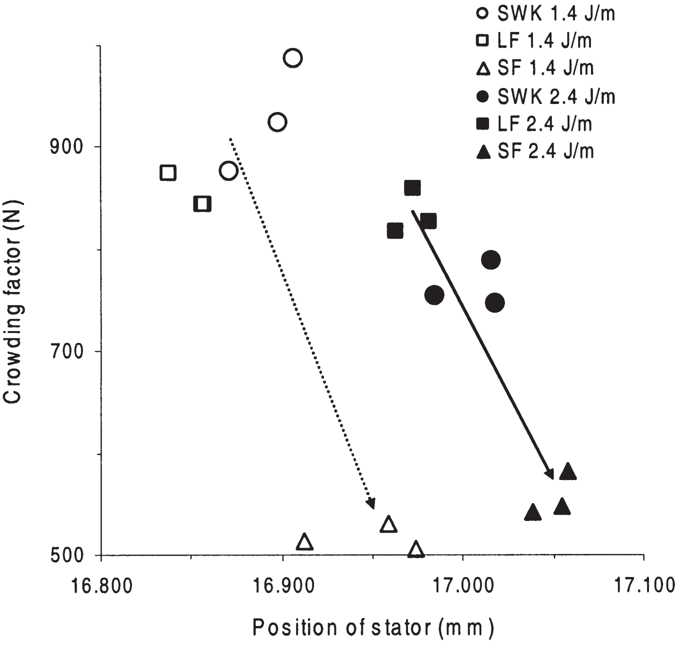

Figure 8 Crowding factor versus position of stator for pressure-screen fractions at refining intensities of 1.4 and 2.4 J/m.

differing mainly in fibre length and less in coarseness. Whether consistency variations affected the gap significantly is difficult to conclude. The uncertainty related to this is discussed at the end of this section.

The hydrocyclone fractions differed mainly in terms of coarseness. The coarseness for CF was 0.196 mm, for FF 0.158 mm, and for SWK 0.159 mg/m. The correspondent fibre length values were 2.33 mm, 2.23 mm, and 2.30 mm. The cell wall thickness for CF was 2.42 µm, for FF 2.34 µm, and for SWK 2.30 µm. For the hydrocyclone fractions, visual assessment did not suggest differences in flocculation. However, the calculated N = 661 for the unrefined CF fraction suggested lower flocculation than of the feed pulp. The lower calculated number of contact points per fibre for CF was due to increased coarseness.

Figure 9 shows the position of the stator of the hydrocyclone fractions at a refining intensity of 1.4, 2.4 and 3.7 J/m and at varying specific energy. At a given intensity gap behaviour was not fraction-specific as it was for the pressure screen fractions. Only at the highest intensity the gap was wider when CF

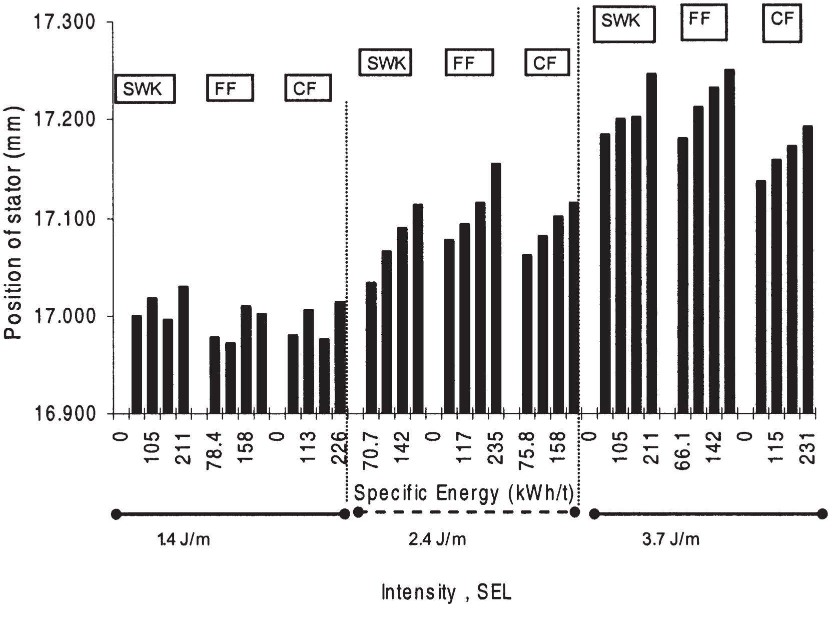

Figure 9 Changes in gap width (position of stator) for hydrocyclone fractions refined under varying intensity and specific energy.

was refined. If compared against FF, the gap of CF was 55 µm wider. The gap behaviour may indicate that at high intensity, and therefore under the high stress imposed by bar surfaces, also the coarseness and cell wall thickness of fibres have a role in determining the gap.

