



Faculty of Technology and Science
Chemical Engineering

Hanna Karlsson

Some aspects on strength properties in paper composed of different pulps

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SE-651 88 Karlstad

SWEDEN

Phone +46 54 700 10 00

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Abstract

For paper producers, an understanding of the development of strength properties in the paper is of uttermost importance. Strong papers are important operators both in the traditional paper industry as well as in new fields of application, such as fibre-based packaging and light-weight building material. In this study, two approaches of enhancing paper strength, reinforcement and multilayering, were addressed. In specific, the effects of adding abaca (*Musa Textilis*) as a reinforcement fibre for softwood pulp were investigated. Moreover, a handsheet former for the production of stratified sheets, the *LB Multilayer Handsheet Former*, was evaluated. The LB Multilayer Handsheet Former was then used to study the effects of placing selected fibres in separate layers, rather than by making homogeneous sheets from a mixture of the pulps.

Handsheets of a softwood sulphate pulp with the addition of abaca fibres were made in a conventional sheet former. It was seen that the addition of abaca fibres increased the tearing resistance, fracture toughness, folding endurance and air permeance. Tensile strength, tensile stiffness and tensile energy absorption, however, decreased somewhat. Still it was possible to add up to about 60% abaca without any great loss in tensile strength. As an example, with the addition of 30% abaca, the tear index was increased by 36%, while the tensile index was decreased by 8%.

It was shown that the LB Multilayer Handsheet Former is suitable for studying the effects of stratification of paper. The sheet former produces sheets with good formation and the uniformity of the sheets, evaluated as the variation of paper properties, is retained at a fairly constant level when the number of layers in the stratified sheets is increased. The uniformity of the sheets produced in the LB Multilayer Handsheet Former are generally at the same level as of those produced in conventional sheet formers.

Homogeneous and stratified sheets were produced in the LB Multilayer Handsheet Former and it was found that by stratifying a sheet, so that a pulp with a high tear index and a pulp with a high tensile index are placed in separate layers, it was possible to increase the tear index by approximately 25%, while the tensile index was decreased by 10-20%.

List of papers

The thesis is based on the following papers, which are referred to by their Roman numerals in the thesis:

- I Karlsson, H., Beghello, L., Nilsson, L., Stolpe, L.
Abaca as a reinforcement fibre for softwood pulp.
Accepted for publication in Tappi Journal.
- II Karlsson, H., Nilsson, L., Beghello, L., Stolpe, L.
Handsheet former for the production of stratified sheets.
To be submitted to Appita Journal.
- III Karlsson, H., Stolpe, L., Beghello, L.
Paper strength evaluation both in homogeneous and in stratified sheets with selected fibres.
To be submitted to Journal of Pulp and Paper Science.

Reprint of paper I has been made with permission from the publisher.

The author's contribution to the papers:

- I Main author of the manuscript, major part of the experiments and analyses.
- II Main author of the manuscript, experiments and analyses in part.
- III Main author of the manuscript, major part of the experiments and analyses.

List of symbols and abbreviations

Symbols, Latin

A	Crack area, for the calculation of energy release rate
d	Diameter of a circle circumscribing a fibre, for the calculation of the shape factor of the fibre
G	Energy release rate
J	Calculated value of the J-integral
l_f	Fibre length
\log_{10}	Common logarithm
m_1	Weight of a centrifuged pulp sample, for the measurement of water retention value
m_2	Weight of a centrifuged and dried pulp sample, for the measurement of water retention value
n	Number of pulp components, for the calculation of properties of pulp mixtures
P_{CD}	Value of any property measured in the cross machine direction of a sheet
P_{Geo}	Geometrical mean value of any property of an anisotropic sheet
P_i	Value of any property of pulp component i, for the calculation of properties for pulp mixtures
P_{MD}	Value of any property measured in the machine direction of a sheet
P_{Mix}	Value of any property for a pulp mixture
s	Arc length of the integration path round a crack, for the calculation of the J-integral
T	Tensile strength
T_i	Traction vector, for the calculation of the J-integral
U	Potential energy, for the calculation of energy release rate
u_i	Displacement vector, for the calculation of the J-integral
w_f	Fibre width
w_i	Mass fraction of pulp component i, for the calculation of properties for pulp mixtures
$w_{1,2}$	Mass fractions of the pulp components, for the calculation of RBA of a binary pulp mixture
Z	Zero-span tensile strength, for the calculation of tensile strength

Symbols, Greek

$\alpha_{1,2}$	Factors calculated from the RBA, the collapsed fibre thickness and the collapsed fibre width of the components, for the calculation of RBA of a binary pulp mixture
Γ	Integration path round a crack, for the calculation of the J-integral
τ_f	Breaking stress of fibre-fibre bonds, for the calculation of tensile strength
ω	Strain energy density, for the calculation of the J-integral

Abbreviations

BET	Method for surface area determination by gas adsorption, named after the originators, Brunauer, Emmet and Teller
CD	Cross machine direction of a sheet
CMC	Carboxymethyl cellulose, can be used as dry strength agent in paper
Comm 1-4	Commercial papers used in Paper II
Geo	Geometric mean value, can be calculated for properties of an anisotropic sheet
HW	Hardwood pulp used in Paper II
IR	Infra-red radiation, used for drying on a paper machine
Iso	Isotropic sheets
LB	Luciano Beghello, originator of the LB Multilayer Handsheet Former
LEFM	Linear elastic fracture mechanics
MD	Machine direction of a sheet
NLFM	Non-linear fracture mechanics
PAM	Polyacrylamide, can be used as dry strength agent in paper
PFI	Papir- och fiberinstitutet AS Paper and Fibre Research Institute, Trondheim, Norway
PQM	Pulp Quality Monitor
RBA	Relative bonded area
rpm	Revolutions per minute
SR	Schopper Riegler, unit for dewatering resistance of a pulp
STFI	Skogsindustrins Tekniska Forskningsinstitut Swedish Pulp and Paper Research Institute, Stockholm, Sweden Current name: STFI-Packforsk
SW _{1,2}	Softwood pulps used in Paper II

TAD	Through-air-drying
TEA	Tensile energy absorption
TMP	Thermomechanical pulp
WFF	Wet fibre flexibility
WFF _i	Wet fibre flexibility index
WRV	Water retention value

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1 Introduction

1.1 Background

The increasing competition on the world paper and board market forces paper producers to continually develop and improve their products. This leads to a desire to increase paper strength properties without any costly change in the process. Not only are strong papers important in the current paper industry, they are also of interest for new fields of application of fibre-based products, such as packages and light-weight building material.

Long-fibre chemical pulp has long been used as reinforcement in mechanical pulps, and softwood pulp is used as an additive to improve the strength properties of hardwood pulp, but the possibility of improving the strength properties of softwood chemical pulps with other types of pulps has not been investigated so thoroughly. Fibres with special properties with regard to length, strength, coarseness and stiffness should be further investigated from this point of view.

