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DIFFERENT APPROACHES TO TAILORING CHEMICAL PULP FIBRES

Doctoral Thesis

Khalil El-Sharkawy

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Opponent(s) :Professor Jouko Niinimäki, Professor Samuel Schabel
Supervisor : Professor Hannu Paulapuro

ABSTRACT

The objective of this thesis work was to examine different approaches to tailor chemical fibres of different raw materials. The focus in searching for new approaches was on pressure screen fractionation, selective treatment of each fraction, mechanical pre-treatment before refining, refiner loadability and its link to fibre properties and filling design, and on-line quality control of fibre properties. The evaluation is based on the impacts on fibre properties, filtration, refining and the resulting paper properties.

Tailoring of fibres using pressure screen fractionation was found to produce a long and coarse (reject) fraction offering high dewatering efficiency, homogeneous and energy-efficient refining, and better strength properties, such as tear index, bulk and fracture toughness, in pure and mixed sheets with other fibres. Although the accept fraction contains short and thin fibres and has a high fines content, it proved possible to use the accept fraction to increase the bonding and scattering of once dried softwood and to reduce the refining energy input needed to reach a certain tensile strength level.

A new mechanical pre-treatment was examined and found to promote lumen collapse and de-swelling of fibres, and hence to improve the strength-dewatering combination of softwood kraft pulp. The treatment involved application of linear loads, heat, and shear forces over multiple passes. In refining, the pre-treated fibres produced better dewatering and a consolidated structure with less cutting, fines creation and external fibrillation compared to never dried fibres. The pre-treated fibres offer better potential for developing a higher tensile index, stiffness and Scott bond than once dried fibres at a certain degree of refining.

Refiner loadability and gap movement are strongly related to fibre properties and filling design. Fibre properties together with pulp consistency contribute to the size and strength of flocs building up inside the refiner, where big and strong flocs are loaded earlier and maintain a wide gap with less floc size changes. Here, pulp consistency was found to have a smaller effect than fibre properties. Filling design, reflected in the cutting edge speed, was found to contribute strongly to the gap movement and refiner loadability. An increase in edge cutting speed caused the refiner gap width to decrease linearly, thus enhancing different refining effects such as fibre cutting, fibrillation and fibre swelling.

A factor network linking on-line measured fibre properties, calculated factors and predicted paper properties was found to be an effective tool for monitoring changes in pulp quality, such as different raw materials with different average fibre lengths. The model was built off-line and tested against on-line mill operation and found to be effective in predicting paper properties of both never and once dried pulp. The refining model was tested with a laboratory refiner and used to explain strength properties such as tensile index, to monitor changes in paper properties due to refining and to determine the optimum refining conditions and different refining effects such as bonding, straightening and fibre cutting.

Keywords: fractionation, refining, dewatering, strength, on-line measurements, softwood, eucalyptus, bagasse.

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To :

The loving memory of my mother (Elsit) and father (Khalil)

اهداء

إلى روح أمى الست وأبى خليل

PREFACE

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This thesis is dedicated to the memories of my late Mother and Father, bless their souls. They were a couple who never got a chance to go to school or be able to even write their names, yet they believed and worked hard for educating their four sons and daughter up to university level.

Espoo, August 2008

Khalil El–Sharkawy

It is what we make out of what we have, not what we are given, that separates one person from another.
(Nelson Mandela, Long walk to freedom)

LIST OF PUBLICATIONS

The thesis is based on seven original publications listed below, which are referred to in the text by roman numerals:

I. El-Sharkawy, K.; Rousu, P.; Haavisto, S.; Paulapuro, H., Control of Bagasse Pulp Quality by Fractionation and Refining, Appita J. 60(2007):5, 404-409,415.
II. El-Sharkawy, K.; Koskenhely, K.; Paulapuro, H., The fractionation and refining of eucalyptus Kraft pulps, Nord. Pulp Pap. Res. J., 23(2008):2, 172-180.
III. El-Sharkawy, K. ; Koskenhely, K. ; Paulapuro, H., Tailoring softwood Kraft pulp properties by fractionation and refining, accepted to Tappi J. (2.5.2008).
IV. El-Sharkawy, K.; Haavisto, S.; Paulapuro, H., The influence of a calendering pretreatment on the refining of chemical softwood pulps, Appita J., 61(2008):1, 41-48, 55.
V. El-Sharkawy, K.; Haavisto, S.; Koskenhely, K.; Paulapuro, H., Effect of fibre flocculation and filling design on refiner loadability and refining characteristics, BioResources, 3 (2008):2, 403-424.
VI. El-Sharkawy, K.; Backman, M.; Hirvonen, K.; Paulapuro, H., The Application of Factor Analysis and On-line Measurements in controlling Chemical Pulp Properties, Paperi ja Puu, 89(2007):6, 343-347.
VII. El-Sharkawy, K.; Liias, P.; Paulapuro H., Factor analysis as a tool to control chemical pulp quality in refining, Paperi ja Puu, 88 (2006):8, 460-463.

AUTHOR'S CONTRIBUTION

I. Design and analysis of experiments except the fractionation of bagasse and filtration experiments, first version of the manuscript.
II. Design and analysis of experiments and first version of the manuscript.
III. Design and analysis of experiments and first version of the manuscript.
IV. Design and analysis of experiments except the filtration experiments, first version of the manuscript.
V. Design and analysis of experiments except the flocculation test, first version of the manuscript
VI. Design and analysis of experiments and first version of the manuscript.
VII. Design and analysis of experiments and first version of the manuscript.

LIST OF ABBREVIATIONS

ECF	Elemental chlorine free
WRV	Water retention value
FSP	Fibre saturation point
CWT	Cell wall thickness
L(l) , L_{av}	Length-weighted average fibre length
C_m	Consistency
SEL	Specific edge load (J/m)
SRE	Specific refining energy (kWh/t)
RR_m	Mass reject rate (%)
CSF	Canadian standard freeness (mL)
PLS	Partial least squares projection to latent structure
VIP	Variable influence in the projection
TMP	Thermomechnical pulp
L_s	Bar edge cutting speed (km/s)
FD	Flow direction
TD	Transverse flow direction
R100, R200	Pulp fraction retained on 100 or 200 mesh wire

INTRODUCTION

There is an acute need for new methods in papermaking to ensure efficient use of available fibre raw materials. The focus has changed from making bulk products to enhancing product quality and raising prices or reducing production costs to improve the profitability of papermaking. Another trend in the market for chemical pulp fibres is towards tailoring and engineering of specific fibres for specific end products and end uses. These changes set strict quality requirements for fibres, from their origin until the final product, motivating researchers and papermakers to find new efficient approaches to tailoring fibres for different paper grades, cut energy and materials costs and enhancing strength properties.

This study was aimed to identify and test certain approaches to tailoring or modifying chemical pulp fibre properties for different products with different strength properties. The examination of these approaches was extended to cover fibres from different sources, including softwood, hardwood and selected non-wood fibres. The tailoring tools tested in this study included process modifications such as fibre fractionation, separate refining and selective use of different fibre fractions. Another approach examined in this study was to use a new mechanical pre-treatment of fibres before refining to optimize the combination of strength and dewatering of pulp fibres. A further step was to look at the link between fibre properties and equipment parameters, such as refiner filling design and how it is reflected in the quality of refined fibre properties. The possibilities to tailor fibres offered by the different approaches proposed in this study were complemented by applying advanced on-line measurement of fibre properties and pulp quality control. Quality control serves as a means to follow up and control the changes in pulp quality due to variability in raw materials (variations in fibre properties) and process impacts on fibres in processes such as pulp drying and refining.

This thesis is structured into four parts examining each approach, as summarized in the following. See also Table 1.

- Part 1 examines the approach of using fractionation and selective treatment of pulp components, such as refining. This covers chemical fibres of different raw materials such as softwood, eucalyptus and non-wood bagasse pulp. This approach was designed to study the ultimate use of each fibre class as a means to cut costs and to optimize the resulting pulp and paper quality. Particular attention was paid to the role of fibre fractionation in fibre network dewatering, to the impacts of refiner fillings and refining conditions, and to the use of different fibre fractions. The quality of fibres produced in fractionation was also examined in relation to the operating conditions (reject rate), the size of pressure screen and the layout of the fractionation unit.

- Part 2 examines the approach of using a new mechanical pre-treatment to modify the fibre structure before refining. The role of the treatment variables was examined together with their role in pulp refining, filtration and resulting paper properties. The treatment was tested with bleached chemical softwood kraft pulp fibres.
- Part 3 examines the approach of using the link between fibre properties and filling design as a means to control refiner loadability and the quality of resulting refined fibres. The floc sizes of different fibres were measured under conditions similar to those in refining, and the relation between refiner loadability and gap movement, and fibre properties and filling design was determined. This approach was found to facilitate the selection of the right filling for specific fibres.
- Part 4 examines the approach of using advanced on-line measurement of fibre properties and factor analysis techniques to control pulp quality. A factor network model was built and tested off-line and on-line against laboratory measurements. The model was designed to follow up changes in pulp quality due to changes in raw materials, pulp production (pulp drying) and fibre preparation (refining), and supply pulp with relevant fibre and paper characteristics.

Table 1. Structure of the study.

	Publications						
	I	II	III	IV	V	VI	VII
Part 1	X	X	X				
Part 2				X			
Part 3					X		
Part 4						X	X

Part 1: Fractionation and selective processing of fibre fractions

In pulp- and papermaking, fractionation refers to the separation of fibre suspensions into different fractions according to fibre properties such as fibre length, cell wall thickness and surface area. Depending on the operating principle, the fractionation equipment can be divided into mechanical barriers (e.g. pressure screens) and devices based on the hydrodynamics of the suspension (e.g. hydrocyclones). Pressure screens are the most common and efficient unit operation for screening and fractionation. Pressure screens are known to separate fibres mainly based on fibre length, whereas other factors such as fibre flexibility and thickness are secondary effects (Karnis 1997, Julien Saint Amand et al. 2001, Vollmer et al. 2001).

Although fractionation has been known for many years, its use has been limited to mechanical and recycled fibres (Knut and Wakelin 1999, Nazhad and Sodtivarakul 2004). Driven by the need for strength improvement, energy savings and the development of new pulp and paper grades, fractionation has become a flexible tool to optimize the properties of chemical pulp fibres (Bolton 1974, Paavilainen 1992, Häggblom-Ahnger 1998, Sloane 1999, Vomhoff 2003, Olson et al. 2001, Panula-Ontto 2002, Koskenhely et al. 2005, Ortner et al. 2006).

Refining (beating) is one of the most important steps in developing the strength properties of papermaking fibres. Pulp refining involves drastic mechanical actions that produce a number of modifications in the fibre morphology, such as internal and external fibrillation, fines creation, fibre cutting, and fibre curling or straightening (Ebeling 1980, Page 1989). However, beating also impairs some other paper properties like optical properties and dimensional stability.

Materials

The experiments were aimed to cover fibres from different sources including softwood and hardwood and selected non-wood fibres. The wood pulps used in this work were industrial pulps obtained from different pulp mills in Finland and the non-wood bagasse pulp was obtained from India. The characteristics of the pulps used in the trials are described in the following. More details are given in the articles in the appendix.

- A once-dried (air-dried) bleached bagasse pulp was obtained from an Indian soda pulp mill. The bagasse pulp had a brightness of 82.1% ISO, a length-weighted average fibre length of 0.73 mm and a freeness level of 290 mL.
- A once-dried eucalyptus market pulp was obtained from a Finnish pulp mill. The pulp was produced by ECF bleaching without ozone and the pulp had a final kappa number of 18-19. The pulp had a length-weighted average fibre length of 0.735 mm, a freeness level of 540 mL and a brightness of 89% ISO.
- A once-dried softwood kraft pulp was obtained from a Finnish pulp mill producing ECF-bleached pulp. The pulp had a length-weighted average fibre length of 2.32 mm and a freeness level of 718 mL. The pulp contained 61% pine and 39% spruce.