Maximum intensity

In addition to the fraction-specific gap at a given intensity, the maximum load-carrying capacity was found to be different for the SF fraction. When the maximum refining intensity for pressure screen fractions was mapped, the results showed that the maximum intensity for both the SWK and the LF fraction was approximately 3.7 J/m, while the maximum intensity for the SF fraction was approximately 2.4 J/m. The maximum intensity-carrying capacity of the SF fraction was found to be close to the "universal" intensity 2.0–2.5 J/m often recommended for softwood refining. In contrast to the pressure screen fractions, all the hydrocyclone fractions tolerated the intensity of 3.7 J/m.

As a result, for fractions which differ mainly in terms of fibre length, the crowding factor could serve as a first indicator in selecting a suitable refining intensity, because at a given intensity the lower crowding factor of SF predicted relatively well the reduction in the gap. The argument for using the crowding factor instead of fibre length, which later is shown to correlate to a certain extent with the gap when specific energy is increased, relates to the possible process variations which can change the fibre flocculation but not the fibre length. Consequently, the magnitude of the gap may relate to floc compressibility. This phenomenon is discussed in more detail in the section entitled "Discussion on mechanism behind gap behaviour".

Impact of specific energy on the gap

A low refining intensity of 1.4 J/m caused the properties of all fractions to develop favourably, and SF could be refined at a very low intensity of 0.9 J/m. Furthermore, the tensile strength-dewatering relationship was most prominent at low-intensity refining. Interestingly, when the gap behaviour of FF, CF, and SWK was analysed, when they were refined at a low intensity of 1.4 J/m, the gap did not decrease as a function of the increase in specific energy. The SF fraction refined at 0.9 J/m and the LF fraction refined at 1.4 and 2.4 J/m showed a similar unexpected trend. The bars in Figure 7 and 9 illustrate this phenomenon. However, the gap decreased as a function of specific energy at medium 2.4 J/m, or high 3.7 J/m refining intensity, except that for LF the decrease was only seen at a high refining intensity of 3.7 J/m. A decrease in the gap due to increased specific energy has been reported by several authors [40, 15, 41, 42, 43, 44]. Therefore, the gap development due to increased specific energy found in the present study must indicate that something in the floc network structure and in the components affecting its ability to resist compression remains more stable at low-intensity refining.

The development of average fibre length, the crowding factor and coarseness versus the gap were analysed in order to detect a possible correlation. Among the fibre properties studied, the most prominent parameter affecting the gap was the fibre length. The average fibre length indicated the best correlation with gap changes at medium 2.4 J/m and high 3.7 J/m intensity for FF, CF and SWK fractions, and at medium 1.4 J/m and high 2.4 J/m intensity for SF, and at high intensity for LF. An example is given in Figure 10, in which the fibre length of CF versus the position of the stator is shown at varying specific energy. The correlation coefficients are satisfactory, but the number of points is too small to warrant a final conclusion. Range [44] has reported that "the gap maintained under given pressure is related to the fibre length of pulp and fibre shortening is one of the main factors contributing to

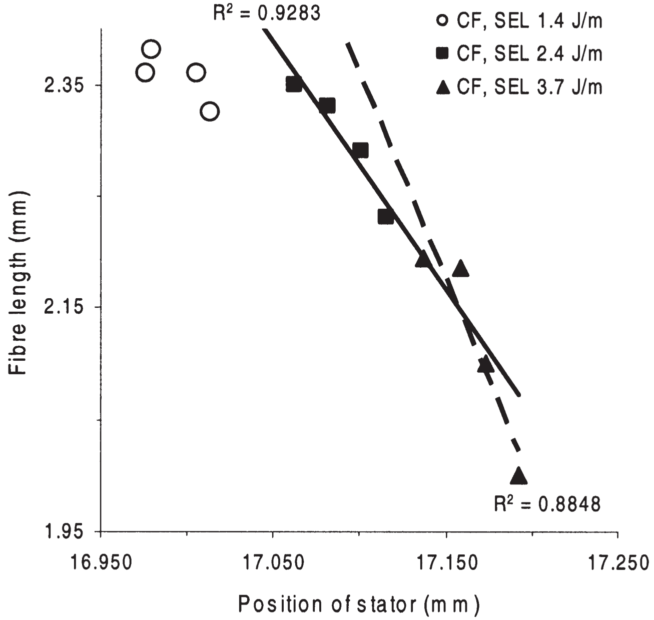

Figure 10 Average fibre length of refined CF versus the position of the stator.

the gap reduction that occurs during beating". Steenberg [45] added that the gap at constant speed and load is influenced also by other factors than fibre length; addition of slime- producing substances such as carboxy-methyl cellulose, starch, cellulose ethers, locust beam gum, alkalis and fatty oils and of hydrophilic solids such as asbestos fibres and bentonite reduced the gap holding capacity when added at a specific point of beating.