Multilayer forming techniques are commonly used in the manufacture of paper board where a low-cost, bulky mechanical pulp is placed in the middle layer and a chemical pulp with higher strength properties is placed in the outer layers. The mechanical pulp gives bulk and the chemical pulp gives a surface with high tensile stiffness. This composition results in a board with high bending stiffness, high strength and a smooth surface. Multilayer forming is also widely used in tissue production where the middle layer is composed of a pulp with high bulk for good absorbency while the top layer is composed of a pulp with shorter fibres, giving a smoother surface. Multilayer forming of paper products with a lower grammage than board, such as wood-free fine paper, is gaining some attention but there is a need for further studies in this area to improve the strength properties and/or lower the cost of the raw material.

1.2 Objectives of this work

The aim of the work reported in this thesis was to examine possibilities of enhancing the overall strength in paper products. The addition of a reinforcement fibre to a softwood pulp and the stratification of paper consisting of different pulps were examined.

The purpose of Paper I was to investigate the reinforcement potential of abaca (*Musa Textilis*) fibres for a softwood sulphate pulp. Paper II presents results from a study of the operating function of a multilayer handsheet former for the production of stratified sheets, i.e. the LB Multilayer Handsheet Former. In Paper III, the question at issue was whether a more positive combined effect on paper strength properties is obtained by placing fibres with special properties, i.e. high fibre length and coarseness, in separate layers rather than by making homogeneous sheets of a pulp mixture.

2 Theory

2.1 Papermaking

2.1.1 *Paper production*

The process of producing a paper consists of several steps;

- Production of pulp from a selected raw material
- Refining and other treatments of the pulp
- Possible addition of chemicals
- Distribution of the stock on a wire through a headbox
- Dewatering and forming of a web
- Pressing
- Drying
- If necessary, surface sizing, coating and calendering

The most common raw materials for papermaking are vegetable fibres, mainly from wood, grass or cotton. Synthetic fibres are used in special papers. In Sweden, most of the total paper production is based on virgin fibres, although recycled fibres are used in the production of newsprint, tissue and corrugated board materials. There are several different methods for the production of pulp from the raw material and the pulps produced can be graded as mechanical, chemimechanical, semi-chemical and chemical pulps. Within these categories, there are several processes for pulp production. In Sweden, most of the mechanical pulp produced is thermomechanical pulp (TMP). Further, the dominating cooking method for chemical pulp is the sulphate process, but the sulphite cooking process and other cooking methods are also used for the production of chemical pulps. The yield of mechanical pulp is higher than that of chemical pulp. The single fibres in chemical pulps are longer but weaker than the mechanical pulp fibres. However, chemical pulp produces stronger fibre networks, due to better bonding between the fibres, and thus paper with higher strength properties.

In the refining of the pulp, the single fibres are subjected to mechanical treatment. The fibres are made more flexible, enhancing the fibre-fibre contact, and parts of the fibre walls are removed or loosened producing fines

and fibrils which also promote bonding. The refining also causes a cutting of the fibres, reducing the fibre length, an often unwanted effect.

Chemicals can be added to the pulp to improve the runnability on the paper machine, to facilitate the process or to give or enhance special properties of the end product. Examples are fillers, biocides, retention and defoaming agents, and wet and dry strength agents.

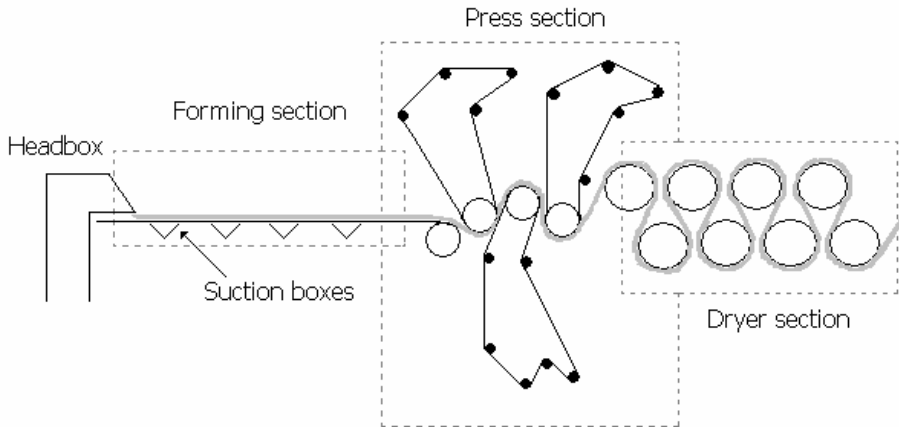


Figure 1. Schematic sketch of a fourdrinier paper machine. After the dryer section, the paper web may be subjected to surface sizing, coating and calendering before being transferred to a converting operation.

After the addition of chemicals and dilution, the pulp is distributed onto the wire through a headbox, as shown in Figure 1. There are several designs of headboxes with different functions, but common to all is that the pulp is ejected through a slice. The grammage profile can be adjusted through control of the slice opening profile or by local dilution of the pulp.

In the forming section, the pulp is dewatered on a wire and a continuous web is formed. Three main types of paper machines exist where the forming section has different designs, the fourdrinier, the gap and the hybrid former. In the fourdrinier machine, the pulp is distributed onto a single wire and the water is removed by gravity and vacuum applied in suction boxes. The gap and the hybrid formers are twin-wire machines where the dewatering is two-sided, resulting in a higher dewatering capacity and a reduction in the two-sidedness of the finished paper, which is an undesirable characteristics of one-sided dewatering.

In the press section, the paper web is pressed against one or between two press felts through several roll nips and the dry solids content is increased. The press roll nip can be extended to increase the length of the press impulse and a commonly used technique is the shoe press.

The most common way of drying the paper web is by passing the web over a number of drying cylinders heated by steam. Other drying methods that are used are convection drying, where hot air is blown onto the paper web, through-air drying (TAD), where hot air is pulled through the sheet by vacuum, and infra-red (IR) drying, where the wavelength is chosen to give high absorption in the water and low absorption in the fibres.

Sizing is used to make the fibres or the paper surface more hydrophobic. When the sizing agent is added to the pulp it is called internal sizing, while application of size at the dry end of the paper machine is called surface sizing. Internal sizing is the most commonly used method. A coating is applied to paper to provide a smooth surface, to improve optical properties and to give a good printing surface. A coating slip is applied to the paper surface, the excess slip is metered and the coated paper is dried, usually through convection drying or IR-drying. During calendering, the paper web is led through several nips to smoothen the surface and to give a higher gloss. The calender can be located in the paper machine, a so-called machine stack, but for some paper grades, the machine stack is not sufficient and an off-line calender is needed.

