Koskenhely K., Ämmälä A., Jokinen H., Paulapuro H., Effect of refining intensity on pressure screen fractionated softwood kraft. Nordic Pulp and Paper Research Journal, 20 (2005): 2/2005, 169-175.

Effect of refining intensity on pressure screen fractionated softwood kraft

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KEYWORDS: Refining, Chemical pulp, Fractionation, Energy, Swelling

SUMMARY: The role of refining intensity in developing paper and fibre properties of screen-fractionated and selectively refined softwood kraft was examined. The critical refining intensity which enhances fibre cutting is significantly lower for the short-fibre fraction. In addition, the maximum applicable intensity is lower for the short-fibre fraction than for the two other components. The results emphasise the importance of optimising refining intensity and specific energy. Paper and fibre properties were found to be sensitive to changes in refining intensity and the type of fibre fraction. Low-intensity refining of the long-fibre fraction improves tensile strength slightly, while dewatering resistance remains low. Fibre swelling appears to be proportional to the specific energy, except at very high energy levels, and at a given intensity swelling is insensitive to the width of the refiner gap and to the fraction's flocculation tendency indicated by the crowding factor.

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Bleached softwood kraft pulp is a heterogeneous raw material. The morphology of wood affects the length and cell wall thickness (CWT) distribution of fibres. Tracheid growth during spring and summer is very different. As a result, the CWT of latewood fibres is greater than that of earlywood fibres, which makes latewood fibres less flexible. The tracheids of latewood are also often longer (Kärkkäinen 2003). The differences in fibre dimensions are frequently in contradiction with the demands set for the fibres by different paper or paperboard grades. Improved strength may be a desirable property, while at the same time a smooth paper surface may be required. Long and stiff fibres improve the bulk of paper but impair its strength, and may have a negative effect on smoothness or other surface properties. Clearly, there is a need to control fibre properties better in papermaking to meet increased quality requirements.

There are a number of methods for selecting fibres for a given product. A traditional way is to use hardwood and softwood fibres in different proportions. Selecting the right kind of chips in the wood yard is another way to deal with this question. An additional method based on fibre fractionation after chemical pulping has attracted increased interest lately. 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. In fractionation, the feed pulp is usually separated into a fine and a coarse fraction, using a pressure screen or a hydrocyclone. Pressure screening is the most efficient process to fractionate fibres by length (Scott and Abubakr 1994, Olson et al. 1998).

Several authors have studied mechanical pulp fractionation combined with selective refining of the resulting fractions, analysing the development of fibres and the properties of the fractions (Reme et al. 1999, Tchepel et al. 2003, Kure et al. 1999 and Ouellet et al. 2003). During the past ten years, fractionation of chemical pulp has been increasingly studied for the purposes mentioned above. Paavilainen (1993) and Vomhoff and Grundström (2003) used a hydrocyclone in fractionating bleached softwood kraft (SWK) and Sloane (1999) used a pressure screen in kraft pulp processing. These studies show the potential of fractionation. For example, 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 affects paper strength (Paavilainen 1993). Another study showed that the fractions after refining may have significantly different strength properties when specific energy is varied (Vomhoff and Grundström 2003). Despite these studies, only limited information can be found on how the different SWK fractions should be selectively refined. Of special interest is the role of refining intensity in further improving the strength and surface properties of fractionated kraft pulp.

The role of fibre flocculation in refining was identified long ago by Page et al. (1962). An increase in the level of interfibre contact increases the formation of coherent flocs which resist rupture in the flow, which changes the degree of non-uniformity in the suspension. At the contact points, several types of cohesive forces exist and the fibre properties may differ. For example, fibre length, fibre stiffness and fibrillation affect the magnitude of mechanical surface linkage and elastic fibre bending (Kerekes et al. 1985). Especially, fibre crowding in rotation and floc size depend on the fibre length (Kerekes and Schell 1995, Beghello and Eklund 1997). Different gap widths for the short- and the long-fibre pulps have been reported by Watson and Phillips (1964). McKenzie and Prosser (1981) 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 (1991) 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 rotating refiner fillings.