All in all, the above results show certain agreement with earlier results, in which a less flocculating short-fibre hardwood pulp was found to form a narrower gap than long-fibre softwood pulp [15, 41, 42, 43]. However, as pointed out earlier, also the coarseness and consistency may influence the gap. A direct effect of coarseness on the gap has not been reported earlier, but the effect of consistency has been reported by several researchers.

In summary, the consistency of pressure screen fractions varied because of refiner pulper leakage. In other experiments with the same laboratory refiner and with the same plate filling with relatively sharp bar leading edges, when consistency was intentionally varied, and with the same SWK pulp, the gap narrowed by 59 µm when consistency was raised from 4.1 % to 5.0 %, whereas for conical fillings with relatively dull edges the gap widened by 19 µm when consistency was raised from 4.1 to 5.2 % [46]. In a study by Lundin [40] using a conical laboratory refiner, a similar increase in the consistency of SWK pulp was found to widen the gap by about 70 µm. Watson and Phillips [15], Watson et al. [41], Watson et al. [42] and Murphy [43] have reported increased gap widths in experiments with a PFI mill due to increased consistency. When consistency is increased from 5 to 10 %, the gap increases, but the largest gap variations were caused by different wood species (Radiata vs Eucalyptus). On the other hand, the treatment in a PFI mill is shown to be less "harsh" than the treatment in an industrial refiner, indicating a significant difference in the treatment. The effect on the gap by different wood species is stronger than the effect by consistency, but if the fractions originating from same feed pulp and consequently from the same wood species are considered, the magnitude of different factors affecting the gap is far more difficult to determine.

If the refiner and plate configuration is the same, primarily different fibre and fibre suspension parameters, especially those which affect flocculation, may together determine the final gap width. In addition, differences in the bar leading edge roundness as well as different refiner configurations with centrifugal force in different directions may together with fibre parameters form a combination which determines the final gap. Additional studies would be needed to clarify in detail this complicated phenomenon. Since the same refiner configuration was used in all the experiments of the present study, the next discussion focuses on the role of fibre and floc parameters in explaining the gap behaviour found in the experiments. In recent studies on the forces acting on fibres an effort has been made to explain refining by a force-based model [19, 20, 21, 47, 48]. In these studies, floc compression in refining is noted.

Discussion on mechanisms behind gap behaviour

First, it is assumed that the heterogeneity of refining did not vary significantly when intensity was changed. In other words, the number of flocs entering between the bars did not change significantly. Naturally, this cannot be confirmed in any way, but the increased swelling of all the fractions purely due to specific energy might indicate that approximately the same amount of flocs was treated.

Second, it is assumed that the average diameter of flocs of different fractions did not vary substantially or at least the power of variation in floc diameter was clearly less compared to the increase or decrease in the number of contact points per fibre in the floc. The increase in the number of contact points by fibre length is in the power of 2. Consequently, the flocs with a larger number of contact points and apparently with a larger number of fibre layers per floc should have higher density when they are in uncompressed form flowing in the plate grooves. According to Kerekes et al. [11], the mechanical strength of a floc network increases when the number of contact points increases and the floc size appears to have the characteristics of a given stock, the minimum dominant size one to two times the longest fibre length. In a study by Martinez et al. [20], it was assumed that flocs are spherical in shape. On the other hand, in a study by Law [49], the flocs leaving the refining zone of a TMP pilot refiner were found to have various shapes and sizes. This finding indicates a wide distribution of floc size and shape at high consistency. Very little information is available on the actual floc size and floc density existing in low-consistency refiners. Han [50] and Elias [51] have studied the compressibility of fibre mats and the effect of fibre dimensions on mat structure, but in these studies the conditions in mat formation were different compared with the strong flocculation of pulp in low-consistency refining.