2.1.2 Multilayer forming on the paper machine

The technique of multilayer forming in paper production started in 1830 with the addition of a second forming cylinder to John Dickinson's cylinder machine (Attwood 1998). Figure 2 shows the principle of operation of the two-cylinder machine. Multiply paperboard has been produced continuously for almost 150 years (Attwood 1980). At first, the main target was to increase the speed at which heavyweight paperboard products were produced. Nowadays, multilayer forming is also used to produce paper products with improved or maintained stiffness properties at a lower grammage, to improve the fibre economy by placing a low-cost pulp in the middle layer, to improve surface properties by placing a high-quality pulp in the top layer, and to produce products with special properties by placing selected pulps in the different layers.

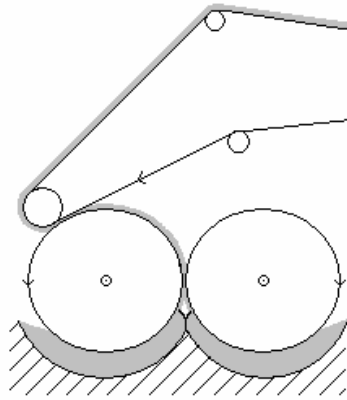


Figure 2. Operating principle of a two-cylinder paper machine. (Redrawn from Attwood 1998).

Multilayer papers are produced either by forming separate layers and combining them into one web, by forming a new layer on a pre-formed layer or by simultaneously forming a web in a multilayer headbox. The bond between the layers, i.e. the ply bond, is important for the properties of the end product. Critical parameters for the ply bond strength when combining different layers together is the dry solids content and the amount of fines in the interface. Several design concepts are used for the successive forming of layers. For example, the first layer can be formed in a fourdrinier former, with the subsequent layers being formed in minifourdriniers with separate headboxes and wire sections, as shown in Figure 3. In a multilayer headbox, the different pulps are distributed through channels separated by vanes, as shown in Figure 4. Eddies in the flow created by the vane tips cause some mixing of the layers in the interface. Paper produced in a multilayer headbox is referred to as stratified paper, in contrast to multiply paper.

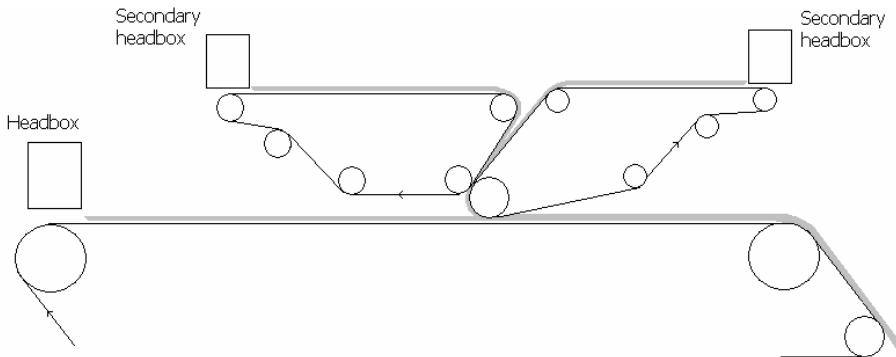


Figure 3. Schematic sketch of a machine concept for multilayer forming: A fourdrinier with two top minifourdriniers. (Redrawn from Foulger 1998).

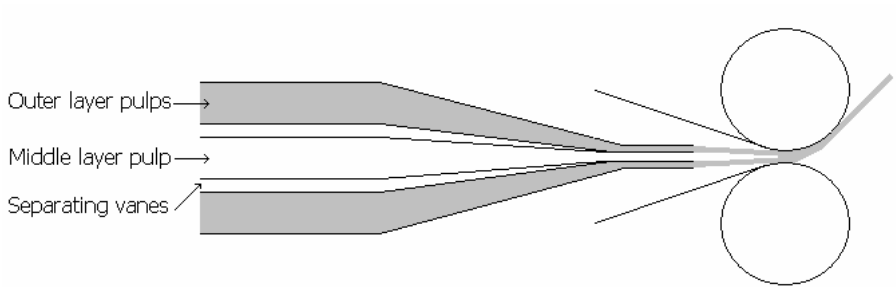


Figure 4. Schematic sketch of a multilayer headbox for stratified forming in a gap former. (Redrawn from Page and Hergert 1989).

2.2 Fibre network properties

2.2.1 Fibre properties

Several chemical and physical properties of the fibre affect the strength of the paper. Some of the properties discussed in this thesis and the appended papers are described briefly below.

Coarseness

Coarseness is the dry fibre mass per unit length. The unit is $\mu\text{g}/\text{m}$. Coarseness affects the conformability and collapsibility of the fibre; fibres with higher coarseness usually have thicker cell walls and are thus stiffer and less

conformable. A fibre quality analyser, such as the STFI Fibermaster (Karlsson et al. 1999), can be used to determine the coarseness of pulp fibres.

Flexibility

Flexibility affects the ability of the fibres to conform around other fibres, and thus affects the number of fibre-fibre contacts and the number of bonds and the bonded area in the sheet. Figure 5 shows the measurement principle for wet fibre flexibility. Fibres are placed across thin metal wires on a glass plate and the projected length of the arc not in contact with the plate is measured (Mohlin 1975; Steadman and Young 1978). The unit of wet fibre flexibility, WFF, is $1/\text{Nm}^2$ but it is commonly given as a dimensionless index, WFF_i , calculated according to:

$$\text{WFF}_i = 25 * (\log_{10} \text{WFF} - 9.5) \quad (1)$$

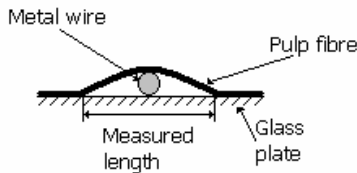


Figure 5. Measurement principle for wet fibre flexibility. (Redrawn from Mohlin 1975).

Shape factor

Shape factor is defined as the diameter of the smallest circle that can contain the projected fibre, divided by the length of the fibre (Karlsson et al. 1999). The shape factor is dimensionless and is calculated according to:

$$\text{Shape factor} = \frac{d}{l_f} \quad (2)$$

where d is the diameter of the circle circumscribing the fibre and l_f the length of the fibre, as shown in Figure 6.

For a single fibre, it can be recalculated to curl index according to:

$$\text{Curl index} = \frac{l_f}{d} - 1 \quad (3)$$

The shape factor indicates the shape of the fibre governed by kinks, curls and dislocations. Thus, a low shape factor does not necessarily mean a high flexibility. A fibre analyser using image analysis can be used for determining the mean shape factor for a pulp sample.

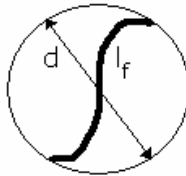


Figure 6. Definition of shape factor. d: diameter of the circle, l_f : length of the fibre. (Redrawn from Karlsson et al. 1999).

Water retention value

The water retention value, WRV, can be used as an indication of the degree of swelling of the fibres (Retulainen et al. 1998). The measurement of WRV includes a centrifuge filtration treatment and WRV is the amount of water retained by the pulp after the treatment. The WRV is calculated according to:

$$WRV = \frac{m_1 - m_2}{m_2} \quad (4)$$

where m_1 is the mass of the centrifuged pulp sample and m_2 is the mass of the dried, centrifuged sample. The unit of WRV is g/g, grams per gram.