Fractionation

All pressure screen fractionation test runs of softwood and hardwood eucalyptus pulps were performed with a pilot-scale screen at the Savonlinna FibreTech research unit of the Lappeenranta University of Technology. The pressure screen was an Andritz ModuScreen F designed for high-consistency fine screening applications. In all trials, only the bump rotor design was used and the rotor speed was in the range of 20-30 m/s. The trials were conducted with different slot and hole screen sizes.

Before fractionation, the once-dried pulp sheets were slushed in a hydrapulper (6 m^3) at a consistency of 4% and a temperature of 40-50°C for 30 minutes. The rotor speed was 1000 rpm and the power input 27kW. After slushing, the pulp was diluted to the target consistency of 2.5±0.2% before fractionation.

The bagasse pulp was fractionated using an axial-feed Valmet TAP03 laboratory pressure screen at the University of Oulu, in the Fibre and Particle Engineering Laboratory. Before fractionation, the dried bagasse pulp was slushed in a Grubbens pulper for 60 minutes. The motor power was 5.5 kW and rotor speed 1680 rpm. The fractionation was carried out as a single-stage fractionation using slot screen at around 1% pulp consistency and a temperature of 21°C.

Refining

All refining trials were conducted with a Voith LR 40 laboratory refiner at the Department of Forest Products Technology of the Helsinki University of Technology. The specific edge load theory (Brecht and Siewert 1966) was applied to control the refining trials. Different refiner fillings were used in refining: the first and second were typical conical and wide-bar disc filling commonly used to refine softwood pulps. The third filling was a narrow-bar disc filling commonly used to refine hardwood pulps. The specifications of fillings are shown in Table 2.

Table 2 Fillings used in refining.

Filling	**Ls (km/s)**	**Bar width (mm)**	**Groove width (mm)**	**Bar angle (°)**
Conical	0.67	3.6	8.0 - 12.0	30
Wide-bar disc	1.067	3.6	5	30
Narrow-bar disc	2.840	2.0	3	30

Measurements

The procedures and the tests used for pulp and paper properties are as follows:

- Measurements of fibre length and the percentage of external fibrillation using the Kajaani FibreLab® analyzer have been described in detail by Richardson et al. (2003) and Turunen et al. (2005). The measurement made done according to the Kajaani FibreLab operating manual and in agreement with TAPPI standard T271.
- Acetone extracts (SCAN-CM49)
- Cell type content, KCL internal 2160 (SCAN G3, G4).
- Pulp freeness, CSF (SCAN C21)
- Water retention value (WRV) in accordance with the proposed standard SCAN–C 62:00.
- Fibre saturation point (FSP) measured by the solute exclusion technique (Stone and Scallan 1968).
- The pore size distribution was measured by the cyclohexane thermoporosimetry technique based on the melting temperature depression of an absorbate in the

capillaries of porous material caused by increased pressure. The cyclohexane was used as absorbate and the melting temperature depression was then linked to the pore size as described in detail by Maloney (2000) and Wang (2006).

- The consolidation of the fibre network during filtration was measured using a gravity-driven filtration device equipped with a pulsed ultrasound-Doppler anemometer. This device provides detailed information on the dynamics of filtration and the material properties of the consolidating fibre layers. A detailed description of this device and measurement method is contained in a publication by Kataja and Hirsila (2001) and article [I].
- Handsheets of 60 g/m^2 were prepared in compliance with SCAN-C 26:76 and conditioned before testing at 23°C and 50% RH. The tensile properties of the handsheets were measured according to SCAN-P 38:80, tearing resistance according to SCAN-P 11:96, Scott internal bond strength according to TAPPI T833 and fracture properties according to SCAN-P 77:95.

Nonwood bagasse pulp

Nonwood fibres can be divided into four categories based on their position in the plant: grass fibres, bast fibres, leaf fibres and fruit fibres. Grass fibres, such as rice straw, wheat straw, bagasse and bamboo are usually used for the most common paper grades and sugar cane bagasse is ranked as the second biggest nonwood fibre resource (Atchison 1996, FAO 1999). Papermaking using nonwood fibres is hampered by various difficulties, some of which are due to the chemical composition of the fibres, for instance their high silica content. Other difficulties are due to their morphological properties, for instance, nonwood fibres are slender and comparatively short and are accompanied by a high weight percentage of parenchyma cells and a dense epidermis and dirt (non-fibrous cells) (Swamy Veerabhadra 1986, Hua et al. 1988). Because of their high non-fibrous content, fines and hemicellulose contents, nonwood pulps have a high water retention value (WRV) and are difficult to dewater (Cheng et al. 1994, Subrahmanyam et al. 1999). Their short fibres impair their runnability in papermaking and make them less suitable for fast and large paper machines. Despite these difficulties, nonwood fibre pulps are a good raw material for printing papers, improving their formation and smoothness. Consequently, nonwood fibre pulps offer good papermaking potential compared to hardwood market pulps (Rousu 1997, Paavilainen 2001).

Fractionation of bagasse pulp

In bagasse pulp fractionation, fines and short fibres tend to accumulate and be easily directed to the accept fraction. At a high reject rate, the accept freeness and average fibre length are decreased dramatically, as shown in Table 3, whereas at a low reject rate, the accept fraction has almost the same quality as the feed pulp. At a low reject rate, part of the long fibres are forced to pass through the screen aperture, thus raising the accept's average fibre length and freeness. Adjusting the reject rate will alter the fibre quality (fines content, average fibre length and coarseness) of each fraction and therefore the potential offered by fractionation.

Table 3 Bagasse fractionation data.

	Test run1, screen basket slot # 0.06mm			**Test run2, screen basket slot # 0.09mm**		
	Feed	**Accept**	**Reject**	**Feed**	**Accept**	**Reject**
Consistency, %	0.968	0.475	2.111	0.989	0.786	1.645
Reject rate,%			**65.9**			**20.4**
Freeness, ml	290	200	459	290	272	449
L(l), mm	0.73	0.49	0.85	0.73	0.70	0.85
Coarseness, mg/m	0.132	0.130	0.135	0.132	0.128	0.142
Fines, %	12.37	20.08	8.68	12.37	12.55	9.93
Width, µm	21.9	21.1	22.4	21.9	22.0	21.6
CWT, µm	6.1	5.9	6.3	6.1	6.0	6.3

Fractionation and filtration

Figures 1.a and 1.b show the filtration data with the consistency of different fibre layers plotted as a function of dewatering time for both the original bagasse pulp and the reject fraction. After a certain dewatering time, the reject fraction fibre layers are dewatered faster and reach a higher consistency than the original un-fractionated bagasse. The permeability (given by the Kozeny-Carman constant) of both the reject and original pulp is affected by several fibre properties such as fibre length, coarseness and fines content, following the trend of pulp freeness. Not only does the reject fraction provide a more open network but also its fibre layers are able to carry more structural pressure at the same consistency than the original bagasse pulp.

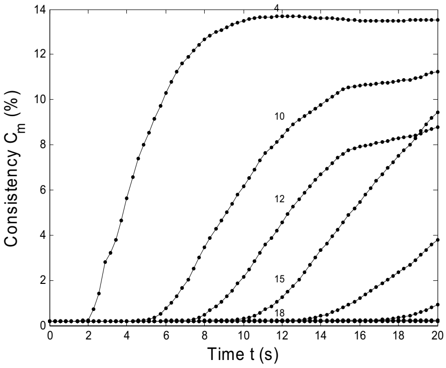


Figure 1.a. Mass consistency of fibre layers as a function of time during filtration of reject fibre fraction. The curves are labelled according to the initial distance from the wire of the corresponding pathline (fibre layer).

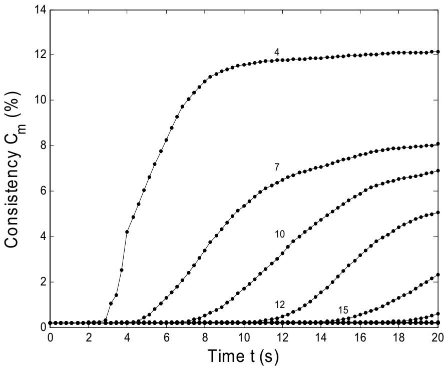


Figure 1.b. Mass consistency of fibre layers as a function of time during filtration of original un-fractionated bagasse pulp. The curves are labelled according to the initial distance from the wire of the corresponding pathline (fibre layer).

Fractionation and refining

A big proportion of the swelling (FSP value) of bagasse pulp is due to its original high fines content, which is also increased with refining. Htun et al. (1981) and Maloney et al. (1999) explained the high swelling of fines by their higher content of micropores water and their higher proportion of amorphous cellulose compared to fibres. Figure 2 shows the increase in swelling (FSP) of fibres retained on a 100-mesh wire, separated from refined reject and unfractionated bagasse pulp, as a function of refining energy. At the same refining energy input, fibres separated from the reject fraction display greater swelling than fibres separated from unfractionated refined bagasse pulp. Accordingly, the refining of the reject fraction was apparently homogeneous and energy-efficient. Refining causes an increase in fibre swelling and the fines content, which greatly increases fibre bonding and is reflected as higher sheet density, as shown in Figure 3. At a certain sheet density, the reject fraction retained a higher tear index than the original pulp and the tear index was decreased with the increase in refining energy due to the fast breakage of cell wall bundles of bagasse fibres. Against this background, light beating can be recommended for the reject fraction and the original un-fractionated pulp.

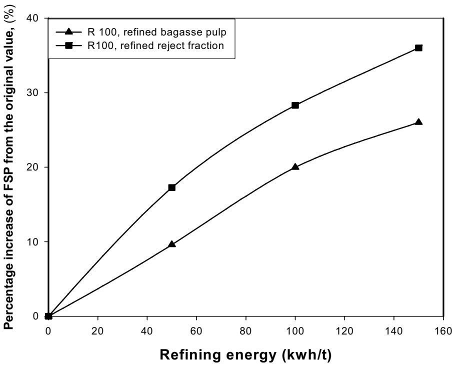


Figure 2. Percentage increase of FSP vs. refining energy for fibres (R100) from refined bagasse pulp and refined reject fraction.

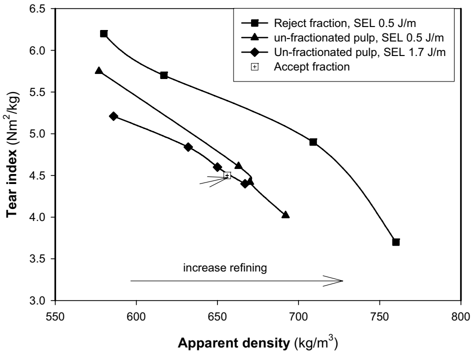


Figure 3. Tear resistance vs. apparent sheet density for bagasse pulp and reject fraction.

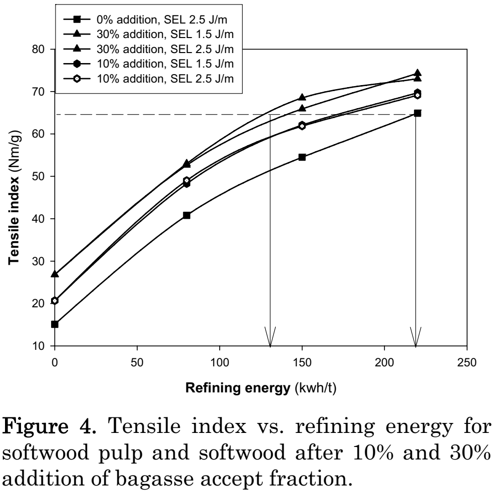


Figure 4. Tensile index vs. refining energy for softwood pulp and softwood after 10% and 30% addition of bagasse accept fraction.

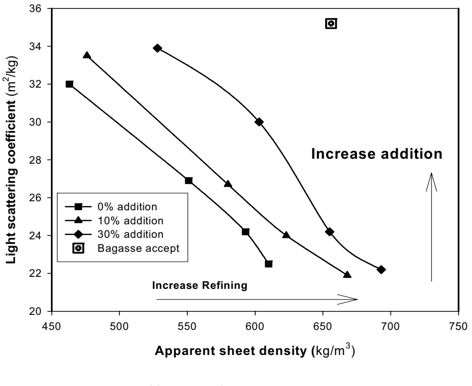


Figure 5. Effects of bagasse accept addition to softwood on light scattering - sheet density combination.