Consequently, fibres are refined as fibre flocs rather than individual fibres. Preliminary tests made in the present study indicated that the maximum refining intensity differed significantly for different screen-fractionated SWK fractions. Thus, the refining intensity and refiner gap may play a very important role in developing the properties of fibre fractions.

The objective of this study was to find out whether the short-fibre (SF) and long-fibre (LF) fractions of pressure-screen-fractionated SWK should be refined at the same intensity as the feed pulp (SWK) or at a totally different intensity, when looking for improved strength, or e.g. improved smoothness of paper. An effort was made to link the flocculation tendency of the fractions and the refining intensity to the behaviour of the refiner gap, and ultimately to determine how these properties affect fibres and handsheet properties. The results indicated that the refining parameters of a specific fraction need to be carefully optimised, because the intensity-carrying capacity of the accept fraction may be totally different from that of the feed pulp.

Materials and Methods

Pulps and experimental

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 and reject fractions according to SCAN standards. Handsheet properties were measured according to SCAN standards, except Scott internal bond strength, which was measured according to 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 (Stone and Scallan 1967). In measuring the pore size distribution of the cell wall, the thermoporosimetry method developed by Maloney (1998) was used. FSP and thermoporosimetry were measured for the fibre fraction, with the P200 fines washed away in a Dynamic Drainage Jar. 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 was fractionated with the small-scale fractionation process at the University of Oulu. The process includes a 300-litre feed tank, a small Metso FS-03 pressure screen and pump to feed the pulp through a screen and valves to split the accept (i.e. SF fraction) and reject (i.e. LF fraction) pulp into separate containers. The feed flow is adjusted by controlling the rotation speed of the feed pump, while the accept and reject flows are adjusted with manual ball valves. The volumetric flow split of the screen is monitored with magnetic flow meters mounted in the feed and accept pipes. The screen has a foil-type rotor with adjustable rotation speed. The diameter of the screen basket is 0.11 m and the screening area is 0.03 m^2.

The aim of the fractionation was to produce a strong fractionation effect, i.e. a great difference in fibre length between the accept and the reject, which in practice means intensive reject thickening at screening. To achieve this, a narrow slot width (0.09 mm) and a relatively smooth contouring of the screen plate (profile height of 0.8 mm) were selected for single-stage fractionation. In addition, low feed consistency (0.82 %) was selected to achieve high reject thickening without causing blinding of the screen plate. The most practical slot velocity for stable running was found to be 1.0 m/s with a foil tip speed of 16.5 m/s. The volumetric reject rate was kept constant at 25 %. The pulp temperature was 28 °C.

Before fractionation, dry pulp was slushed with a retention time of 30 min in a Grubbens pulper at a consistency of 3 %. About 30 kg o.d. of the SF- and LF-fractions was used for the refining study. Because of the limited capacity of the fractionation process, several batches had to be run. The consistency and temperature of the feed pulp were measured and adjusted for every batch and the operating parameters were kept unchanged. After fractionation, the dilute fractions were thickened with a belt wire thickener to a dry content of about 20 %. During thickening, a small amount of fines was probably lost, but the effect of this loss 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. To describe the fibre flocculation numerically, the crowding factor (N) of the pulps was calculated based on *Eq 1*, put forward by Kerekes and Schell (1992). 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 *Table 1*.

$$N \approx \frac{5C_m L^2}{\omega} \qquad [1]$$

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 (1991) and by Wultch and Flucher (1956). The specific edge load (SEL) theory developed by Wultch and Flucher (1956) and by Brecht and Siewert (1966) 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

Table 1. Characteristics of refining parameters and properties of refined pulp.