Kappa number

The Kappa number is commonly used as an indication of the amount of lignin in the pulp. Pulps with low lignin content produce papers of high brightness and lignin is removed in the cooking and bleaching processes. In bleached kraft pulp the lignin content is almost zero. Moreover, a low lignin content gives fibres with high flexibility, high conformability and high swelling ability. The Kappa number is determined by oxidation of the lignin with potassium permanganate and is a dimensionless number.

Hemicellulose content

Hemicellulose is, together with cellulose and lignin, one of the main substances in wood. Hemicellulose affects the flexibility of the fibre and promotes fibre-fibre bonding. The dominating hemicelluloses in wood pulp

are glucan, mannan, arabinan, xylan and galactan. To measure the hemicellulose content of a pulp sample, the sample is subjected to chemical reactions to obtain alditol acetates from the hemicellulose components. The amounts of the components are then determined by chromatography.

2.2.2 Fibre network build-up

During pressing of the paper web in the press section of the paper machine, the dry solids content is increased from about 20% to 40%. Fibres and fines are drawn towards each other by the capillary forces, created by the surface tension in the liquid meniscus formed at the contact area between two fibres. Mechanical entanglement of fibrils also pull fibres closer together and fines give an increase in the capillary forces and lead to a stronger network. Flexible fibres more easily conform to each other and give a larger fibre-fibre contact area.

Hydrogen bonds are generally believed to be the dominating force that builds up a paper. Dispersion forces between the fibres and van den Waals' forces are other factors that slightly contribute to the strength. The hydrogen bonds are formed between a hydroxylic group and an oxygen atom where the hydrogen atom oscillates between the oxygen atoms. Hydrogen bonds exist between glucose units in the cellulose molecule, between fibrils in the fibre wall, and between fibres in the fibre network (Retulainen et al. 1998).

2.2.3 Bonded area

The term relative bonded area, RBA, is often used to describe the bonding level in a paper. RBA is the quotient of the bonded surface area to the total surface area of the fibres (Batchelor and He 2005). The measurement of RBA is not straightforward. Direct methods based on image analysis and microscopic studies have been used, but they involve difficulties in producing sufficiently sharp images of paper cross-sections (Uesaka et al. 2001). RBA is commonly measured indirectly, either by gas adsorption or by optical scattering. In the gas adsorption method, the unbonded surface area in a sheet is determined by measuring the adsorption of nitrogen gas by the BET (Brunauer, Emmett and Teller) method (Haselton 1954; Haselton 1955). The total area available for bonding in unbonded sheets can be measured on spray-dried fibres (Batchelor and He 2005) or on unbonded handsheets

formed in acetone and butanol (Haselton 1955). However, the gas adsorption method measures not only the area available for bonding, but the total surface area of the fibre accessible to the gas, such as the internal lumen area and the pores in the cell wall (Uesaka et al. 2001).

The light-scattering method of Ingmanson and Thode (1959) is often preferred since it is less time-consuming. The method is based on the assumption that the light scattering coefficient is proportional to the area available for light scattering. Only free fibre surface areas scatter the light, and a lower light scattering coefficient indicates a higher degree of bonding. To obtain the total surface area, it is assumed that there is a linear correlation between light scattering coefficient and tensile strength. The total surface area can be determined by extrapolating the light scattering coefficient to zero tensile strength. This way of determining the total surface area is however the subject of debate (Uesaka et al. 2001; Batchelor and He 2005). The use of increased refining or increased pressing to vary the tensile strength may introduce additional differences, such as fibrillation and lumen collapse, which affect the light scattering. Another objection to the method is that two fibre surfaces closer than half the wavelength of light, which do not scatter light, do not necessarily have to be bonded to each other, since the bonding distance may be shorter (Davison 1980). As in the case of the gas adsorption method, surfaces in the lumen and in the fibre wall may contribute to the light scattering (Uesaka et al. 2001). Further, the presence of fines may give misleading results, since fines increase both bonding and light scattering. The addition of mechanical pulp fines to a kraft fibre network has been shown to increase the light scattering without increasing the tensile strength appreciably, whereas chemical fines were shown to increase the tensile strength but slightly decrease the light scattering (Retulainen 1997).

Batchelor and He (2005) developed a method of calculating the RBA without the need for extrapolation to obtain the scattering coefficient for unbonded sheets. The model uses available experimental data; cell wall density, fibre wall area, fibre cross-sectional area, area of a rectangle circumscribing the fibre, sheet density and light scattering coefficient of the sheet. Figure 7 shows a fibre circumscribed by the smallest possible rectangle, the fibre wall area being shaded.

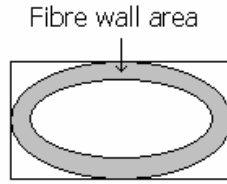


Figure 7. Fibre wall area and the smallest rectangular circumscribing the fibre. (Redrawn from Batchelor and He 2005).

2.2.4 Bond strength

Bond strength is another property of the fibre network which is not easy to determine, see section 2.2.3 *Bonded area*. The specific bond strength is the ratio of the bond strength to the bond area. The methods for determining specific bond strength are based on measurements of either single fibre bonds or of paper. Measurement of the strength of a single fibre bond is tedious, both because it requires careful precision to form and measure a bond, and because the great variability among fibre and bond properties demands a large number of bonds to be tested. Measurements on paper have the advantage that a large number of bonds are represented in each test, the bond structure is that resulting from the forming process and is not constructed artificially, and the measurement methods are rational. However, the sheet structure affects the loading behaviour to a large extent and the bond strength cannot be separated from the network strength. Thus the result of a measurement of specific bond strength is valid only for the specific structure and loading mode used (Retulainen 1997).

Retulainen and Ebeling (1993) compared different ways of determining the bond strength from measurements on paper. Eight methods were studied, including extrapolation of the tensile strength from wet pressing curves and the Scott-Bond test. They found disagreement between the methods and concluded that the differences were due to three factors: a) the method of measurement of bonded area, b) the method of measurement of strength; force or energy, and c) the loading mode during the strength measurement; in-plane or z-directional (thickness). Koubaa and Koran (1995) compared the z-directional tensile strength test, the delamination test and the Scott-Bond test and suggested that the z-directional tensile strength test was the most

suitable method among these for measuring bond strength. Section 2.3.5 further discusses the measurement of the internal bond strength in paper.

Page (1969) proposed a model for tensile strength that is still widely used. The method is based on the measurement of RBA, shear bond strength and fibre properties. A modified version of Page's equation where the tensile strength is given in force per cross-sectional area (Niskanen and Kärenlampi 1998), can be written:

$$\frac{1}{T} = \frac{9}{8Z} + \frac{3w_f}{\tau_f l_f RBA} \quad (5)$$

where T is tensile strength, Z is the zero-span tensile strength of paper, w_f is fibre width, τ_f is the breaking stress of bonds, l_f is fibre length and RBA is the relative bonded area.