Rousu and Niinimäki (2005) in their study on non-wood pulp constituents concluded that even though nonwood fines impair dewatering and tear index, a partial presence of these fines is beneficial for optical and tensile properties. Retulainen (1997) explained the role of both TMP and kraft fines to the fibre network, and optical and strength properties. The bagasse accept was added to once dried softwood pulp before refining in percentages of 10 to 30%. The addition of short, thin fibres and the high fines content of the bagasse accept improved the strength properties of softwood pulp, making it possible to reach the same tensile index with less refining energy as shown in Figure 4. The additions also introduce more surface areas that scatter more light and thus improve the light scattering coefficient of softwood pulp at a certain density as shown in Figure 5. At certain tensile index and up to 20% addition of bagasse accept, there was no clear decrease in the tear index of softwood pulp, whereas further addition decreased the tear index notably.

Eucalyptus pulp

Since the mid-1960s, when eucalyptus kraft pulp was first introduced, eucalyptus pulps have gradually evolved to dominate the world hardwood pulp market, driven by technical and economic reasons. Eucalyptus wood grows fast and produces a high pulp yield with excellent technical properties which make it suitable for a wide range of paper grades, such as writing and printing paper, specialty papers and tissue (Cotterill et al. 1997, Santos et al. 2005, Celso Foelkel 2007). Though bleached eucalyptus kraft pulp produces excellent paper properties such as good bulk, strength, formation, uniformity, and optical properties, eucalyptus pulps are still blended with up to 50% long-fibre softwood pulp to meet the overall end-use requirements of paper (Demuner et al. 1991, Brindley and Kibblewhite 1996, Mansfield et al. 2004).

Hardwoods contain a variety of different cells in the form of fibres, vessel elements, tracheids and parenchyma cells. The chemical composition of each type of cell and their percentage in the wood vary widely with different species. Only a few studies (Demuner 1999, Li et al. 1999) have been conducted on eucalyptus fractionation using a hydrocyclone, showing that different fractions have different chemical and morphological compositions and therefore different papermaking properties

Compared to softwood, hardwood fibres are shorter, thinner and unable to resist high refining loads, so they require gentle treatment with low refining intensity (Sigl 2001). Baker (2001) and Manfredi (2004) have concluded that the optimum refining conditions for eucalyptus pulp are 3.0-6.0% consistency, 0.3-1.0 specific edge load (J/m) and up to 160 kWh/t refining energy. Demuner et al. (2005) proposed the use of ultra-low intensity (0.05 J/m) with a special filling design that promotes fibre straightening and fibre cell wall hydration during refining.

Fractionation of eucalyptus pulp

Figure 6.a shows the changes in average fibre length of accept and reject average fibre length compared to feed pulp with different screen sizes. A hole screen with a hole of size 0.6 mm seemed to produce the greatest difference in average fibre length between accept and reject. At a low reject rate, both the reject and accept had a high average fibre length, and an increase the reject rate tended to reduce the average fibre length of both the reject fraction. Both consistency and pulp freeness show the same trend as average fibre length. In two-stage fractionation, only a hole screen with a hole size of 0.6mm was used and the trials were arranged so that the reject from the first screen was used to feed the second-stage screen after dilution. In Figure 6.b, the average fibre length of the final reject and combined accept are compared to those obtained from single-stage fractionation. Two-stage fractionation strongly increased the reject's average fibre length and pulp freeness.

The fibre content was higher in the reject fraction than in the accept, whereas the accept fraction contained more vessel and ray cells. Although the percentage of vessels was higher in the accept than in the reject fraction, the distribution of vessels based on their length and width was different in the accept and reject. The coarser (high width) and longer vessels (0.2-1.0 mm) were mainly accumulated in the reject fraction, while thinner (low width) and shorter vessels were mostly accumulated in the accept fraction. There were also differences in the chemical composition of accept and reject compared to the feed pulp, for instance the extractives content, with the reject showing less acetone extract compared to the feed and accept pulps

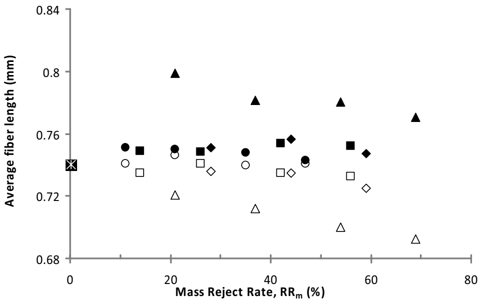


Figure 6.a Length weighted average fibre length as a function of mass reject rate: triangles refer to a hole screen of 0.6mm, circles to a hole screen of 1.0 mm, diamonds to a slot screen of 0.12mm, squares to a slot screen of 0.15mm, with filled symbols denoting reject and open symbols to accept.

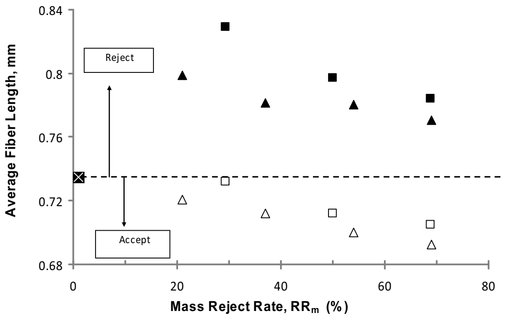


Figure 6.b. Average fibre length vs. mass reject rate with a 0.6mm hole pressure screen. Triangle symbols refer to single-stage fractionation, and square symbols to two-stage fractionation.

Fractionation and refining

In two-stage fractionation trials, which were proceeded by refining, a hole screen with a hole size of 0.6mm was used. The two-stage trials were arranged so that the reject from first screen was used to feed the second-stage screen after dilution. A layout of the fractionation and quality of pulp in each fraction is shown in Figure 7.

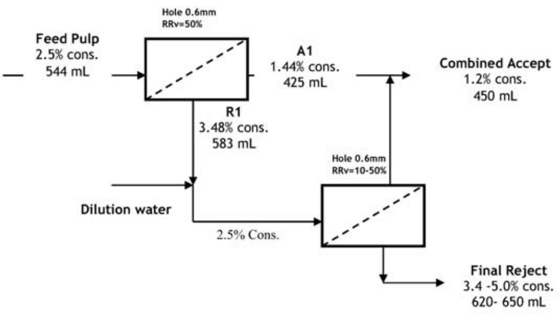


Figure 7. Layout of two-stage fractionation trials.

Figure 8 shows the pore volume as a function of pore size, measured using the cyclohexane-based thermoporosimetry of the unrefined original eucalyptus and the reject fraction. The original eucalyptus pulp had a bigger pore size than the reject fraction, which contributed to the high swelling measured as the fibre saturation point (FSP) of the original eucalyptus compared to the reject fraction. At the same refining energy, the increase in pore volume due to refining was greater in the reject fraction than the original pulp, as shown in Figure 9. Due to refining, the small pores (<20nm) of the reject fraction increased in size to the same level as that of the refined eucalyptus pulp, whereas the big pores (>20nm) expanded more in the reject fraction than in the eucalyptus pulp, which explains why the FSP of the reject fraction was higher than that of the original pulp after refining. Accordingly, the refining of the reject fraction was apparently homogeneous and efficient in opening pores and the increase in swelling compared to the original eucalyptus pulp.

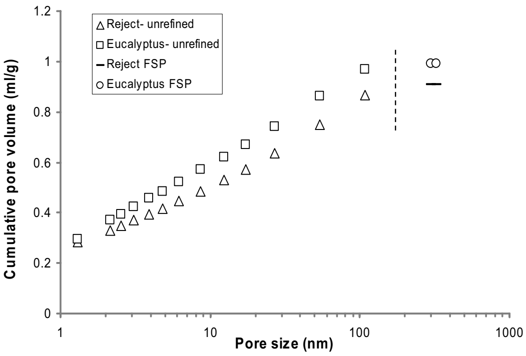


Figure 8. Pore size distribution and fibre saturation point of original eucalyptus pulp and reject fraction before refining.

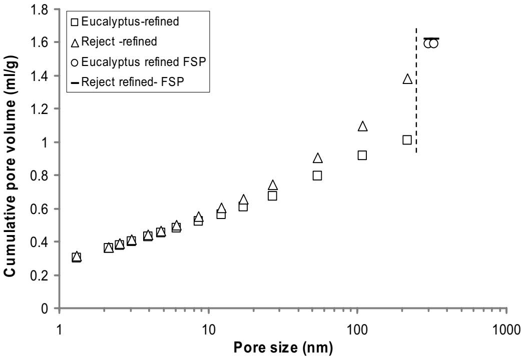


Figure 9. Pore size distribution and fibre saturation point of original eucalyptus pulp and reject fraction after refining (SEL 0.3 J/m, SRE 160 kWh/t).

The total reject rate of the fractionation unit plays the main role in determining the quality of the reject pulp produced. Figure 10 shows two pulps produced at a reject rate of 21% and 69 % and refined under the same conditions compared to the original pulp. At a tensile index of 70 Nm/g, the reject pulp produced with a low reject rate (21%) reached the same tensile index, while maintaining the highest pulp freeness (434 mL) and consuming the lowest amount of refining energy (62

Kwh/t), whereas the reject pulp produced with a high reject rate (69%) reached the same tensile index but at a lower freeness (300 mL), while consuming more refining energy (122 kWh/t).

The original eucalyptus pulp and different pulp fractions were blended with refined softwood pulp, using 50 and 75% eucalyptus pulp in the mixture sheets. Both the reject and original eucalyptus were refined with a specific edge load (SEL) of 0.3 J/m and refining energy inputs of 110 and 160 kWh/t. Using the reject fraction as a furnish component was found to be beneficial in developing a higher tensile index, fracture toughness and bulk compared to the original unfractionated eucalyptus pulp. A higher refining energy input of 160 kWh/t was beneficial in promoting the tensile index and fracture toughness, as shown in Figure 11, whereas a lower refining energy input of 110kWh/t was beneficial in preserving the bulk of the mixture sheets. Properties such as the mixture average fibre width and average fibre length were found to be the most important variables in controlling the resulting paper properties, with the percentage of hardwood pulp and the degree of hardwood refining being the next most important. Therefore, replacing the original eucalyptus pulp by the reject fraction in mixture sheets would allow reducing the addition of softwood pulp while maintaining a certain paper quality. Consequently, the possibility to minimize the expensive part of the furnish shows the economic potential of using fractionated eucalyptus pulp.

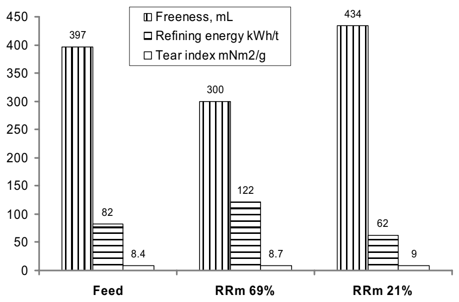


Figure 10. Freeness, refining energy and tear index of pulps at a tensile index of 70 Nm/g.

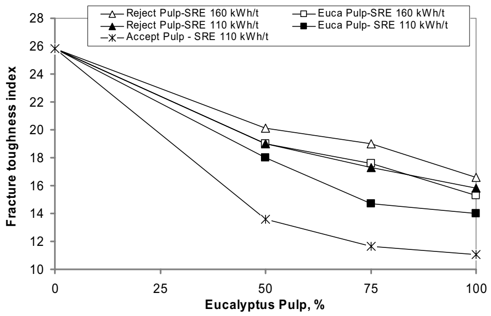


Figure 11. Fracture toughness index of mixture sheets vs. eucalyptus pulp percentage.

Softwood pulp

Softwood is often used as reinforcement pulp to improve runnability in papermaking and to improve the strength properties of paper. Refining (beating) has been the traditional way to enhance the quality of reinforcement pulp for optimal strength properties. Recently, fracture toughness has been proposed to be related to breaks and the sheet resistance to break propagation (Page and Seth 1982, Kettunen 2000, Yu 2001), where fibre strength, bonding and fibre length are important in enhancing fracture energy. Uesaka et al. (2001) concluded that the press room runnability of paper is strongly influenced by the uniformity of strength, elastic stretch and tensile strength, whereas tear index is not a good runnability indicator.