Third, it is assumed that the flocs are not disrupted between the bars, except possibly at the highest intensity. Martinez and Kerekes [21] observed that the flocs behaved in two ways when the bars crossed each other. Flocs remained intact with wider gaps, but with a very narrow gap they were disrupted into two parts, which implies a connection with the plate clash phenomenon, which is sometimes called “pad collapse”. Senger and Oullet [19] assumed that flocs generally remain intact during bar crossings and they observed no floc shearing at high consistency. They also concluded that a floc with higher density must have more fibre layers at the front of the bar leading edge. This should mean that if a floc with more layers enters between the bars it has more load-carrying crossing points in z-direction, as illustrated schematically in Figure 11. Consequently, these crossing points will carry the load. Senger [48] has presented a similar figure of fibres strained under stress. He suggested that the normal force in refining develops both through transverse compression of the fibre wall and through fibre bending. Martinez et al. [20] assumed that a floc cannot support significant normal load until the majority of fibres are in contact. Kerekes [47] has suggested that the normal force is transmitted from one fibre to another and consequently the force per fibre depends on how the fibres are distributed in the gap.

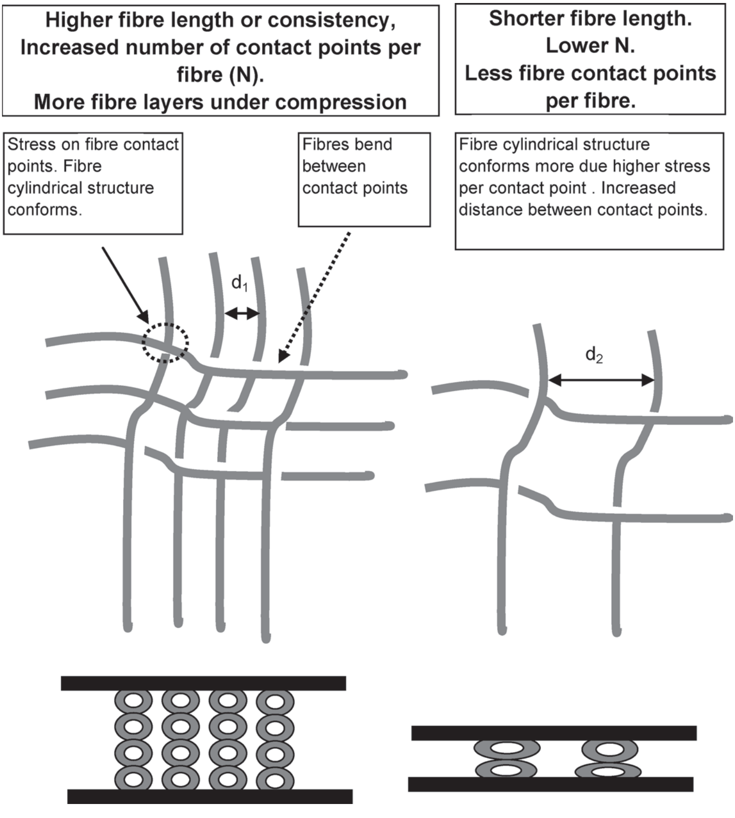

Figure 11 Schematic illustration of the role of fibre contact points and fibre conformability when a floc is compressed between the bar surfaces. The effect of the increased number of contact points is artificially intensified.

In summary, when refining the fractions, the gap showed three distinctive types of behaviour which here are called type-1, type-2 and type-3 behaviour. Type 1: At a given intensity the short-fibre fraction formed a narrower gap and its maximum load-carrying capacity was lower than expected. Type 2: At the highest 3.7 J/m intensity the coarse fibre fraction formed a wider gap than the other two fractions. Type 3: When gap changes were studied as a function of specific energy, the gap was found not to decrease systematically at low-intensity refining.

Type-1 and type-3 behaviour may indicate that the floc compression between bar surfaces, i.e. the thickness of a compressed floc at a given stress, is related to the original floc structure formed in the grooves. The structure is affected by the type of pulp, consistency, fibre properties and the flow and turbulence in the grooves. The number of contact points per fibre in a floc and the number of fibres in a given floc volume, in other words the floc density, may be important factors for the compression behaviour. A denser floc will have more fibre contact points and more fibre layers vertically. Under compression they can act as load carriers.