	Intensity (J/m)	Specific Energy (kWh/t)	Consistency (%)	Stator Position (mm)	Crowding Factor (N)	Fibre lenght $_{lw}$ (mm)	Coarseness (mg/m)
SWK	1.4	0	5.82	0	949	2.27	0.158
		65	5.82	16.907	986	2.31	0.158
		131	5.82	16.898	923	2.23	0.156
		197	5.82	16.871	876	2.23	0.165
	2.4	0	5.21	0	850	2.27	0.158
		68	5.21	16.985	754	2.25	0.175
		142	5.21	17.016	788	2.21	0.162
		213	5.21	17.018	746	2.15	0.162
	3.7	0	4.91	0	801	2.27	0.158
		69	4.91	16.966	817	2.23	0.150
		145	4.91	17.01	788	2.17	0.146
		218	4.91	17.021	706	2.04	0.144
LF	1.4	0	5.15	0	904	2.45	0.171
		66	5.15	16.838	874	2.47	0.179
		132	5.15	16.857	844	2.43	0.180
		198	5.15	16.856	843	2.37	0.172
	2.4	0	4.78	0	839	2.45	0.171
		70	4.78	16.981	827	2.44	0.172
		144	4.78	16.973	859	2.39	0.159
		216	4.78	16.963	817	2.35	0.162
	3.7	0	5.1	0	895	2.45	0.171
		66	5.1	17.003	799	2.38	0.180
		137	5.1	17.012	821	2.34	0.170
		205	5.1	17.015	791	2.23	0.160
SF	0.9	0	4.11	0	540	2.01	0.153
		76	4.11	16.858	559	2.02	0.150
		152	4.11	16.794	594	2.01	0.139
		225	4.11	16.83	602	2.00	0.137
	1.4	0	3.92	0	515	2.01	0.153
		80	3.92	16.912	513	1.99	0.151
		162	3.92	16.959	531	2.00	0.147
		242	3.92	16.974	506	1.97	0.150
	2.4	0	4.36	0	573	2.01	0.153
		71	4.36	17.039	543	1.96	0.154
		148	4.36	17.058	582	1.92	0.138
		221	4.36	17.055	548	1.84	0.134

Table 2. Properties of unrefined feed pulp, LF fraction and SF fraction.

Sample	FIBRE LENGTH$_{lw}$ (mm)	COARSENESS (mg/m)	CWT (µm)	SR	EARLY WOOD (%)	LATE WOOD (%)	INTERMEDIATE (%)
SWK	2.27	0.158	2.32	13.1	79	19	2
LF fraction	2.45	0.171	2.57	11.6	77	20	3
SF fraction	2.01	0.153	2.22	14.6	84	14	2

Table 1. The rotation speed of the rotor filling was 2000 rpm. The stator filling moves and closes the refiner gap. Its position was recorded, and the position value was used to indicate the gap width. The absolute gap was not known. Before the actual refining series, the maximum intensity for the 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.

Results and Discussion

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 2*. 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 achieved 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 2*, CWT and the early wood-latewood contents of the SF fraction were lower than those of the LF fraction and SWK, which is in accord with the fibre length results. Typically, thick-walled latewood fibres are longer than earlywood fibres. 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.

Refining

Mapping of the maximum refining intensity for specific fractions showed that the fractions had different load-carrying capacity. The maximum intensity for both 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 intensity-carrying capacity of the SF fraction was found to be somewhere between that of softwood and hardwood pulp. Hardwood is often recommended to be refined below 1.5 J/m. 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.

Fig 1 shows the crowding factor of all the fractions versus the position of the stator at a refining intensity of 1.4 and 2.4 J/m and varying specific energy. At a given intensity, the stator plate moved closer to the rotor filling when SF was refined. At an intensity of 1.4 J/m the average gap was 66 µm narrower for the SF fraction than for SWK and for 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. Also, between SWK and LF a trend can be seen at

2.4 J/m but not at 1.4 J/m. Thus, the level of flocculation indicated by the crowding factor might indicate major differences in the level of the gap for different fractions. This would be in agreement with the results of short-fibre hardwood pulp refining experiments, in which a less flocculating short-fibre hardwood was found to form a narrower gap than long-fibre softwood pulp (Watson and Phillips 1964, Watson et al. 1962, Watson et al. 1966, Murphy 1962). It should be noted that "major differences in the level of the gap" in this context does not refer to the gap decrease due to increased specific energy input, which has been reported by several authors (Lundin 2003, Watson and Phillips 1964, Watson et al. 1962, Watson et al. 1966, Murphy 1962). In the present study, at the highest 3.7 J/m intensity a correlation seemed to emerge between gap and fibre length as well as between gap and fibre coarseness of the SWK and the LF fraction, when specific energy was increased. Unfortunately, the number of points is far too small to warrant any further conclusions.