The good strength properties of softwood originate from the fact that the fibres are long, strong and flexible. Although fibre length and strength are important in controlling the paper properties, cell wall thickness is also another important for the papermaking potential of specific fibres (Paavilainen 1993). Fibre deformations and other defects which originate during the course of the pulping process (McLeod et al. 1995, Clark et al. 1997, Tikka et al. 2001) have been found to influence the fibre network properties (Page et al. 1985) and the resulting paper strength properties (Mohlin et al. 1996, Mohlin et al. 2003, Joutsimo et al. 2005, Seth 2006).

Fractionation of softwood pulp

The first stage of the fractionation trials in the present study consisted of a coarse screening using a hole screen with a hole size of 1.6 mm diameter operated at reject rate of 45% by mass. From the reject stream a coarse fraction with 2.41 mm average fibre length and a coarseness of 232 mg/m was separated at a consistency around 5.3%. The corresponding accept fraction had a shorter average fibre length of 1.95 mm and a coarseness of 191mg/m. The accept fraction from coarse screening was directed to a slot screen with 0.15 mm slots operated at around 50% reject rate by mass. A layout of the fractionation and quality of pulp in each fraction is shown in Figure 12.

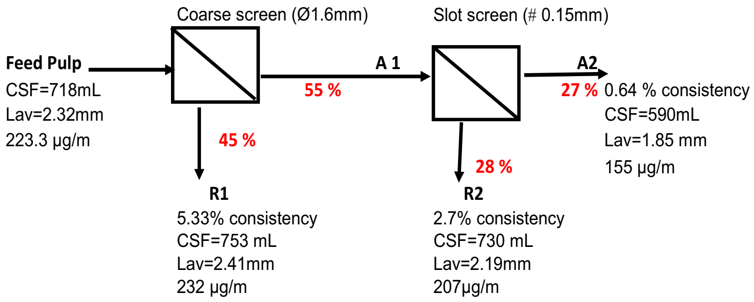


Figure 12. Layout of fractionation trials and fibre quality of each fraction.

Fractionation and refining

The reject pulp from coarse screening (R1) was refined with conical fillings with a SEL of 1.0 J/m and 4.2 J/m and compared to the unfractionated pulp refined with a SEL 2.5 J/m. In the laboratory refiner it was possible to measure the movement of the stator and refiner gap during refining of each pulp. Figure 13 shows the stator movement (indication of gap closure) plotted against different levels of refining energy. The reject fraction R1 contained pulp of high coarseness and average fibre length, therefore result in a wider and more open gap. At a low SEL intensity, the fibres maintained a wide gap, whereas an increase in refining intensity reduced the refiner gap.

Figure 14 shows the pulp freeness against the percentage of external fibrillation calculated as the area of fibrils divided by the area of fibres from images taken by the fibre length analyzer (FibreLab 3.0). At a certain refining energy, the reject pulp treated with high SEL showed a higher degree of external fibrillation compared to refining with low SEL, with a strong correlation between freeness and degree of fibrillation.

To reach a tensile index of 70 Nm/g, the coarse reject fraction (R1) needs a higher energy input compared to unfractionated pulp, and the lower the intensity (SEL), the more refining energy is needed, as shown in Figure 15. On the other hand at the same tensile index, the reject fraction treated with a low SEL of 1 J/m had a higher tear index (+25%) than the original pulp, as shown in Figure 16.

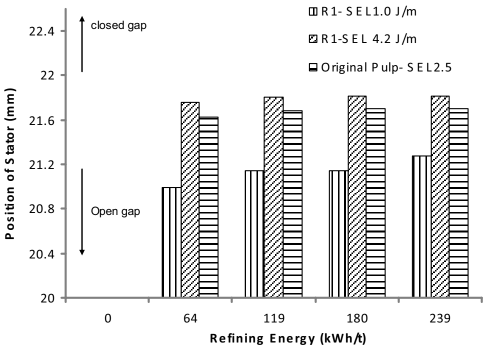


Figure 13. Gap movement vs. refining energy for reject fraction and original pulp.

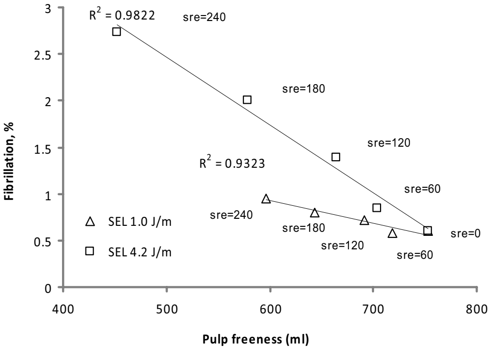


Figure 14. Fibrillation vs. pulp freeness.

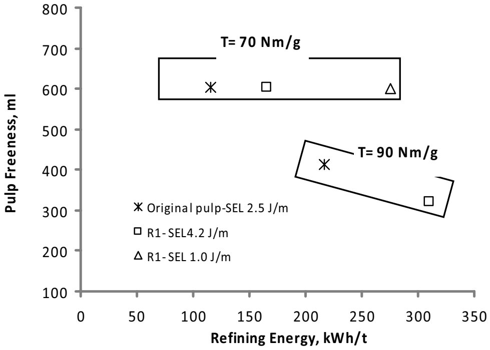


Figure 15. Pulp freeness and refining energy combination at a tensile index of 70 and 90 Nm/g.

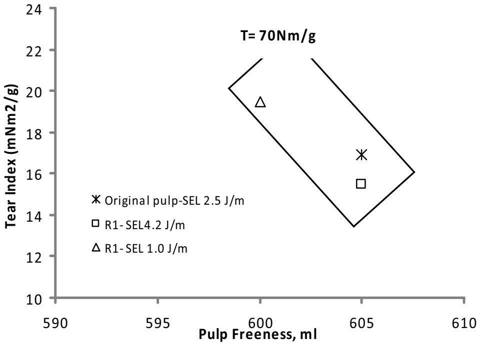


Figure 16. Tear index vs. pulp freeness at a tensile index of 70 Nm/g

The mixed reject of R1 and R2 was treated with two different fillings and compared to the unfractionated pulp treated under the same refining conditions. The two fillings used were conical filling (Ls=0.67 km/s) and narrow-bar disc fillings (Ls=2.84 km/s). The characteristics of the filling are listed in Table 2. Figure 17 shows the changes in average fibre length against the refining energy input. In refining with conical fillings, the average fibre length of the mixed reject and original pulp are hardly changed, not even at a high energy input of 240kWh/t. In refining with narrow-bar bar disc refining, the changes in average fibre length were more noticeable, and as the energy input increases, the decrease in average fibre length becomes more prominent and low specific edge load of 0.5 J/m is beneficial in preserving the fibre length. In Figure 18, pulp freeness is plotted against the refining energy at a tensile index of 70 and 90 Nm/g. At the same tensile index, pulps refined with conical fillings maintain a slightly higher freeness compared to pulps refined with narrow-bar disc fillings but with a higher energy input. The difference in refining energy between the two fillings is in the range 70-100 kWh/t when the target is a certain tensile index of 70 or 90 Nm/g.

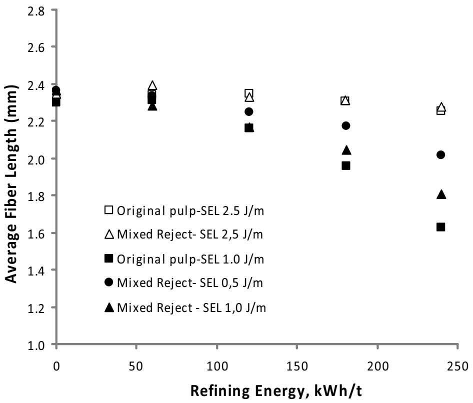


Figure 17. Average fibre length vs. refining energy; empty symbols refer to conical fillings and filled ones to narrow-bar disc fillings.

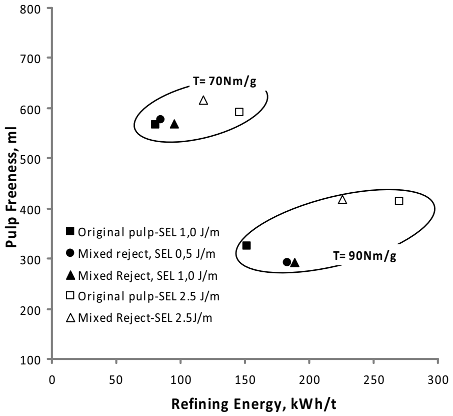


Figure 18. Pulp freeness vs. refining energy at a tensile index of 70 and 90 Nm/g; empty symbols refer to the conical fillings and filled ones to narrow-bar disc fillings.

The final accept fraction (A2) has an average fibre length of 1.85 mm, which make it less competitive as a common softwood pulp. On the other hand, the accept fraction mostly consists of short, thin fibres and fines, which make it very beneficial when high strength properties are needed. One possibility pursued in the present study was using the accept fraction to replace a certain proportion of the once dried softwood pulp as a means to improve the strength properties, similar to the addition of hardwood pulp to a softwood furnish. To reach a certain tensile index, at 26% accept addition, the refining energy of once-dried softwood pulp was reduced by 60 kWh/t (-35%) while maintaining the same freeness level, as shown in Figure 19. Figure 20 shows the development of internal bond strength due to refining and addition of accept fraction. Replacing part of the original pulp with the accept fraction strongly increased the Scott bond value and at the same refining energy level of 240 kWh/t, the Scott bond was doubled by the addition of 26% accept fraction.

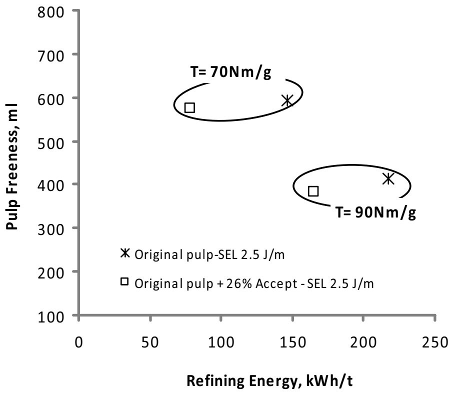


Figure 19. Pulp freeness and refining energy combination at a tensile index of 70 and 90 Nm/g.

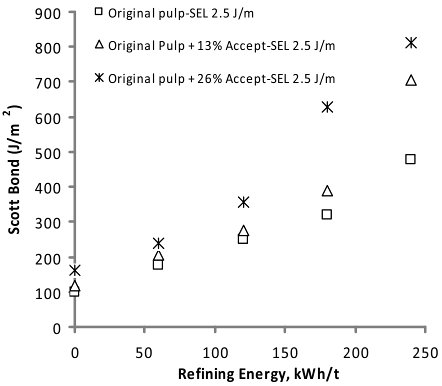


Figure 20. Scott bond vs. refining energy.

Summary of part 1

Pressure screen fractionation was used as a tool to fractionate the original bagasse, eucalyptus and softwood pulps into a reject fraction with longer and coarser fibres compared to those accumulated in the accept fraction. The operating reject rate, screen dimensions and the fractionation layout (single or two stages) determined the quality of each fraction produced. The reject fraction showed better dewatering efficiency than the original pulp. This was reflected as increased consistency in fibre layers and higher solid structure pressure, resulting in good wet runnability and improved drainability (bagasse pulp trials). The refining of the reject fraction was apparently more homogeneous and energy-efficient in increasing fibre swelling compared to the refining of the original unfractionated pulp, when compared at certain refining energy input (kWh/t). Low-intensity refining of the reject fraction was beneficial in preserving the average fibre length and in maintaining a higher tear index, but at the expense of a higher refining energy input to reach a certain tensile index. In mixture sheets of eucalyptus and softwood pulp, the use of fractionated eucalyptus pulp showed potential to reduce the amount of expensive softwood pulp by optimizing the mixture fibre properties. The accept fraction from bagasse and softwood pulp was used to enhance the strength properties of once dried softwood pulp, reducing the refining energy input needed to reach a certain tensile index. Therefore, fractionation and selective treatment and use of fibre fractions serve as a useful tool to produce fibres of different strength properties for different paper grades, while reducing operating costs through a lower refining energy input.