For example, a short-fibre floc from pressure screen accept with a calculated low number of contact points formed a floc which under compression gave a narrower gap. When the floc has fewer load-carrying contact points, the stress is distributed through fewer fibre beams from one bar surface to another, and consequently the normal force on fibres increases. Kerekes [47] has presented the mechanism governing how the distribution of fibres in the gap affects the force on the fibres. Consequently, the fibre wall should undergo a larger deformation. On the other hand, since the less dense floc may have fewer fibre layers, the floc is compressed to a smaller thickness when initial compression has ended. This mechanism assumes that no major fibre slippage occurs. The above mechanism may explain the type-1 behaviour. However, it is reasonable to ask whether fibre flexibility affects floc compression in LC refining. The fibre swelling of all fractions increased due to specific energy, and it was not dependent on the type of fraction or the intensity. Apparently, fibre flexibility should have increased, though it was not measured. Therefore, type-1 behaviour could also be partly due to fibre bending, as proposed by Senger [48]. It could be assumed that fibres in a short-fibre floc can bend and conform between the contact points to a greater extent and that increased floc densification will progress through this mechanism. However, in type-3 behaviour at low-intensity refining, the gap did not decrease systematically, though fibre flexibility most probably increased when more specific energy was applied. Therefore, fibre bending between contact points may occur already at lower stress ranges than applied here – a conclusion which would be in accord with the study by Martinez et al. [20]. They separated two regimes under uniaxial compression in low-consistency refining. The first regime includes initial compression and densification of the floc. Floc pore size decreases and fibre contacts increases. However, at a certain degree of compression, the number of fibres in contact is such that further compression of the floc requires significant force to be applied to reduce interfibre spacing. This second regime requires additional force to be applied to cause individual fibres to collapse and to squeeze water out of the cell wall. Finally, they concluded that in the typical operating conditions of a low-consistency refiner (gap 60 – 200 µm) flocs are compressed under regime two. In summary, it appears possible that type-1 and type-3 behaviour are due to initial compression and densification of the floc where the original floc structure and its density, the number of contact points per fibre and the number of layers in compression are the most important factors and fibre flexibility and bending are in a secondary role in the floc compression.

Type-1 behaviour also included reduced maximum intensity for the short-fibre fraction, above which the risk of severe metal-to-metal contact between plate surfaces increased. How much the flocs tolerate stress at the highest intensity before “pad collapse” occurs may well relate to floc structure. If the number of contact points per fibre decreases, the floc network strength decreases and the force per single fibre increases. Consequently, under high stress the actual stress-carrying contact points are too few to resist the stress, so the fibre breakage increases and simultaneously the floc network becomes weaker and may break up into smaller ones, which leads to “pad collapse”. Floc rupture under high stress has been observed by Martinez and Kerekes [21].

The gap behaviour in high-intensity refining (type-2 behaviour) indicated that for fibres of equal length, the fibre cell wall thickness may affect the magnitude of the final gap. The coarse-fibre fraction formed a wider gap at the highest intensity of 3.7 J/m, even though the calculated number of contact points per fibre was slightly lower. The compressed floc density values presented in the study by Senger [48] indicate that coarser CTMP fibre flocs have a clearly lower compressed density than flocs of softwood kraft, supporting that the fibre coarseness may have an important role under high stress.

Additional studies would be needed to clarify the actual mechanism and role of the most significant fibre and refiner parameters affecting the compressibility of flocs formed under the conditions prevailing in low-consistency refining. Since controlling the refiner de facto means controlling the gap, linking fibre flocculation and compression of flocs due to forces applied by the bars to the forming refiner gap, might offer new potential for improved refiner control.

CONCLUDING REMARKS

Several fibre and handsheet properties can be improved by fractionation and selective refining of fractions. To avoid excessive fibre shortening, and to prevent the dewatering resistance of the pulp from increasing, low-intensity refining is recommended. Increasing specific energy input results in increased fibre swelling, which contributes to a higher handsheet density and improved tensile strength. With fibre fractions which have higher coarseness, more specific energy is needed to achieve the same density and tensile strength of handsheets as with finer fractions.

If pressure-screen fractionation is applied, and the fractions differ mainly in terms of fibre length, special attention should be paid to mapping the optimum refining intensity for the fractions, because with a less flocculating short-fibre fraction the maximum intensity which enhances fibre shortening and "pad collapse" may be lower than expected.

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APPENDIX 1 Characteristics of refining parameters and properties of refined pressure-screen fractions