Additional studies would be needed to clarify the actual mechanism and role of the most significant fibre parameters causing the gap difference between SF and LF fractions and SWK; in addition to the fibre length and coarseness variation due to fractionation, also the consistency varied after refining because of pulper leakage, and consistency is also known to influence the gap width. In other experiments with the same plate filling, with relatively sharp bar leading edges 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 % (Koskenhely et al. 2004). In a study by Lundin (2003) 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 (1964), Watson et al. (1962), Watson et al. (1966) and Murphy (1962) 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 are caused by different wood species (Radiata vs Eucalyptus). On the other hand, the treatment in a PFI mill is believed to be less "harsh" compared to the treatment in an industrial refiner, indicating a significant difference in the treatment. Against this background, it appears possible that different refiner configurations, fibre suspension parameters and filling edge profiles may together determine how much material enters between the bars' surfaces, thus influencing the final gap width. The information available on modern laboratory or industrial refiners is still incomplete, with the exception of the PFI mill.

Effect of refining intensity and specific energy on fibre properties

Fig 2 illustrates the reduction in fibre length when refining intensity and specific energy were increased. The average fibre length decreased more strongly when the intensity was increased to the maximum for the specific fraction. Increased cutting through higher intensity is a well-known phenomenon, but it should be noted that the type of fraction appears to play a significant role for the intensity at which cutting is most severe. For the SF fraction, the critical refining intensity which enhanced fibre cutting was 2.4 J/m. Otherwise, fibre cutting increased with an increase in specific energy. According to Stephansen (1964), cutting is due to squeezing of fibres between the bars. The findings of the present study support Stephansen's theory and the floc refining theory proposed by Hietanen (1991); when refining intensity was increased, the gap decreased, thereby increasing the susceptibility to fibre cutting. The internal strength of the fibre flocs and fibres which enter between bars must carry the increased load and tension created by the rotating rotor surfaces. Consequently, at some point, the internal strength of the fibre is exceeded and the fibre is broken.

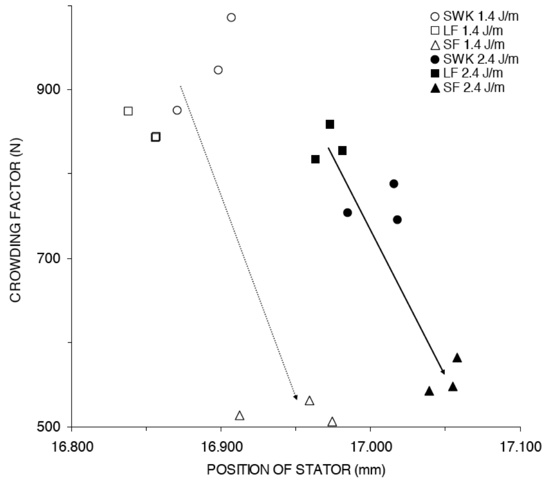

Fig 1. Crowding factor versus position of stator at refining intensities of 1.4 and 2.4 J/m.

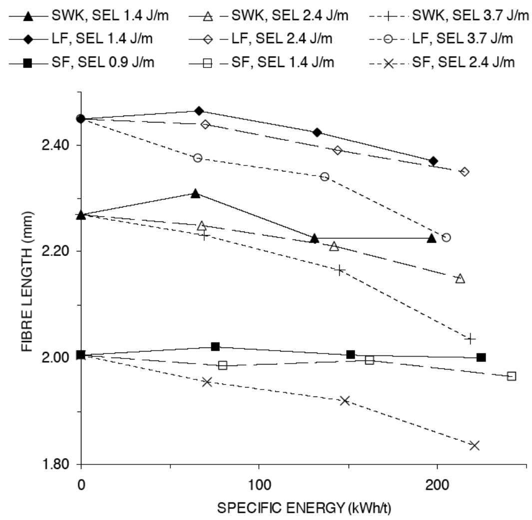

Fig 2. Effect of specific energy on average fibre length.