Part 2: Mechanical pre-treatment before refining

The strength of softwood pulps deteriorates in the fibre line, in bleaching and in pulp drying (Howard and Bichard 1992, Clark 1997, Tikka and Sundquist 2001, Seth 2001, Gurnagual and Page 2001). The strength loss throughout the fibre line is due to increased fibre deformation, and in pulp drying to the reduction in the swellability of fibres. Another effect of drying is the closing of pores, which are not fully re-opened under normal refining conditions (Stone et al. 1968, Maloney and Paulapuro 1999). Normally, fibres collapse under deformation and bending from external pressures. In the absence of external pressures, fibres collapse under surface tension as water evaporates, as it does in pulp drying.

In mechanical pulping, mechanical pre-treatment before refining has been found to be highly justified in improving the efficiency of refining, resulting in improved fibre quality, and reduced refining energy consumption (Sabourin 2000, Kure et al. 1999, Law et al. 2000, Viffor and Salmén 2008). Yung et al. (2002) conducted experiments by using a mixer with compressive and shear action on chemical pulps fibres and old corrugated containers (OCC). They concluded that the WRV and strength properties of a pre-treated fibre furnish were higher than those of an untreated furnish. Wang et al. (2006) used a Material Test Simulator (MTS) to subject a thick pulp pad to compression action, finding a similar improvement in strength properties for the treated pulp.

Mechanical pre-treatment

To generate a treatment that involves a combination of compression, shear forces and heat, an EP-210 laboratory calender was used. The design of the calender is shown in Figure 21. The EP-210 calender consists of two rolls with two independent motors, a hydraulic unit to generate hydraulic pressure in the calender nip, a load cell, an IR heater to adjust the temperature of the rolls, and a speed control unit to adjust the calender speed. The nip load of the two rolls can be varied in the range 0-300 kN/m, the calender operated in speed range 0-40 m/min, and the speed difference between the two rolls changed (from+1 m/min to –1 m/min) to create shear forces.

The pulps used in the trials were a never-dried softwood kraft pulps; for details, see article [IV]. Pulp sheets of 500 g/m^2 were prepared for mechanical treatment using a traditional laboratory sheet mould measuring 16 x16 cm. The pulp sheets were couched with two dry blotters without any pressing and the final solids content of the pulp sheets was in the range of 20±3%.

Figure 21. Design of EP-210 calender.

The compression forces applied as linear loads in the pre-treatment caused different types of deformation in the direction of fibre axis and transverse dimensions. The decrease in fibre cross section area was assessed by Confocal Laser Microscopy (CLSM) and represented as the collapse index of the lumen area and calculated according to equation number 1, based on Jang et al. (1998). $A_{collapsed}$ is the lumen area obtained from cross sectional images of treated fibres, and $A_{uncllapsed}$ is the lumen area before the treatment. Increased linear load caused a higher degree of lumen collapse, and an increased number of passes promoted the collapse of fibres, as shown in Figure 22.

$$\text{Collapse Index (CI)} = 1 - \frac{A_{collapsed}}{A_{uncollapsed}} \qquad [1]$$

The application of linear loads on wet pulp tends to close a proportion of pores in the fibre wall structure, and therefore the pore water and fibre saturation point (FSP) decrease, as shown in Figure 23. Consequently, linear loads cause increased fibre collapse and flattening of fibres, and thereby an increased fibre area for bonding and densification of the fibre network which is reflected as an increased tensile index. An increased number of passes through the calender nip enhances the development of the tensile index, with the increasing trend levelling out after four passes, as shown in Figure 24.

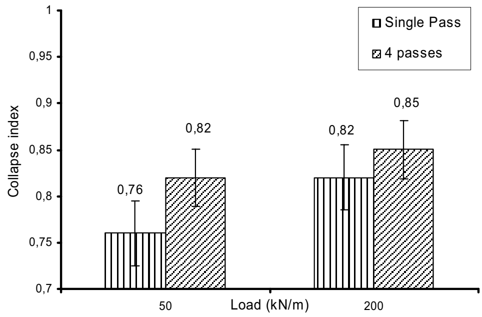


Figure 22. Collapse index vs. linear loads

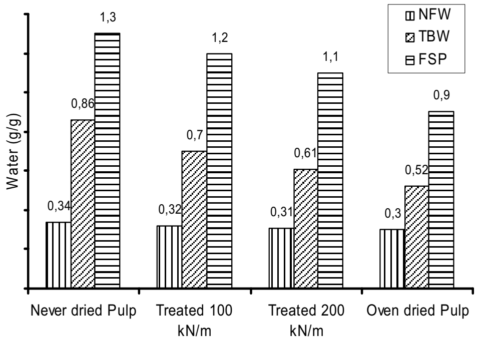


Figure 23. Fibre saturation point (FSP), non-freezing pore water (NFW) and total bound water (TBW) vs. linear load.

The running speed or the nip residence time, together with the linear load, determines the load impulse. An increase in running speed decreased the fibre residence time under load, thus reducing fibre deformation, and consequently the collapse and deswelling of fibres. The effect of shear forces on the tensile index was rather low compared to the changes in tensile index caused by increasing linear loads. An increase in the roll temperature was found to have a positive effect on the tear index as the roll temperature increased from 30°C to 150°C. The presence of heat tends to increase the plastic deformation and relative compressibility of fibres, which results in increased fibre deformation under load.

To determine the importance of each calender variable studied, a Partial Least Squares Projection to Latent Structure (PLS) statistical model was built. The model was designed to clarify the importance of each calender variable (inputs) for the measured fibre and paper properties (Ericksson 1999), as shown in Figure 25. The number of passes and load applied in each pass are the most relevant in explaining the changes in fibre and paper properties, followed by heat, running speed and speed differences (shear forces)

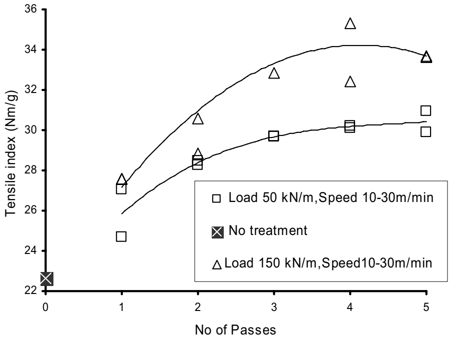


Figure 24. Tensile index vs. number of passes.

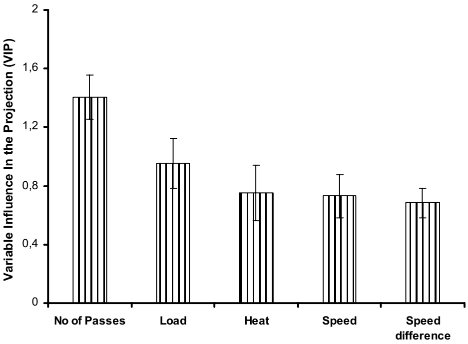


Figure 25. Importance of calender variables.

Mechanical pre-treatment and refining

Three types of pulps were compared under the same refining conditions: never dried, once dried and mechanically pre-treated pulp. The details of the pulps and their treatment are given in article [IV, Table1]. Pulp freeness is closely related to several phenomena in refining, such as external fibrillation, fibre shortening and fines creation. Never dried pulp lost its freeness faster during refining than dried pulp and mechanically pre-treated pulps, and the pre-treated pulp retained a higher freeness than once dried pulp, as shown in Figure 26. External fibrillation is calculated as the proportion of the fibril area of the total fibre area in microscopy images. Never dried pulp showed the highest amount of fibrillation and mechanically treated pulp the lowest, when compared at the same refining energy input, as shown in Figure 27. Mechanically treated fibres showed a lower tendency to fibrillate, to shorten and to produce fines in refining, compared to other pulps, which contributed to its higher freeness.

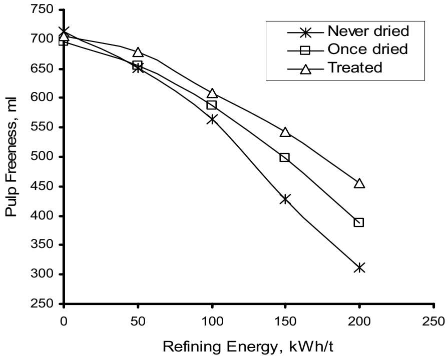


Figure 26. Pulp freeness vs. refining energy.

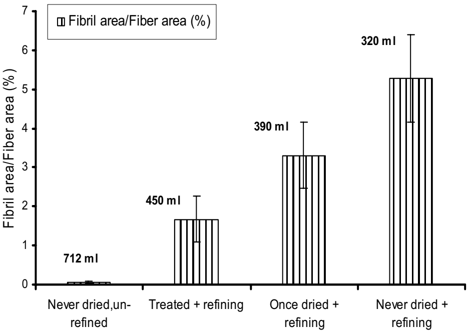


Figure 27. External fibrillation vs. refining (200 kWh/t), the number above each column represents the pulp freeness.

The filtration properties of fibres were examined in terms of the flow resistance of fibres (R200) collected from refined pulps at a refining energy level of 200kWh/t. Figure 28 shows the flow resistance during dewatering as a function of dewatering time. The refined never dried fibres showed the highest dewatering resistance, whereas mechanically pre-treated fibres and dried fibres showed lower dewatering resistance, which means better drainability. The flow resistance showed a strong correlation ($R^2=0.8$) with the fibre swelling FSP value; hence, the greater the swelling, the higher the dewatering resistance.

At a given refining energy level and pulp freeness, both never dried and mechanically pre-treated pulps developed a higher tensile index than once dried pulps, as shown in Figure 29. In Figure 30, the tear index is plotted against refining energy. At a given level of refining energy, the mechanically pre-treated pulp showed an average value between the high tear index of once dried and the low tear index of never dried pulp. In both mechanical pre-treatment and drying, water is pressed out from the fibres, causing the fibres to de-swell, pores to be closed and bonding to develop between microfibrils. This makes the fibre wall stiff and rigid, so the resistance to tear increases. However, the effect is stronger in drying than in mechanical treatment. Fibres are also curled, kinked and micro-compressed during water removal, so a paper sheet made of such fibres has a poor tensile index, but improved tear strength (Page 1985, Fellers et al. 2001).

The tensile stiffness and probably also the dynamic visco-elastic behaviour of the paper web are a good measures of the paper machine's output rate (Uesaka 2001). Wathén (2006) commented on the importance of tensile stiffness and web uniformity for problem free runnability. Figure 31 shows the development of tensile stiffness with refining. When all pulps are compared at a given freeness, the pre-treated fibres show a greater tensile stiffness than never dried and once dried pulps.

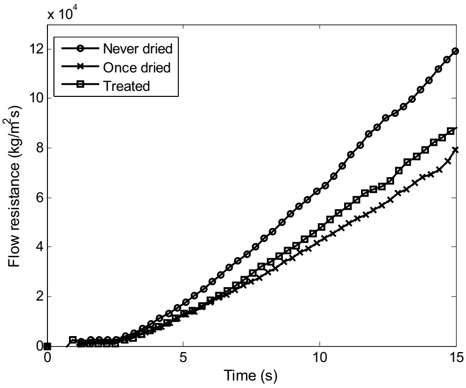


Figure 28. Flow resistance vs. dewatering time (R200).

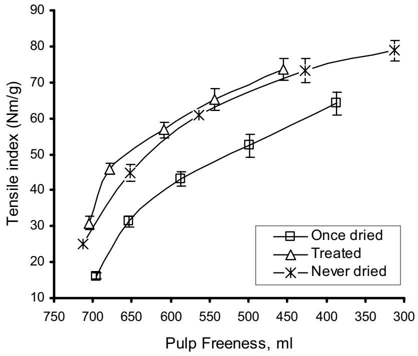


Figure 29. Tensile index vs. pulp freeness.