	Intensity (J/m)	Specific energy (kWh/t)	Con-sistency (%)	Stator Position (mm)	Crowding Factor (N)	Fibre length lw (mm)	Coarse-ness (mg/m)	SR	Tear strength (mNm^2/g)	Light-scatt. (m2/kg)	Apparent Density (kg/m^3)
SWK	1.4	0	5.82	0	949	2.27	0.158	13.1	17.0	32.8	477
		65	5.82	16.907	986	2.31	0.158	15.3	22.3	26.6	560
		131	5.82	16.898	923	2.23	0.156	21.0	18.0	23.6	611
		197	5.82	16.871	876	2.23	0.165	32.0	14.7	22.3	656
	2.4	0	5.21	0	850	2.27	0.158	13.1	17.0	32.8	477
		68	5.21	16.985	754	2.25	0.175	15.0	23.5	27.4	551
		142	5.21	17.016	788	2.21	0.162	21.0	16.4	23.8	616
		213	5.21	17.018	746	2.15	0.162	34.0	13.1	22.6	670
	3.7	0	4.91	0	801	2.27	0.158	13.1	17.0	32.8	477
		69	4.91	16.966	817	2.23	0.150	15.0	21.0	28.4	549
		145	4.91	17.01	788	2.17	0.146	20.1	16.0	25.0	603
		218	4.91	17.021	706	2.04	0.144	31.0	13.0	23.1	672
LF	1.4	0	5.15	0	904	2.45	0.171	11.6	15.8	31.9	442
		66	5.15	16.838	874	2.47	0.179	13.6	25.9	28.3	574
		132	5.15	16.857	844	2.43	0.180	17.0	21.9	24.6	633
		198	5.15	16.856	843	2.37	0.172	23.2	19.1	22.8	684
	2.4	0	4.78	0	839	2.45	0.171	11.6	15.8	31.9	442
		70	4.78	16.981	827	2.44	0.172	14.2	23.7	27.0	530
		144	4.78	16.973	859	2.39	0.159	18.3	19.8	23.9	593
		216	4.78	16.963	817	2.35	0.162	28.0	15.3	22.4	643
	3.7	0	5.1	0	895	2.45	0.171	11.6	15.8	31.9	442
		66	5.1	17.003	799	2.38	0.180	13.7	26.8	27.3	525
		137	5.1	17.012	821	2.34	0.170	18.0	19.2	24.6	588
		205	5.1	17.015	791	2.23	0.160	27.0	14.8	22.4	651
SF	0.9	0	4.11	0	540	2.01	0.153	14.6	17.5	34.3	492
		76	4.11	16.858	559	2.02	0.150	19.0	15.9	27.2	586
		152	4.11	16.794	594	2.01	0.139	28.5	13.9	24.4	642
		225	4.11	16.83	602	2.00	0.137	43.0	12.1	22.3	681
	1.4	0	3.92	0	515	2.01	0.153	14.6	17.5	34.3	492
		80	3.92	16.912	513	1.99	0.151	17.0	17.3	28.3	574
		162	3.92	16.959	531	2.00	0.147	24.0	14.1	24.6	633
		242	3.92	16.974	506	1.97	0.150	37.3	12.2	22.8	684
	2.4	0	4.36	0	573	2.01	0.153	14.6	17.5	34.3	492
		71	4.36	17.039	543	1.96	0.154	18.5	17.1	28.0	582
		148	4.36	17.058	582	1.92	0.138	28.0	13.0	24.5	655
		221	4.36	17.055	548	1.84	0.134	46.0	10.2	21.8	708

APPENDIX 2 Characteristics of refining parameters and properties of refined hydrocyclone fractions