Fig 3 shows the fibre saturation point versus specific energy for all fractions refined at different intensities. The fastest increase in fibre swelling (total pore volume of fibres), as represented by the FSP, was seen at the beginning of refining. Later when more energy was

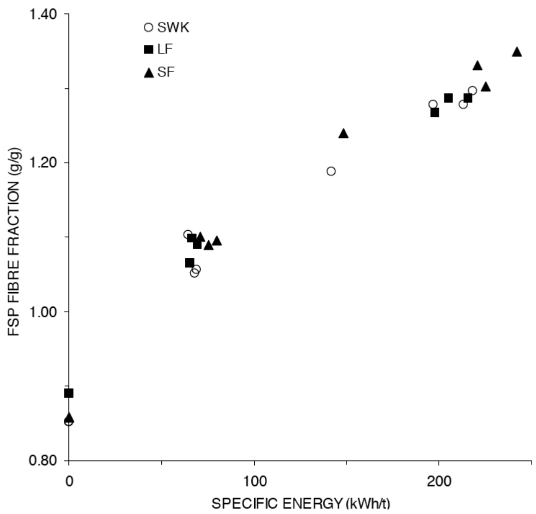

Fig 3. FSP versus specific energy of all the fractions.

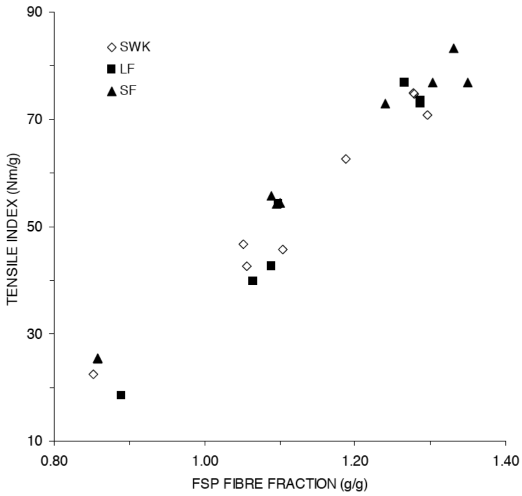

Fig 4. Effect of FSP on tensile strength.

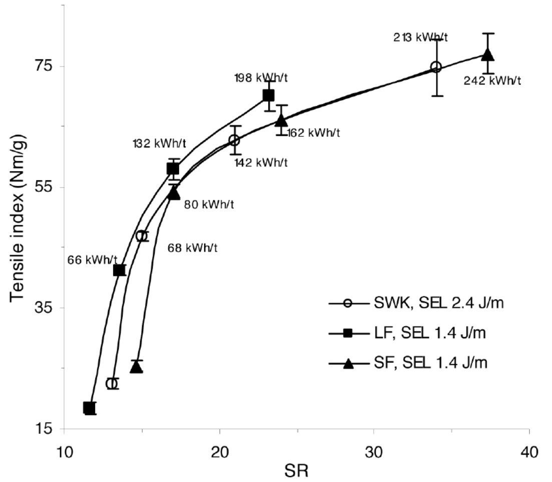

Fig 5. Characteristics of dewatering resistance (SR) - tensile index combination. The best intensity for the specific fraction was selected.

applied, the increase in total pore volume diminished. The opening of micro pores due to specific energy, which was measured by thermoporosimetry strongly supported the detected behaviour. Nanko et al. (1989) 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 are generated as external fibrils are loosened from the fibre frame. The specific refining energy seems to explain the swelling tendency of fibre fractions treated in the laboratory refiner LR40, except at very high specific energy levels, when the fibre swelling slightly levels off. A similar swelling tendency was detected both for the SF and LF fractions. SWK had slightly lower FSP values, possibly because it had been stored for a shorter time in wet state. Surprisingly, at a given intensity level, the fraction's flocculation tendency, indicated by N, and the refiner gap were irrelevant for the development of fibre swelling. In order to confirm if a single parameter, such as the number of impacts per fibre (n) in the C-factor theory (Kerekes 1990), could alone explain fibre swelling, n for a test points was calculated. When intensity was decreased, fibre swelling developed less linearly as a function of n. In general, the development of fibre swelling and tensile strength, when the number of impacts is increased and intensity is varied, were comparable to the results reported earlier by Kerekes et al. (1993), and by Welch and Kerekes (1994).