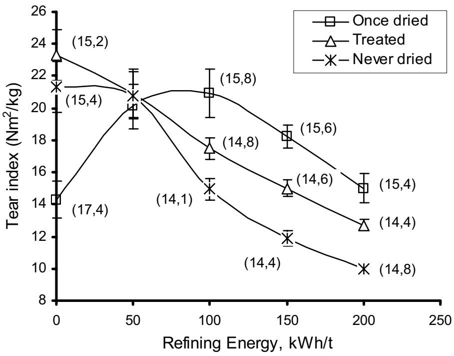


Figure 30. Tear index vs. refining energy, the numbers beside the points indicate the curl index in %.

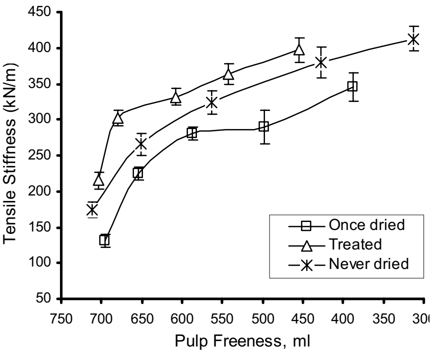


Figure 31. Tensile stiffness vs. pulp freeness.

Summary of part 2

The new mechanical pre-treatment examined was found to significantly influence the strength-dewatering properties by promoting lumen collapse and the de-swelling of fibres. Optimum conditions for the treatment were a high linear load and temperature, low speed, high shear forces and multiple-pass treatment. In refining, mechanically pre-treated fibres showed a consolidated structure that resulted in less external fibrillation, and less fibre cutting and fines creation and they therefore retained a higher freeness after refining. Mechanically pre-treated fibres showed good dewatering comparable to that of once dried pulp and better than that of never dried pulps. At a given level of refining energy, mechanically pre-treated fibres develop higher tensile strength, tensile stiffness and Scott bond than once dried pulp. Compared with never dried pulps, the mechanically pre-treated fibres develop a better tear index. The treatment offers a flexible industrial tool to modify pulp before refining and the possibility to optimize the combination of strength and dewatering of refined fibres.

Part 3: Impact of fibre properties and filling design on refiner loadability and refining characteristics

Papermaking fibres tend to agglomerate and form flocs by mechanical or chemical mechanisms. Kerekes et al. (1985) generalized the idea of Mason (1950), and Meyer and Wahren (1964) and proposed the crowding number “N” to define the numbers of fibres in a volume swept out by the length of a fibre. At low shear or decaying turbulence the fibres tend to build up and form flocs, and at high turbulence and high shear, the fibre flocs are dispersed and broken up. Floc formation, floc dispersion and floc size measurements have been studied by several researchers (Steen 1989, Stoere et al. 2001, Switzer et al. 2003, Salmela et al. 2005).

A number of refining effects have been identified and characterized by many authors, including Higgins and de Yong (1961), Giertz (1980), Ebeling (1980), and Page (1989). Primary refining effects consist of the structural changes associated with refining, distinguishing beaten fibres from unbeaten fibres, i.e., internal fibrillation (swelling), external fibrillation, fines formation, fibre cutting or shortening, and fibre curling or straightening. Internal fibrillation is related to the breakage of internal bonds between microfibrils under the strains imposed by normal forces inside the refiner (Stone et al. 1968, Kerekes and Senger 2006). External fibrillation is the peeling off of fibrils from the fibre surface while fibrils are still attached to the fibre body (Page 1989). Formation of fines is similar to external fibrillation but the fibrils are completely detached from fibres. Both fines and external fibrillation are created by the shear strains inside the refiner. Fibre straightening/curling originates from the tension strain inside refiner.

The behaviour of the refiner gap during refining has attracted the interest of many researchers (Range 1951, Steenberg 1951, Page et al. 1962, Fox et al. 1979), concluding that the refiner gap is related to fibre characteristics and that the pulp flows as flocs inside the refiner grooves. In 1990, Hietanen and Ebeling proposed a floc refining hypothesis which entails an increase in the refiner gap with an increase in pulp flocculation. In experiments with a single-bar refiner, the forces and force distribution among fibres have been used to characterize the refining action (Martinez and Kerekes 1994, Martinez et al. 1997, Batchelor et al. 1997).

Floc size measurement

In the present study, the flocculation of pulps was studied in a flow loop system simulating refiner grooves and the flow velocities in refining, see Figure 31. The loop consisted of a 0.2 m^3 tank, a centrifugal pump, and a plastic flow loop with an inner diameter of 40mm and slit height of 5 mm (refiner groove width). The average size of flocs was evaluated downstream after the abrupt contraction from 40 mm through the slit of 5 mm using a fast CCD camera mounted above the slit. A computer program was used to adjust the flow speed, light source, and position of the camera. A total of 200 images per position along the slit were taken. After correcting the images for uneven illumination, the floc size was determined in the flow direction (FD) and the transverse flow direction (TD) as a run-length average of the median thresholded image, described in detail by Kellomäki et al. (1999), Karema et al. (2001), and Salmela et al. (2005).

As the pulp flows through the slit (5 mm) and after the contraction from the 40 mm size tube, the flocs are subjected to both deformation and stretching. The deformation seen as the floc size has decreased at the end of the slit by 30% from its original size at the slit inlet. The floc deformation is due to turbulence and wall shear forces, which deform the flocs and reduce floc size along the slit, as shown in Figure 32. The stretching seen as the flocs aspect ratio (FD/TD) was 1.5-1.9 times larger in the FD than in the TD at the slit inlet. By the end of the slit the flocs retain their spherical shape and the floc aspect ratio reaches the level of 1.0, as shown in Figure 33. The stretching strain is due to the abrupt contraction at the slit inlet. Pulp with long and coarse fibres forms large and strong flocs that are able to resist floc size reduction better along the slit compared to pulp of shorter and thinner fibres. The change in floc size is also related to floc residence time inside the slit; the longer the residence time the greater the deformation and the more floc size changes due to floc deformation.

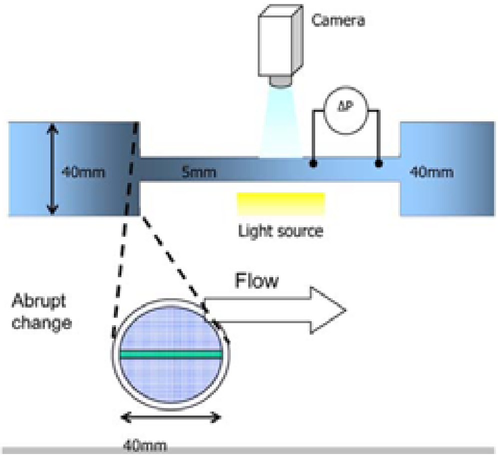


Figure 31. Flow geometry used in measurements. The tube and slit dimensions (height and length) were used to simulate refiner grooves.

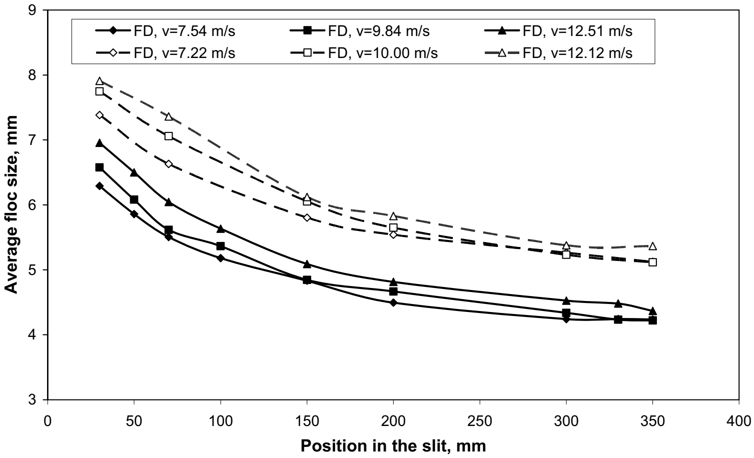


Figure 32. Average floc size in flow direction (FD) along the slit at different flow rates. Results for pulp 1 are marked with solid symbols and for pulp 2 with open symbols. The pulps' characteristics are listed in Table 1- Article [V].

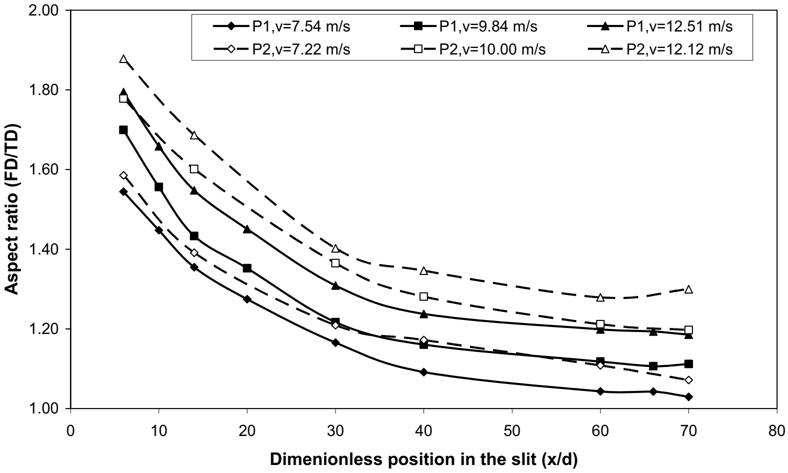


Figure 33. Floc aspect ratio along the slit at different flow rates, position is scaled with height of the slit. Results for pulp 1 are marked with solid symbols and for pulp 2 with open symbols. The pulps' characteristics are listed in Table 1- Article [V].

Fibre properties and refiner loadability

The refining trials were conducted with a Voith LR 40 Laboratory refiner. The refining was carried out at the same conditions of 2000 rpm, a refining energy input of 50 kWh/t and a specific edge load of 2.0 J/m. The data collected from the refiner includes the no-load power, total power and the stator movement indicating the refiner gap between the rotor and stator during refining. The refiner loadability and the trapping point at which the fibres start being picked up by the rotor and stator bars, and, accordingly, the power consumed in actual refining, were calculated using a technique similar to the one proposed by Batchelor et al. (2006). Figure 34 shows the net power in refining against the gap movement. The pulp with long and coarse fibres was trapped early in gap closure, maintaining a wider gap than the pulp with shorter and thinner fibres.

Figure 35 shows the net power and gap movement for pulp with short and thin fibres at a constant consistency of 4% when the fibre characteristics were changed by adding 30% and 60% by weight of pulp with long and coarse fibres. Increased addition is reflected as an earlier trapping point and an increase in gap width due to the increase in floc size caused by long fibres. An increase in pulp consistency (from 2.0% to 5.5%) hardly changed the trapping point, causing only a minimal change in gap width. The effect of increased pulp consistency was small compared to the change in fibre characteristics caused by addition of long and coarse fibres.

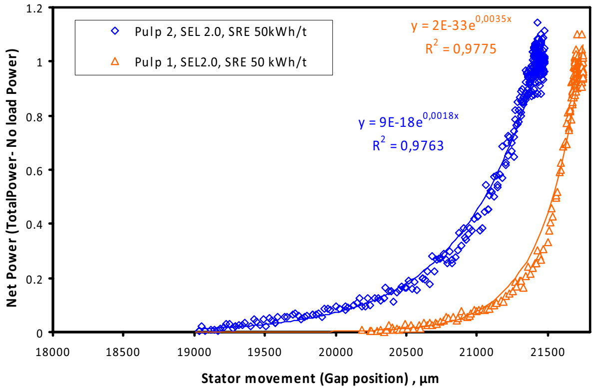


Figure 34. Net power as a function of stator movement (gap closure) in refining with conical fillings. The pulps' characteristics are listed in Table 1- Article [V].

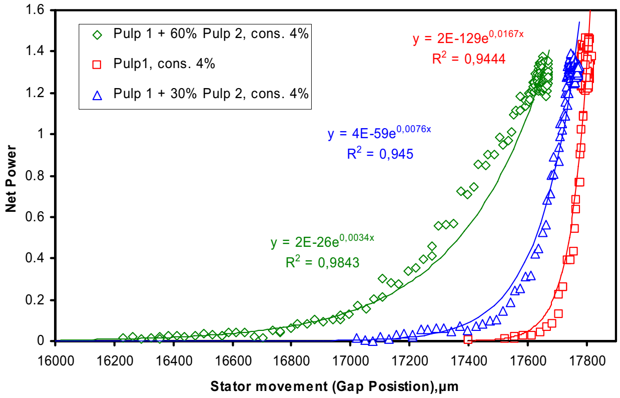


Figure 35. Net power as a function of stator movement (gap closure) in refining of pulp 1 with 30 and 60% addition of pulp 2.