	Intensity (J/m)	Specific energy (kWh/t)	Consistency (%)	Stator position (mm)	Crowding factor (N)	Fibre length lw (mm)	Coarseness (mg/m)	SR	Tear strength (mNm^2/g)	Zero-span Tensile (Nm/g)	Light-scatt. coeff. (m2/kg)	Apparent Density (kg/m^3)
SWK	1.4	0	5.12	0	848	2.30	0.159	14.5	16.5	124.9	33.4	454
		70	5.12	17	871	2.33	0.160	17.3	22.7	144.8	27.8	546
		105	5.12	17.018	916	2.32	0.151	19.4	20.2	143.6	26.4	579
		141	5.12	16.995	903	2.32	0.152	23.6	18.0	149.8	24.8	597
		211	5.12	17.03	862	2.29	0.155	37.5	14.9	153.8	23.2	641
	2.4	0	5.07	0	840	2.30	0.159	14.5	16.5	124.9	33.4	454
		71	5.07	17.034	816	2.32	0.167	17.3	24.1	138.4	28.8	532
		106	5.07	17.066	821	2.29	0.162	19.7	19.5	142.3	26.9	570
		142	5.07	17.09	840	2.29	0.158	23.6	18.0	145.8	25.4	598
		213	5.07	17.113	700	2.17	0.171	38.7	14.3	154.2	23.4	651
	3.7	0	5.11	0	846	2.30	0.159	14.5	16.5	124.9	33.4	454
		66	5.11	17.185	876	2.28	0.151	17.1	24.3	139.4	29.5	528
		105	5.11	17.201	799	2.22	0.158	19.5	20.3	147.9	27.9	562
		141	5.11	17.203	772	2.20	0.160	23.4	16.9	145.7	26	595
		211	5.11	17.246	747	2.08	0.148	39.0	12.3	147.6	24	655
FF	1.4	0	4.56	0	714	2.23	0.158	13.2	18.1	131.9	33.3	466
		78	4.56	16.977	804	2.30	0.150	15.6	20.6	148.3	27.9	557
		118	4.56	16.972	825	2.28	0.143	17.7	17.5	154.3	26.4	586
		158	4.56	17.01	790	2.23	0.144	21.5	15.3	151.2	24.9	619
		237	4.56	17.002	1012	2.23	0.112	30.8	13.3	158.0	23.2	651
	2.4	0	4.58	0	718	2.23	0.158	13.2	18.1	131.9	33.3	466
		75	4.58	17.078	827	2.29	0.145	14.7	19.2	148.4	28.4	556
		117	4.58	17.094	716	2.22	0.157	18.3	17.0	151.9	26.4	590
		157	4.58	17.114	710	2.20	0.156	21.7	15.7	161.6	25.5	616
		235	4.58	17.155	709	2.12	0.145	35.0	11.6	157.9	23	670
	3.7	0	5.03	0	788	2.23	0.158	13.2	18.1	131.9	33.3	466
		66	5.03	17.181	784	2.20	0.155	15.2	21.0	144.8	29.3	539
		107	5.03	17.212	858	2.19	0.140	16.7	17.1	150.2	27.6	572
		142	5.03	17.233	737	2.10	0.151	20.0	15.0	144.1	26.3	605
		214	5.03	17.25	651	2.00	0.155	30.0	12.4	148.3	23.8	666
CF	1.4	0	4.78	0	661	2.33	0.196	10.5	10.7	131.8	30.1	409
		75	4.78	16.979	752	2.38	0.180	13.2	23.0	152.4	26.2	507
		113	4.78	17.005	817	2.36	0.163	15.0	23.5	151.7	24.7	549
		151	4.78	16.976	790	2.36	0.169	17.8	21.7	153.6	23.9	563
		226	4.78	17.013	673	2.33	0.192	25.5	17.2	153.8	22.4	611
	2.4	0	4.55	0	629	2.33	0.196	10.5	10.7	131.8	30.1	409
		76	4.55	17.062	677	2.35	0.186	13.3	24.4	144.5	25.7	520
		118	4.55	17.081	632	2.33	0.196	15.5	20.5	149.6	24.5	550
		158	4.55	17.1	648	2.29	0.184	19.3	19.0	151.5	23.8	577
		238	4.55	17.115	591	2.23	0.192	33.5	15.1	145.7	22.4	637
	3.7	0	4.67	0	646	2.33	0.196	10.5	10.7	131.8	30.1	409
		73	4.67	17.137	728	2.20	0.155	13.0	20.9	146.7	26.5	503
		115	4.67	17.158	796	2.19	0.140	15.0	20.5	142.3	25.4	539
		154	4.67	17.173	684	2.10	0.151	18.7	17.8	141.9	24.4	575
		231	4.67	17.192	605	2.00	0.155	32.0	13.9	143.2	22.8	638

Transcription of Discussion

REFINING CHARACTERISTICS OF SOFTWOOD FIBRE FRACTIONS

Kari Koskenhely,[1] *Ari Ämmälä,*[2] *Hanna Jokinen*[2] *and*
Hannu Paulapuro[1]

[1]Helsinki University of Technology, Laboratory of Paper Technology
[2]University of Oulu, Laboratory of Fibre and Particle Technology

Errata received from the authors to be included in the proceedings

Appendix 1 on p. 455: The light scattering coefficient and apparent density values for the long-fibre fraction (LF) refined at 1.4 J/m intensity are erroneous. The correct values are presented in the Amended Appendix 1.

AMENDED APPENDIX 1 Characteristics of refining parameters and properties of long-fibre fraction refined at 1.4 J/m intensity.