2.3 Paper properties

Some of the paper properties discussed in this thesis and in the appended papers are described briefly below. It is common practice to report most paper properties in the form of an index, i.e. normalized with respect to the grammage.

2.3.1 Tensile properties

The tensile properties of paper are measured by clamping a strip of the sheet between two grips and applying a tensile load until break occurs. The applied load and the elongation are constantly measured throughout the test. A load-elongation curve, as shown Figure 8, can be obtained, where the load is plotted versus the elongation. Stress is the force required to elongate unit cross-sectional area of the material, but in the paper literature, the term stress is often used for force divided by width since it can be difficult to measure the thickness of the paper. The elongation can be reported as fractional, the elongation divided by the original length, or as a percentage, the fractional multiplied by 100. Factors affecting the test results are grip pressure, specimen size, strain rate, moisture content and temperature. The test should be performed with sufficiently long strips to give a state of pure tensile stress in the middle of the strip, a standardized sample width, a constant strain rate

and in a standardized climate. The tensile test is performed both in the machine direction, MD, and the cross machine direction, CD, and, when comparing papers with different fibre anisotropies, a geometric mean is usually calculated according to:

$$P_{Geo} = \sqrt{P_{MD} * P_{CD}} \quad (6)$$

where P_{Geo} is the geometric mean value of any property, P_{MD} the value of the property in the machine direction and P_{CD} the value of the property in the cross machine direction.

Tensile strength is defined as the breaking force divided by the width of the strip and has the units kN/m. Tensile index is the tensile strength divided by the grammage and the unit is Nm/g.

Tensile energy absorption, TEA, or tensile strain energy, is the amount of energy per unit area of the paper absorbed during straining until the onset of rupture in a tensile test. It can be illustrated as the area under the load-elongation curve and has the units J/m², or N/m.

Stretch-at-break or tensile strain to failure, is defined as the ratio of the increase in length until the onset of rupture to the original length. It has units of m/m or percent.

Tensile stiffness is determined from the slope of the initial linear part of the load-elongation curve. Tensile stiffness is the force divided by the elongation and the width of the strip, and it has the unit kN/m. The elastic modulus can be obtained by dividing the tensile stiffness by the thickness of the strip. The unit for elastic modulus is MN/m², or MPa.

The nature of the fracture is dependent on the degree of bonding in the sheet. A high degree of bonding leads to a large amount of fibre breaks, whereas in a poorly bonded sheet the dominating process in the fracture zone will be fibres being pulled out of the network as the fibre-fibre bonds break. Refining improves the tensile properties in several ways. The fibres become more flexible which facilitates the formation of fibre-fibre bonds. Also the fines content in the pulp is increased leading to an increase in bond strength. Wet pressing increases the density and improves the tensile properties as a result of an increase in bonded area. The stretch-at-break is highly dependent on the strain during the drying of the paper; freely dried paper has a much higher

stretch-at-break than paper dried under restraint. Seth (1990a) showed that tensile strength increased with density and decreased with decreasing fibre strength. He also showed a similar correlation for stretch-at-break. Further, Seth showed that both tensile strength and stretch-at-break increased with increasing fibre length. Paavilainen (1993a) saw a decrease in tensile strength with increasing coarseness and suggested that the most important factors for high tensile strength are good bonding ability and intrinsic fibre strength. In a different study, Paavilainen (1993b) continued the discussion, suggesting that the tensile strength is determined by the bonded area, thus collapsibility, external fibrillation, amount of fines and especially wet fibre flexibility.

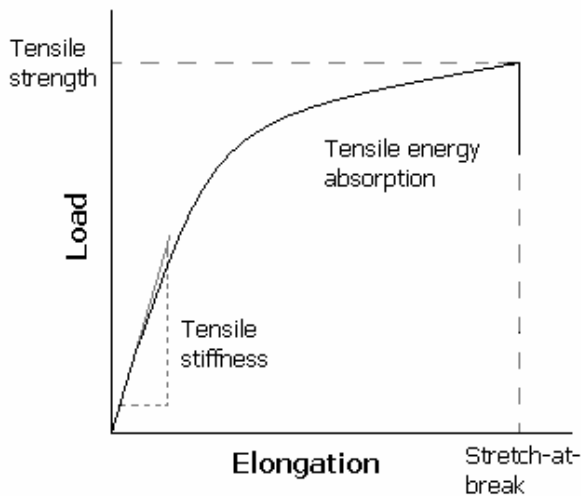


Figure 8. Schematic sketch of a typical load-elongation curve for paper, for the determination of tensile strength, tensile stiffness, tensile energy absorption and stretch-at-break.

2.3.2 Fracture toughness

Fracture mechanics, when the loading situation, geometry of the test piece and fracture toughness are mathematically related, can be applied to paper. Mäkelä (2000) has presented a thorough literature review of the fracture of paper. Over the years, both linear elastic fracture mechanics, LEFM, and non-linear fracture mechanics, NLFM, have been applied to paper. However, Mäkelä's conclusion is that the application of LEFM to paper is limited since paper show no pronounced linear elastic behaviour. Instead NLFM should be

used. In fracture mechanics, the energy release rate is the potential energy released per unit area of the crack (Irwin 1956) according to:

$$G = -\frac{dU}{dA} \quad (7)$$

where G is the energy release rate, U is the potential energy and A is the crack area.

For non-elastic materials, the energy release rate can be calculated by the J-integral (Rice 1968) according to:

$$J = -\frac{dU}{dA} = \oint_{\Gamma} \left[\varpi dy - T_i \frac{\partial u_i}{\partial x} ds \right] \quad (8)$$

where Γ is an integration path surrounding the crack tip, ϖ is the strain energy density, T_i and u_i are the traction vector and displacement vector, respectively, and s is the arc length of the integration path, as shown in Figure 9.

The fracture toughness is the critical value of the energy release rate when a crack starts to propagate. However, when dealing with paper it is of more practical interest to analyse failure than crack growth initiation, and further, the point of crack growth initiation is ill-defined. It has therefore become common practice to use the load at failure as the fracture toughness instead of the load at crack growth initiation. In practical terms, the fracture toughness of a paper is its ability to resist crack propagation. In this work, fracture toughness has been measured by means of a tensile test where an initial crack of a given length is introduced into the strip. The fracture toughness is then calculated by the J-integral method using an evaluation procedure described by Wellmar et al. (1997). Fracture toughness has the unit J/m and the fracture toughness index has the unit Jm/kg. Fracture toughness can be determined both in MD and CD and a geometric mean value can be calculated according to Equation (6).

Seth (1996) showed a linearly increasing relationship between fibre length and fracture toughness. He also showed that finer fibres had a higher fracture toughness than fibres with a higher coarseness. Yu (2001) showed for different mixtures of softwood kraft, TMP, birch and straw pulps that fracture energy

increases approximately linearly with increasing fibre length, confirming Seth's findings.