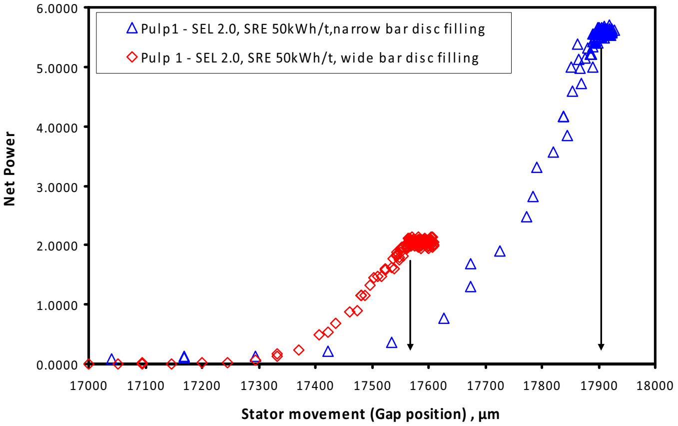


Figure 36. Net power as a function of stator movement (gap closure) in refining pulp 1 with wide-bar and narrow-bar disc fillings.

Filling design and refiner loadability

For a certain pulp, both wide-bar and narrow-bar fillings have the same trapping point, where the wide-bar disc fillings maintaining a wider gap than the narrow-bar disc fillings and the net power for narrow-bar disc fillings being almost three times the net power for wide-bar disc fillings, as shown in Figure 36. This is explained by the high edge cutting speed of the narrow-bar disc fillings; the gap width was found to decrease linearly with the increase in net power and bar edge cutting speed.

When refining different pulps with the narrow-bar disc fillings (high cutting edge speed), both pulps tended to behave similarly with the same trapping point and gap width. The narrow-bar disc fillings with narrow grooves and high cutting edge speed create a high shear field inside the refiner which disperses and breaks fibre flocs in the refining zone and differences in floc sizes do not cause big differences in the gap width, trapping point or loadability of the refiner.

Impact on refined fibres

The fibre straightening or fibre curl occurring in pulp refining has recently attracted a lot of attention, as uncurled fibres have been found to improve tensile strength and load-transferring efficiency (Page 1985, Mohlin 1996, Seth 2006). Both conical and wide-bar disc fillings showed a straightening effect as the measured average fibre length tended to increase due to refining (SRE=50 kWh/t). Both fillings had low cutting speed and wide grooves, which are assumed to be beneficial in reforming and relaxing the fibres after impacts between the rotor and stator bars. The effect of narrow-bar disc fillings was fibre cutting, with the cutting effect being greater in pulp with long and coarse fibres, as shown in Figure 37. The big flocs are easily trapped between bars and are therefore subject to more intensive cutting action compared to small and weak flocs which tend to break easily and pass through the refining zone.

External fibrillation is another refining effect whose importance for strength properties has been examined in only a few studies (Casey 1960, Nanko 2003, Kang 2007). Figure 38 shows the changes in external fibrillation as a function of the type of pulp and filling design. The big flocs formed by long and coarse fibres are able to resist high shear forces between fibres and friction, which leads to higher external fibrillation. In contrast, small flocs are not so easily trapped between bars, especially in the wide grooves of conical fillings, which showed the smallest increase in external fibrillation. Narrow-bar disc fillings produced the greatest external fibrillation due to the high shear forces of the filling.

Big flocs maintained a wide gap between rotor and stator, and the bigger the flocs, the less the fibres were subjected to forces, and the less they swelled. The increase in the cutting speed of fillings tends to increase the intensity of forces acting on fibres, causing more fibre strain and more cell wall breaking, and, accordingly, greater fibre swelling (increase in FSP). Therefore, conical fillings with the lowest cutting speed showed the smallest increase in fibre swelling, whereas the narrow-bar fillings with the highest cutting speed showed the greatest increase in fibre swelling.

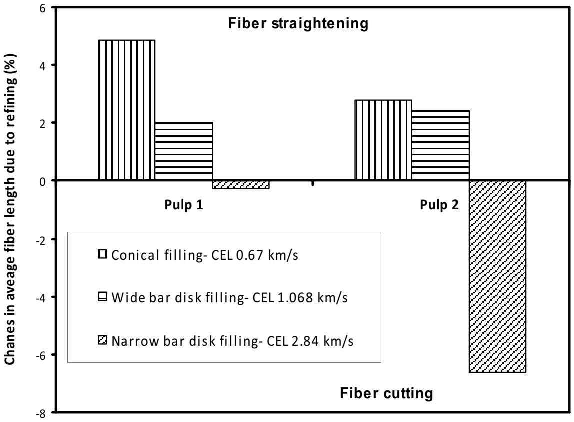


Figure 37. Change in average fibre length in refining with different fillings.

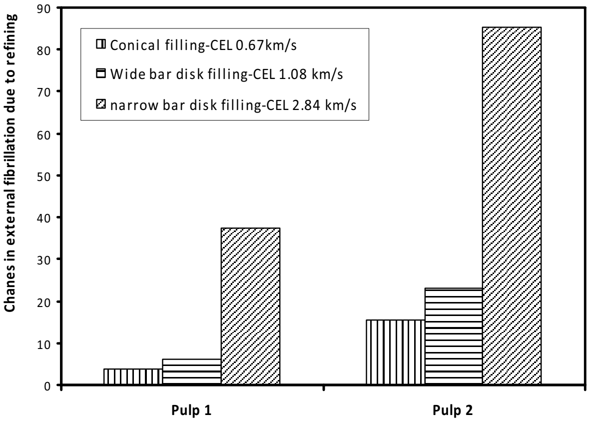


Figure 38. Change in average external fibrillation in refining with different fillings.

Summary of part 3

Fibres characteristics such as fibre length and coarseness together with pulp consistency, contribute to the type of flocs formed during refining. Long and coarse fibres form big and strong flocs that are stable with less reduction in size under deformation. This was also reflected in the trapping of fibres and gap width during refining. Big flocs were trapped early in refining and maintained a wider gap compared to fibres that form smaller flocs. The effect of pulp consistency on fibre trapping (loadability) and gap width was smaller than that of fibre properties (length, coarseness)

The trapping point and gap width are also linked to details of the filling design, such as groove width and bar edge cutting speed (km/s). Fillings with wide grooves and low edge cutting speed impart a mild effect on fibres flocs and maintain a wide gap, whereas in refining with high edge cutting speed fillings, the differences in floc size originating from differences in fibre properties did not produce clear differences in gap width or the trapping of fibres. The refining results such as swelling, external fibrillation and fibre cutting are dependent on the filling design, the type of fibres and fibre properties, so selecting the right type of fillings for a specific fibres is the most effective way to optimize the obtained refined pulp properties.

Part 4: On-line measurements of fibre properties and control of pulp quality in drying and refining

Wood fibre properties differ within a species, between trees of the same species, inside the tree stem (juvenile wood, mature wood) and even within one growth ring (earlywood, latewood). One step further towards tailoring pulp quality for specific paper products is to apply advanced on-line fibre property measurements. The fibre length, perimeter, wall thickness and wall area, as well as the number of fibres per unit weight, have been found to be critical in designing or selecting fibres for different paper grades (Lee et al. 1993, Kibblewhite 1999).

Since the early 1970s, optical fibre quality analyzers have been available in the market, making it possible to measure fibre length, width, deformation, fines and bendability. These analyzers use polarized light to project images of the fibres in the measured sample (Robertson et al. 1999, Guay et al. 2005, Turunen et al. 2005), one of such analyzers is the L&W Fibremaster which can be used to measure fibre length, width, shape, kink, fines, coarseness, bendability, vessels, and shives (Karlsson et al. 1999, Karlsson 2004).

For mechanical pulp characterization, Forgacs (1963) used two quality parameters, the shape and length factors. Mannström (1967) divided the length factor used by Forgacs into mean fibre length (d) and fibre length distribution (n). Later on Strand (1987, 1989) introduced the factor analysis technique to explain variations in the measured pulp and paper properties of mechanical pulps based on independent factors. This technique was also found to allow good control of the grinding process (Paulapuro and Ryti 1976). For chemical pulp, Howard et al. (1994) and Page (1989) concluded that beating of chemical pulps is a process that should be examined by factor analysis and laboratory beating was explained by three factors: bonding, fibre length and fines, and micro-compressions.

Factor analysis is a data reduction technique used to reduce a large set of interrelated variables into a few common factors. Therefore, factor analysis is well suited for processing fibre and paper property data sets, as they involve strong interrelations. The data reduction is carried out by examining the degree of correlation among the data sets and expressing each variable in terms of common factors. The basic sets of equations which relate variables to the common factors are explained with details at Strand (1987), Strand et al. (1989), and Sharma (1996).

Factor network and control model

A factor network was developed and used to link the measured fibre properties and paper characteristics. In the first phase of the work, an off-line quality control model was constructed. In the second phase, the quality model was tested on-line with real pulp mill trials, as shown in Figure 40. The factor network was built to comprise input variables, common factors and output variables and was used to evaluate the relationship between all variables for never-dried and machine-dried pulps. On one side of the network are input variables which cover the measured pulp properties (freeness, fines content, average fibre length, fibre width, shape factor and dry solids content). On the other side of the network are the output variables, which cover all measured paper properties. The fibre properties were collected from the FibreMaster measurements and all statistical factor analyses were carried out using the Pacific simulation software package FactNet® (Pacific simulation 2002).

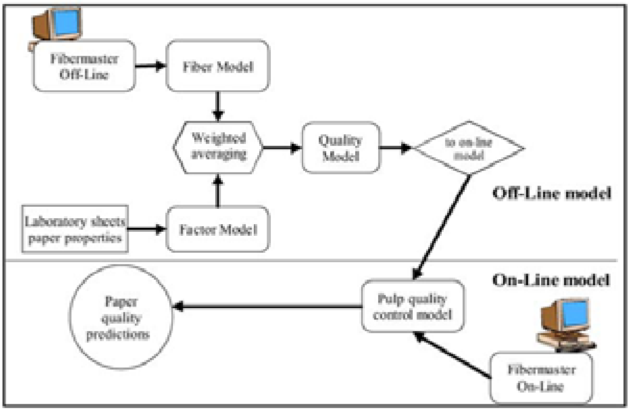
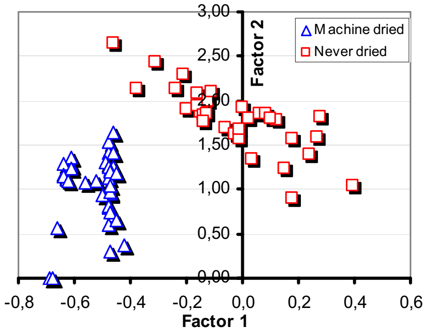


Figure 40. Off-line and on-line model combination layout.

Quality control of never and machine-dried pulp

From the off-line model, it was found that only three factors were enough to explain around 84.6% of the total variability in the pulp and paper data set. Factor 1 was found to represent the bonding factor correlating positively with strength properties, negatively with light scattering and increasing with an increase in fines content. Factor 2 was found to depend on fibre dimensions, basically fibre length and width, correlating positively with tear and fracture toughness index. Factor 3 was found to be related to the fibre shape (curl index), increasing with an increase in elongation and zero span strength.

The on-line data collected from the FibreMaster with the factor model established in the off-line phase were used to calculate a factor network. A quality map of Factors 1 and 2 was set up and used to control the quality of the pulp before and after pulp drying, as shown in Figure 41. This map was updated every 15 minutes using the on-line FibreMaster measurements and the quality of pulp was then described as a point of (X, Y) coordinates in a (F1-F2) map of never and machine-dried pulps.