	Intensity (J/m)	Specific energy (kWh/t)	Consistency (%)	Stator position (mm)	Crowding factor (N)	Fibre length (mm)	Coarseness (mg/m)	SR	Tear strength (mNm^2/g)	Light-scatt. (m^2/kg)	Apparent density (kg/m^3)	Tensile index (Nm/g)
LF	1.4	0	5.15	0	904	2.45	0.171	11.6	15.8	31.9	442	18.5
		66	5.15	16.838	874	2.47	0.179	13.6	25.9	27.1	527	41.2
		132	5.15	16.857	844	2.43	0.180	17.0	21.9	24.5	583	57.9
		198	5.15	16.856	843	2.37	0.172	23.2	19.1	22.9	622	69.9

Figure 5 on page 439: The tensile index values of the long-fibre fraction refined at 1.4 J/m are erroneous. As a result, after plotting correct values, the tensile strength-dewatering resistance relationship benefits only slightly from low-intensity refining of the long-fibre fraction. The amended Figure 5 is presented below.

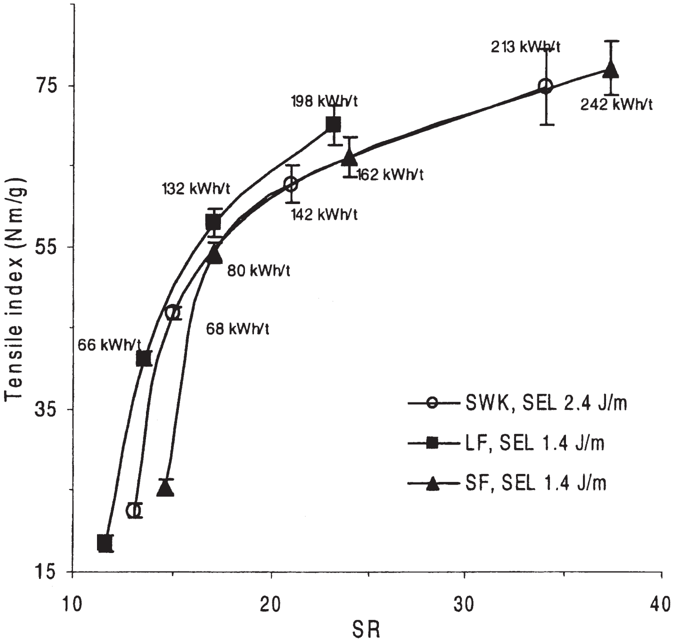

Figure 5 Characteristics of dewatering resistance (SR) – tensile index combination of pressure-screen fractions. The best intensity for the specific fraction was selected.

Other results and conclusions are not significantly affected by the erroneous data.

DISCUSSION CONTRIBUTIONS

Dan Sumnicht Georgia-Pacific Corporation

I am looking at Figure 4 showing your tensile versus density curve. Were you surprised that there was not more separation between the curves for coarse fraction and fine fraction? I guess I was a little surprised because of the differences in coarseness that you achieved. You had a good separation, good fractionation, and yet the curves for each fraction were similar. I may have expected a little bit more separation in the curves.

Kari Koskenhely

I think if you look at tensile as a function of specific energy for this coarse fibre fraction, there is a clear difference, but when we put density there it seems to disappear. Maybe it is a question of bonding and conformability.

Alan Button Buttonwood Consulting

I have seen very similar results to this in Southern Pine. This is very, very similar, so the outcome here is pretty consistent. One question I have for you on your coarse fraction: have you tried to drive the specific energy up to really high levels because we have seen in the past, at least in coarse Southern Pine, you can go to very high energy inputs and produce rather different paper?

Kari Koskenhely

I am not sure if I understood exactly what you mean, but we went up to 240 *kWh/t* and got an increase in the tensile strength of the coarse fraction. You can increase it but you just need more specific energy compared to other fractions. I have read some papers suggesting that the coarse fraction has lower strength at given specific energy. But I see that you can increase the strength by just applying more specific energy, or at least in these experiments, it seems to behave in this way.

Roger Gaudreault Cascades Canada Inc

Can you comment on how you calculated your crowding number in the refiner, and how precise it is?

Kari Koskenhely

In calculation, we used the formula given in equation 1 in the paper:

$$N = \frac{5C_m L^2}{\omega}$$

It is from the Kerekes and Schell paper [reference 28] where they presented the crowding factor.

Discussion

Roger Gaudreault

I agree, but the crowding number equals the number of fibres in a sphere which has a diameter equal to the average fibre length, but in a refiner you do not have a sphere.

Kari Koskenhely

Yes, I guess that question is what do the flocs look like and how do they behave between bar surfaces? This was one attempt to find some kind of indicator for flocculation, but I do not think that it is necessarily the best one, but I tried to bring the message that this might be an area to investigate further, for example, for future control purposes. We know the fibre length and we have, let's say, the crowding number, but in the system there are many other parameters which affect flocculation. The thing behind all this is that the fibre length alone seems not to explain the gap behaviour.