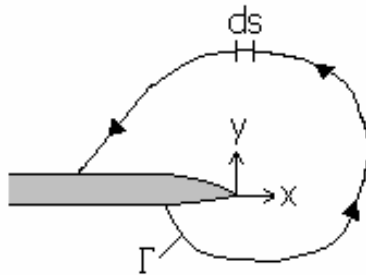


Figure 9. The J-integral contour. (Redrawn from Mäkelä 2000).

2.3.3 Tearing resistance

Tearing resistance is a measure of the notch sensitivity of the paper. There are different methods for measuring the tearing resistance of paper. In the work described in this thesis, the Elmendorf method, which is referred to as an out-of-plane test, has been used. The test is performed by inducing a crack in the test piece and applying a load perpendicular to the face to pull the paper apart, as indicated in Figure 10. A swinging pendulum completes the tearing and the energy consumed during the tearing is measured. The total work is divided by the length of the test piece, and the tearing resistance is given in mN. When tearing resistance is normalized with respect to grammage, i.e. tear index, the unit is mNm^2/g . Tearing resistance can be determined both in MD and CD and a geometric mean value can be calculated according to Equation (6).

The tearing process is complex since the plane of fracture changes during the propagation of the tear. The fracture surface is oriented at 90° to the faces in the beginning of the tear and at almost 180° at the end. Further, the behaviour of the weak plane parallel to the faces is important in the process and the paper tends to split. The degree of bonding in the sheet affects the tearing process (Fellers and Norman 1998). In sheets with a low degree of bonding, the fibres are pulled out of the network during the tear test. The tearing resistance is then dependent on fibre length and on the number of binding points. In sheets with a higher degree of bonding, the fibres are well

anchored in the sheet and the load during the tear test causes fibres to break. The tearing resistance is then dependent on the fibre strength.

Seth (1990a) showed that tearing resistance is increased with increasing fibre length, particularly with lower degree of bonding. Page and McLeod (1992) showed for well-bonded sheets of a given tensile strength that the tearing resistance was proportional to the fibre strength, measured as zero-span tensile strength, raised to a power between 2.5 and 3.0. Seth and Page (1988) and Yu (2001) showed that coarser fibres gave sheets with a higher tear index than finer fibres did. Yu also showed a decrease in tearing resistance with increasing fibre-fibre bonding. Lee et al. (1991) saw no correlation between either fibre coarseness or density and tearing resistance, but they confirmed the correlation with tearing resistance and fibre length.

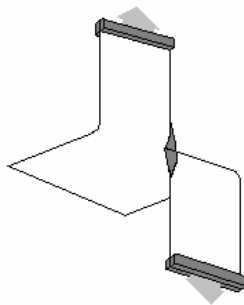


Figure 10. Schematic sketch of the direction of load during the Elmendorf tear test. (Redrawn from Fellers and Norman 1998).

2.3.4 *Folding endurance*

When folding endurance is measured, a strip is subjected to a constant tensile load and folded backwards and forwards. This is the only fatigue test that is used for paper. Fold number is the number of double folds that the strip resists before breakage. Since the fold number varies over a large range and the distribution is severely skew, it is more convenient to report folding endurance, which is the common logarithm of the fold number. Folding endurance can be determined both in MD and CD and a geometric mean value can be calculated according to Equation (6). There are some different principles for measurement of the folding endurance and in this study the

Köhler-Mohlin, see Figure 11, instrument was used. The test strip is clamped vertically between an upper and a lower clamp. The upper clamp can rotate 156° in each direction from the starting point. A weight is attached to the lower clamp so that the test strip is under a tensile load during the test. The folding is conducted by the upper clamp rotating backwards and forwards.

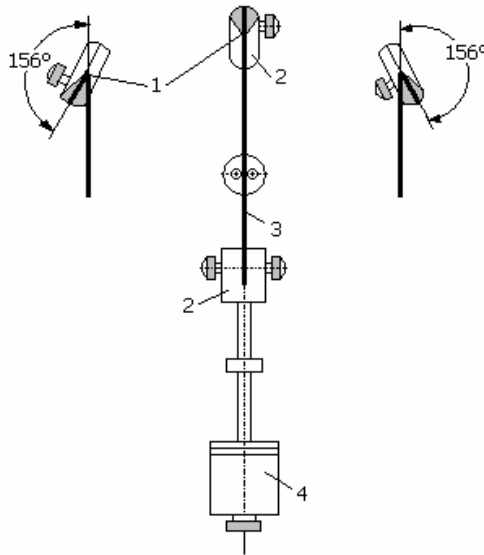


Figure 11. Schematic sketch of the Köhler-Mohlin instrument for folding endurance test. 1-Turning point, 2-Clamps, 3-Test strip, 4-Weight. (Redrawn from Fellers and Norman 1998).

Seth (1990a) showed an increase in folding endurance with increasing fibre length and increasing sheet density, particularly the longer the fibres and the higher the density. He also showed that folding endurance decreased rapidly with decreasing fibre strength.

2.3.5 *Internal bond strength*

Since paper to a large extent has a layered structure, especially in handsheets, measurement of the z-directional tensile strength provides an indication of the internal bond strength. It is important to bear in mind that commercial papers contain fibre entanglement and that the z-directional fibre distribution affects the z-directional strength. The internal bond strength of a paper is commonly measured by the Scott-Bond test or the z-directional tensile

strength test. In the Scott-Bond method, an L-shaped block is attached with double-sided tape to the top face of the test sample and the bottom face is attached to a flat block. The angled block is hit by a pendulum and the energy required to delaminate the test sample is measured. The energy absorbed is then divided by the cross-sectional area of the sample to give a measure of the internal bond strength. In the z-directional tensile strength test, double-sided tape is used to attach two flat, smooth plates to the test sample, one on each face, as shown in Figure 12. The plates are then pulled apart in a tensile tester and the failure stress is measured. Stress-strain or stress-time curves can be obtained. The z-directional tensile strength is defined as the force perpendicular to the test sample required to produce unit area fracture. Neither of the two methods measures the true intrinsic bond strength because of difficulties in determining the number and size of the bonds involved, and because breakage of fibre walls may occur and affect the test result. Further the double-sided adhesive tape may penetrate the test sample and provide unwanted reinforcement. The z-strength method is perhaps preferable, since the Scott-Bond method suffers from non-uniform stress and shear distributions during the fracture process. However, the z-directional strength method involves difficulties in applying a uniform tensile load over the specimen. The plates and the tensile forces have to be perfectly aligned. The gauge length of the test is merely the thickness of the paper and thus the result is sensitive to thickness variations within the sample. In this study the z-direction tensile strength method has been used to measure the internal bond strength with the unit kPa.

Andersson (1981a; 1981b) saw no correlation between either fibre length or intrinsic fibre strength and the internal bond strength, measured as z-directional tensile strength. However, he saw an approximately linear relationship between z-strength and light scattering coefficient and a strong relationship between z-strength and density, supporting the idea that z-directional tensile strength is a measure of the internal bond strength. Seth (1990a) saw no effect of fibre length on internal bond strength, measured by the Scott-Bond test, in sheets of a given density.