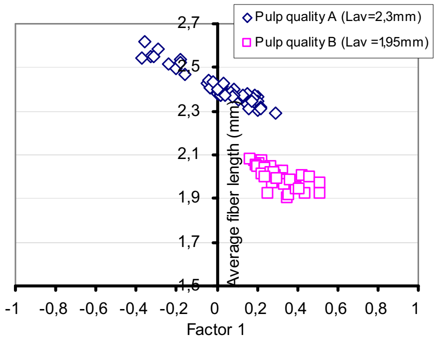


Figure 41. Quality map of F1-F2 for never dried and machine-dried pulps by using on-line model.

Figure 42. Different pulp qualities vs. factor 1.

The quality criterion using calculated factors (F1, F2) and the predicted paper properties were helpful in monitoring the changes in pulp quality and how they are reflected in targeted paper properties. For instance, when the pulp mill switched to a pulp with lower average fibre length (from 2.30 mm to 1.95 mm), the quality window reflects a strong decrease in Factor 2 and tear index. This change was also seen as an increase in Factor 1, as shown in Figure 42. Consequently, the quality window offers a good tool for on-line monitoring of the variations in pulp quality due to variations in raw materials or pulping conditions.

The paper properties predicted with the on-line model were tested and compared against laboratory-measured values for handsheets made from pulp samples of never-dried and machine-dried pulp. Using the measured fibre properties of never dried pulp, the on-line model is able to predict the papermaking properties of both never dried and machine-dried pulps. The on-line model produces a good prediction of the tensile index, Scott bond, light scattering coefficient and sheet density with R^2 values of 0.85, 0.88, 0.76, and 0.73, respectively, see Figure 43. For never dried pulp samples, the laboratory measured tear index values were slightly lower than the values predicted by the model, while for machine-dried samples there was a better fit to line y=x. Therefore, the R^2 value for the tear index was only 0.55, as shown in Figure 44. These results show the suitability of the model for fast and reliable follow-up of quality changes due to effects of pulp process (pulp drying) and variations in raw materials (different average fibre length).

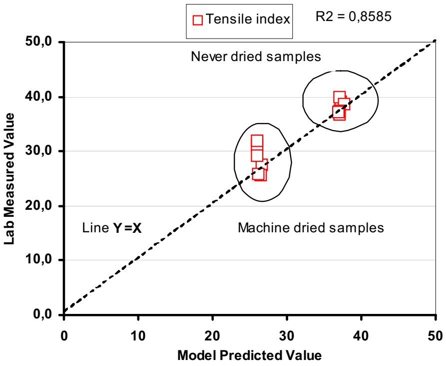


Figure 43. On-line predicted tensile index versus laboratory-measured value.

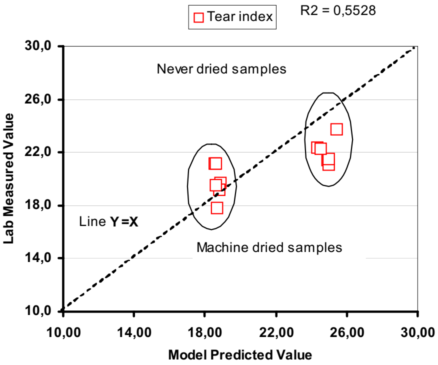


Figure 44. On-line predicted tear index versus laboratory-measured value.

Quality control in pulp refining

In the present study, the factor network was used to link input variables, which cover pulp properties and refining conditions (SEL, SRE), and handsheets paper properties as output variables. From this network, three factors were derived statically and found to account for about 90% of the data set's total variability. The network was used to describe changes in pulp quality due to refining and to predict the paper properties based on measured fibre characteristics and refining conditions (SEL, SRE), as shown in Figure 45. The refiner simulator used measured fibre properties (length distribution and pulp freeness) and refining conditions to calculate the three common factors needed to calculate the output paper properties. To examine the mechanism of strength properties and to find out how common factors could be used, tensile strength mechanism was explained by three factors and being dependent on fibre curl, FSP, fibre strength and fibre length.

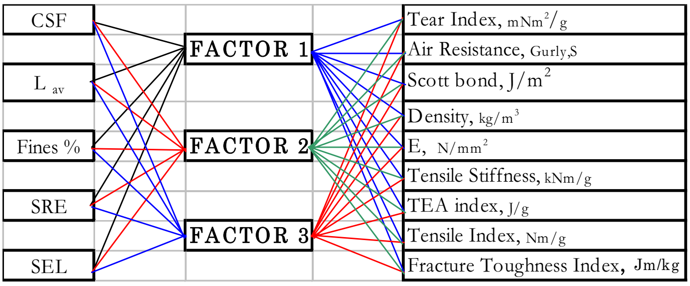


Figure 45. Factor network used in refining analysis.

The calculated factors could also be used also as a basis to define optimum refining conditions and major changes in fibre characteristics due to refining, such as bonding development, fibre straightening/curling and fibre cutting. Figure 46 shows the development of the bonding factor (F1) against refining energy during refining of never dried softwood pulps. An increase in refining energy tends to promote the bonding potential of fibres through increased fibre swelling, conformability, and, accordingly, inter-fibre bonding. The bonding potential (F1) reached a maximum at around 170kWh/t and after that the bonding potential is started to decline. Factor 2, which represent the fibre length reached a maximum at an energy level of 80kWh/t at which the fibre straightening reached a maximum, as shown in Figure 47. After this maximum point, fibres started again to move towards increased curling and when the energy level reached the level of about 170kWh/t fibre cutting began: the higher the energy level, the greater the fibre cutting. The point (SRE 170kWh/t) after which the Factor 2 becomes negative, which indicates vigorous fibre cutting is the same point at which the bonding factor (F1) reaches the maximum. The severe fibre cutting after a SRE of 170kWh/t contributes to the decreases in fibre strength and therefore to a decrease in the bonding factor (F1).

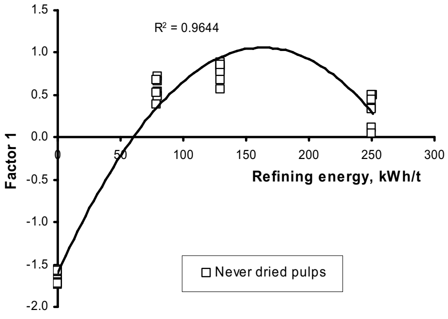


Figure 46. Factor 1 vs. refining energy, SEL =2.0 J/m.

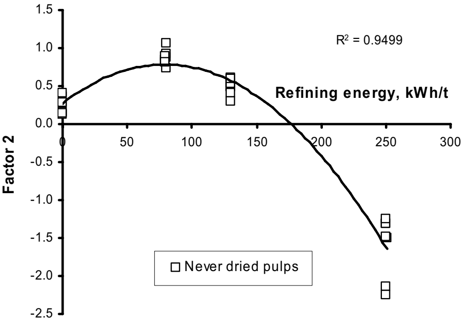


Figure 47. Factor 2 vs. refining energy, SEL=2.0 J/m.

Summary of part 4

Factor analysis and on-line fibre properties measurements could be used as an effective tool to monitor changes in pulp quality such as variations in wood raw materials (changes in average fibre length) and due to pulp processes (drying, refining). It was possible to develop an off-line model that was used later together with on-line fibre properties measurements to control pulp quality before and after drying and to predict paper properties of unrefined never dried and once dried pulps. A similar model of pulp refining, including refining conditions, was used together with fibre properties to predict paper properties of refined pulp and to determine optimum refining conditions and changes in fibre characteristics due to refining. In addition, other variables describing refiner filling dimensions, sharpness and filling material can be added to the factor network for further studies. Accordingly, a combination of on-line fibre property measurements and factor analysis techniques will offer a new approach to control pulp quality, pulp beatability and resulting paper properties.

CONCLUSIONS

The objective of this study was to find and test certain approaches to tailoring and modifying chemical pulp fibre properties. The focus was on the following: fibre classification using pressure screen fractionation, mechanical pre-treatment before refining, the role of fibre properties and filling design for refiner loadability, and on-line measurement and control of pulp quality. The focus was on the impacts of these approaches on fibre properties, energy saving and the improvements of the resulting paper properties as well as the strength-dewatering combination.

Pressure screen fractionation was found to be a useful approach to tailor a wide range of fibres such as bagasse, eucalyptus and softwood. The screen size, fractionation layout (single or two-stage) and the operating reject rate determine the quality of each fraction produced. In bagasse pulp, the reject fraction was found to compensate for the slow drainability of unfractionated fibres maintaining higher consistency with the same dewatering time and carrying higher structure pressure at the same consistency, ultimately resulting in better wet web runnability.

In refining trials, bagasse and eucalyptus pulps reject fibres showed higher swelling than the unfractionated refined fibres at the input of same refining energy. The refining of the reject fraction was found to be more homogeneous and energy-efficient in opening the cell wall pore structure, accordingly producing greater fibre swelling. In mixture sheets of eucalyptus and softwood, the reject fraction was found to be beneficial in developing a higher tensile index, fracture toughness and bulk of mixture sheets. Consequently, when using the reject fraction in this way, the addition of expensive softwood pulp can be reduced by optimizing the average fibre length and width of the mixture. The reject fraction from softwood fractionation resulted in a higher tear index, though more refining energy was needed to reach a certain tensile index. Narrow-bar disc fillings are more energy-efficient than conical fillings, but low refining intensity (specific edge load) is recommended to preserve average fibre length and reduce fibre cutting.

Accept fractions from bagasse and softwood fractionation were used to replace part of the once dried softwood pulp before refining. Up to 20% replacement reduced the refining energy input needed to reach a certain tensile index without causing a major decrease in the tear index. The replacement also improved light scattering and internal bond strength.

A new mechanical treatment that involves the application of linear loads, heat and shear forces over multiple passes was found to be beneficial in altering the fibre structure before refining. The treatment promotes the lumen collapse and deswelling of fibres, and hence the combination of strength and dewatering properties of the softwood fibres. In refining, mechanically pre-treated fibres showed a consolidated structure with less fines creation, less fibre cutting and less external fibrillation, accordingly maintaining high freeness after refining. Compared with once dried fibres, mechanically pre-treated fibres offered the advantage of higher tensile strength, stiffness and Scott bond at a certain freeness level. Compared with never-dried fibres, mechanically pre-treated fibres offered the advantage of higher tear and tensile stiffness. The treatment was carried out with industrial equipment, which makes it a flexible tool for modifying fibres before refining as a means to optimize the combination of strength and dewatering properties.

The trapping of fibres between the rotor and stator bars of the refiner and therefore the consumption of energy and the movement of the refiner gap, are strongly linked to the type of fibres and filling design. Fibres properties and pulp consistency in refining contribute to the size of flocs and the ability of flocs to resist deformation during refining. Fibres that build big and strong flocs are trapped early in the gap closure and maintaining a wide gap. Here, the effect of pulp consistency was found to be smaller than the effect of fibres properties such as fibre length and coarseness. Filling design influences the gap movement and trapping of fibres, and the gap width decreases linearly with an increase of filling edge cutting speed (km/s) or the applied net power. Selecting the right filling design for specific fibres is the most effective way to optimize resulting refining characteristics such as external fibrillation, fibre cutting and fibre swelling.

On-line fibre property measurements combined with factor analysis techniques offer a new method for controlling pulp quality, pulp beatability and for predicting paper properties. The factor network was used to link the measured fibre properties, calculated factors and the resulting paper properties. Thus, it was used to monitor and follow up changes in raw materials such as varying fibre length and changes due to pulp drying and refining. For a pulp mill, the model was built off-line, extended with on-line measurements and verified against laboratory measurements showing high accuracy in predicting paper properties. The factor network was tested with laboratory refining trials, showing good ability to monitor changes in fibre properties during refining such as the developing of bonding, fibre cutting, fibre straightening and curling. The refiner off-line model can also be used to determine optimal refining conditions based on calculated factors and refining energy inputs.

The possibility to incorporate fractionation and pre-treatment before refining into the stock preparation processes are an ideal means to tailor certain fibres for different paper grades, cut energy and raw materials costs and provide a high flexibility with certain raw material on different production lines. The combination of the fibre quality control models with the process modification approaches proposed in this study enable both pulp and papermakers alike to engineer the available raw materials and get the most out of it with a designed fibres for a designed paper product.

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