Fig 4 illustrates the importance of fibre swelling for the development of tensile strength. When the amount of refining is increased, fibre swelling and tensile strength increase, as reported by Stone et al. (1968). As noted earlier, increased refining intensity may be detrimental to fibre length. Therefore, increasing the number of impacts appears to offer more potential than increasing refining intensity as a means to retain the fibre length and promote paper strength.

Paper properties

When a low amount of specific energy (65-80 kWh/t) was applied to the LF fraction at a low intensity of 1.4 J/m, the tensile strength-dewatering resistance relationship benefited only slightly from low-intensity refining of the long-fibre fraction. 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. *Fig 5* shows the tensile index versus SR. In addition, the dewatering resistance of the 198 kWh/t refined LF fraction reached 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.

Fig 6 shows density versus roughness. 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 strong refining will increase the dewatering resistance and the risk of bulk loss, it would be advisable to refine 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. An SF-type component could be utilized in improving the surface smoothness for example of a layer of multiply paperboard.

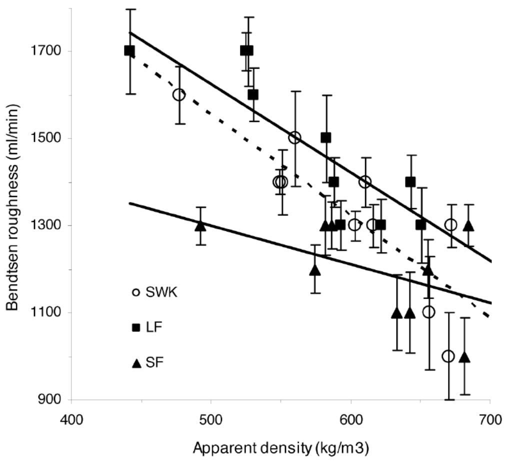

Fig 6. Characteristics of density-Bendtsen roughness combination of fractions.

Conclusion

A combination of screen fractionation and selective refining of bleached softwood kraft fractions can be used to improve the strength and surface properties of handsheets compared to refining the feed pulp as such. The long-fibre fraction could be used as a reinforcement component, since low-intensity refining improves its tensile strength-dewatering resistance relationship, while at the same time maintaining fibre length. The short-fibre fraction may be a suitable component for example for the surface layer of multiply board; it provides a smooth surface at a given density when the fraction is refined mildly. For a specific fraction, the optimum intensity needs to be carefully mapped, since its intensity-carrying capacity may be significantly different from the intensity at which softwood kraft pulp is traditionally treated. In addition, in the present study, fibre shortening was found to be most severe at the maximum intensity, the level which was specific for the fibre fraction treated.

The specific energy appears to explain the increase in fibre swelling for all the fractions, except at very high energy levels. Since fibre swelling contributes to tensile strength, and is a desirable property for paper strength, the question how specific energy could be applied more efficiently without increasing intensity and changing throughput and without causing damage to fibres, still remains open.

Acknowledgements

Financial support from the National Technology Agency, TEKES is acknowledged. The authors would like to thank Eero Hiltunen for bringing up the idea for a combined fractionation and refining study, Eija Korhonen and Minna Mäenpää for their kind assistance in pulp and paper testing, and Leena Nolvi for her assistance in FSP and DSC measurements. Thanks are also due to Mikko Karjalainen and the Fiber and Particle Engineering Laboratory of the University of Oulu for the pulp fractionations.

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Manuscript received June 4, 2004
Accepted December, 2004