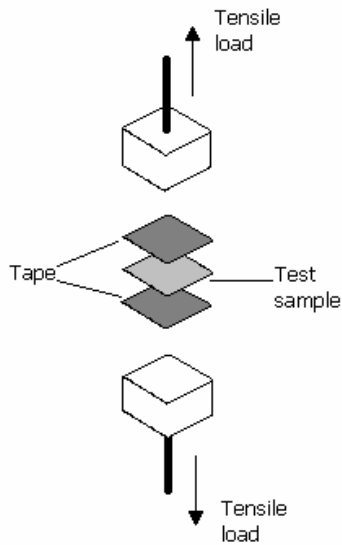


Figure 12. Schematic sketch of the z-strength testing method. (Redrawn from Fellers and Norman 1998).

2.3.6 *Air permeance*

Air permeance is the ability of a paper to permit the passage of air. The air passes the paper through the pores between the fibres and the air permeance can thus be used as an indirect measure of the porosity. There are several methods for measuring the air permeance and in this study the air permeance has been measured according to the Gurley method, which measures the time required for a specific amount of air to pass through the paper under a given air pressure. The air permeance is then calculated as the mean flow of air through unit area in unit time under unit pressure difference. The unit of air permeance is $\mu\text{m}^3/\text{Pas}$. Increased refining gives sheets of higher density and thus lower air permeance.

Seth (1990a; 1990b) determined air permeability, i.e. air permeance per unit sheet thickness, and saw no effect of fibre length or fibre strength on the air permeability. Further, Seth saw a decrease in air permeability with decreasing density of the sheet, whereas for a given density the air permeability increased with increasing fibre coarseness.

2.4 Previous studies

2.4.1 Mechanical and chemical treatment of pulp for enhancing paper strength

The strength properties of paper may be enhanced in several ways. Refining, addition of wet and dry strength agents and chemical modification of the fibre surfaces are discussed briefly here.

The main target of refining is to improve the bonding ability of fibres so that they form a strong and smooth paper. The fibres become more flexible and fines are created, and this promotes bonding and thus enhances the strength properties. Tensile strength, fracture toughness and folding endurance are increased with increasing refining, whereas tearing resistance often has a maximum at a fairly low level of refining and then decreases with further refining (Fellers and Norman 1998; Lumiainen and Partanen 1997). The increase in tensile strength and fracture toughness is a result of the increased bonding level, while the decrease in tearing resistance is due to the shortening of fibres and the increase in the number of bonds, causing fibres to break instead of being pulled out of the fibre network.

When a paper comes into contact with water, hydrogen bonds between fibres are broken and replaced with bonds to water. The strength of a normal paper sheet in a wet condition is thus low. To protect the fibre-fibre bonds and enhance the wet strength, wet strength agents may be added to the pulp. Such agents are commonly resins. They form a protective network around the fibres and thus prevent bond failure. The wet strength agents can also react with chemical groups at the fibre surface forming covalent bonds which enhance the strength of the fibre network. Further, the resin can penetrate and close the pores in the fibres, thus preventing fibre swelling and also stabilizing the network (Fellers and Norman 1998; Bates et al. 1999).

Dry strength additives are used to increase the fibre-fibre bonding in the sheet. Most commercial dry strength agents are polymers such as starches, gums, carboxymethyl cellulose, CMC, and synthetic polymers (Davison 1980; Ketula and Andersson 1999). Among the synthetic polymers, polyacrylamide, PAM, is the most commonly used. In Sweden, the most common way to enhance the dry strength of paper is by adding cationic starch at the wet end of the paper machine (Fellers and Norman 1998). The dry strength agents may take part in the hydrogen bonds in the fibre network

and enhance the degree of bonding. Further, they may form gels which promote the consolidation of the sheet by dissipating stress concentrations (Fellers and Norman 1998).

Retulainen and Nieminen (1996) studied the effects of adding various dry strength agents and fines to sheets produced from a kraft pulp. They found that the addition of a mixture of cationic starch and CMC gave an increase in tensile strength of 70-90%. Further, they showed that adding kraft or TMP fines after starch addition gave an increase in both tensile strength and light scattering coefficient.

An interesting approach is to modify the fibre surfaces in order to improve paper strength properties. A number of articles by Wågberg and several co-authors have been published on the subject (Wågberg et al. 2002; Gernandt et al. 2003; Gärdlund et al. 2003; Torgnysdotter and Wågberg 2003; Torgnysdotter and Wågberg 2004; Gärdlund et al. 2005). In the first of these articles, Wågberg et al. deposited layers of polyelectrolytes on the fibre surface. By building up 5-10 layers on unrefined fibres, they achieved sheets with the same tensile strength as sheets made of conventionally refined pulp. Further, they saw a doubling of the tensile strength in the case of sheets produced from fibres with 5 layers of polyelectrolyte compared to that of sheets made of untreated fibres. The subsequent articles support the conclusion that it is possible to enhance paper strength properties by treatment of fibres with polyelectrolytes.

2.4.2 Strength of pulp mixtures

Mixtures of several pulp components are frequently used in the paper industry. The possibilities of enhancing paper strength by mixing different pulps have been studied extensively, but the performance of different pulp mixtures is not yet fully understood. In a mixture of two pulps, three different types of bonds exist; bonds within each pulp type and bonds between the different fibre types. The formation of these bonds and their impact of the load-bearing capacity of the fibre network have not yet been clarified. It is well known that the linear rule of mixture, or mass fraction additivity,

$$P_{Mix} = \sum_{i=1}^n w_i P_i \quad (9)$$

where P_{Mix} is the value of any property for the mixed sheet, w_i is the mass fraction for pulp component i , P_i the value of any property for a sheet of pulp component i and n is the number of pulp components, is not always valid for pulp mixtures, and that synergetic or negatively deviating results can arise.

The mass fraction additivity of RBA for pulp mixtures was studied theoretically by Gates and Westcott (2002). Based on statistical mechanics of fibres in the network, they derived a general formula for calculating the RBA for a paper consisting of two components:

$$RBA = \frac{w_1 RBA_1}{w_1 + w_2 \alpha_1} + \frac{w_2 RBA_2}{w_1 \alpha_2 + w_2} \quad (9)$$

where w_1 and w_2 are mass the fractions of the two components, RBA_1 and RBA_2 are the relative bonded areas and α_1 and α_2 are factors calculated from the RBA, the collapsed fibre thickness and the collapsed fibre width of the pulp components.

The formula has to be modified for special cases such as non-additive mixtures and mixtures where only the level of refining differs. Gates and Westcott concluded that when the RBA deviated from linear mass fraction additivity, the tensile strength additivity was also non-linear.

Görres et al. (1996) proposed that, in order to predict properties of sheets made from mixtures of pulps, the fibre properties of the component pulps rather than the properties of pure sheets from these pulps should be used. They developed a model for computing the density of mixed sheets using the average fibre properties of each pulp component weighted by their contribution to the total fibre length.

Bovin and Teder (1971) studied different kinds of pulp mixtures and found that it was possible to predict whether or not the tearing resistance of a mixture would deviate from linearity. When the tensile strength is plotted against tearing resistance for a pulp, a maximum usually appears on the curve. Bovin and Teder found that if the pulp components are chosen with the tensile strength on the same side of the maximum, the tearing resistance of the mixture is linearly additive.

Strength properties of mixtures of chemical and mechanical pulps have been shown to deviate from linear mass fraction additivity (Mohlin and Wennberg

1984; Retulainen 1992; Kazi and Kortschot 1996; Hiltunen 2003; Honkasalo 2004). Both synergetic results and results lower than those predicted have been reported. The reason for this behaviour is not clear, but most theories are based on the development of bonds in the mixture.

Mohlin and Wennberg (1984) observed a positive deviation from the linear additivity for tearing resistance, whereas internal bond strength, measured as Scott-Bond, and tensile properties showed a negative deviation. The results indicated that the bonding level of the kraft fibres cannot be fully utilized and Mohlin and Wennberg suggested that the interaction between the pulps is weak and that the bonds between chemical and mechanical fibres are so weak that the pulps behave as if they form two separate networks.

Retulainen (1992) added earlywood and latewood kraft fibres to a TMP and saw a negative, non-linear deviation from linear mass fraction additivity for the apparent density of the sheets. Further, the tearing resistance increased linearly with the addition of latewood fibres but showed a positive deviation when the more conformable earlywood fibres were added. The tensile strength and stiffness were affected only at an earlywood content above 40%, where there was a slight increase in strength. Retulainen suggested that the stiffer fibres prevent the flexible fibres from utilizing their full bonding potential and that the kraft fibres are not fully activated in the tensile test due to curls and kinks. Further, Retulainen investigated the bond strength of the different bonds in the sheet by measuring the z-directional tensile strength of two-layered sheets, i.e. the ply bond strength. He found that the z-strength of the TMP/kraft sheet was higher than that for the TMP/TMP sheet but lower than that of the kraft/kraft sheet and he suggested that the bond strength between the different fibres should follow the same trend.

Kazi and Kortschot (1996) showed a fracture toughness lower than the predicted value, although it increased with increasing kraft addition, for kraft-containing TMP sheets. However, with an 2.5% addition of kraft, a drop in the fracture toughness was observed. Light scattering measurements indicated that the kraft fibres, even in small amounts, were well bonded into the network. Kazi and Kortschot suggested that the kraft/TMP bonds are weak and do not contribute to the energy absorption during the fracture. This would explain the decrease in strength at low kraft contents and the increase when the kraft content increased allowing stronger bonds to form between kraft fibres.

Hiltunen (2003) saw a synergetic effect on fracture toughness when kraft pulp was added to TMP-based sheets. His results suggested that the non-linearity was dependent on the degree of refining of the kraft pulp. However, the average fibre length seemed to have a greater effect than the refining on the absolute level of fracture toughness.

Honkasalo (2004) found a synergism, especially in tearing resistance, but also in fracture toughness, stretch-at-break and TEA, of sheets consisting of mixtures of groundwood, TMP and softwood kraft. The synergism seemed more likely to appear in well-bonded sheets. Further, the synergism in tearing resistance was most prominent when the compounds had bonding levels on opposite sides of their tearing resistance maxima. Honkasalo suggested that an optimum combination of fibre length and bonding degree could give a synergism in paper strength properties.

Fernandez and Young (1994) analysed the results of Mohlin and Wennberg (1984) and Retulainen (1992) and suggested that the collapse behaviour of the kraft pulp fibres is the main reason for the deviation from linearity in density and tearing resistance. The tension induced during drying causes the fibres to collapse but, when the bonding level is low, the fibres are able to shrink in the longitudinal direction and do not collapse to the same extent as they do in well-bonded sheets. Fernandez and Young reasoned that the mechanical pulp reduces the bonding between kraft fibres and thus increases the tendency for the kraft fibres to collapse.

Zhang et al. (2002) saw both linear and non-linear behaviour of the strength properties in sheets consisting of kraft and TMP. They argued that the behaviour was dependent on the degree of bonding in the sheet. When the bonding potential of both the pulps was fully utilized, they saw a linear relationship in the strength properties, whereas a deviation, generally negative, was seen when the bonding potential was not fully utilized.

2.4.3 Reinforcement

An important type of pulp mixture is that involving the use of a reinforcement pulp. Reinforcement fibres are added to a pulp to improve the runnability of the paper web and the mechanical properties of the paper produced. An increase in the drainage rate and wet strength of the web improves the runnability in the wet end (Seth and Kingsland 1990). The

increase in strength of the dry sheet improves the runnability both in the paper machine and in subsequent converting operations. Enhancing the strength of the rewetted sheet, which also improves the runnability of converting operations, may be another reason for adding reinforcement fibres (Seth 1996). The dominant reinforcement situation in papermaking is the use of softwood kraft fibres to improve the properties of weaker pulps such as mechanical or hardwood pulp.

Several studies have been devoted to finding the optimal properties of a reinforcement pulp. Seth and Kingsland (1990) concluded that the reinforcing potential of a softwood pulp was governed by fibre properties and especially by the fibre coarseness. Fine fibres were shown to lead to a greater improvement than coarse fibres in both wet-web and dry sheet tensile strength and stretch-at-break. Coarser fibres however improved the tearing resistance and promoted drainage on the paper machine. Seth and Kingsland recommend moderate beating of coarse reinforcement fibres to improve the tensile strength and stretch-at-break. Retulainen (1992) discusses the load activation of the reinforcement fibres and recommends a pulp with a low content of curls and dislocations, or treatment of the mechanical pulp so that both components are activated during loading. Further, Retulainen argues that the fines content of the mechanical pulp needs to be sufficiently high to tolerate the reduction in fines/fibre ratio when a chemical pulp is added. Seth (1996) recommended papermakers to refine the softwood reinforcement pulp to obtain high tensile strength, extensibility, elastic modulus and fracture toughness and to ignore the loss in out-of-plane tearing resistance, since that property is interesting only in the special cases when paper breaks in that mode.

In the case of chemical fibres to reinforce a mechanical pulp, Alava and Niskanen (1997) concluded that the reinforcement fibres should be long, ductile and of low stiffness in order to enhance fracture toughness, while well-bonded, high-stiffness fibres increase the strength and stiffness. At low concentrations of reinforcement fibres, the low-stiffness mechanical fibres carry more of the load and the reinforcement fibres should be chosen to match the stiffness of the mechanical fibres to prevent matrix failure caused by an increased strain on the mechanical fibre network. Ebeling (2000) followed a similar line of argument, concluding that a strong reinforcement pulp should have long, slender fibres with well anchored and colloid-covered fibrils and a sufficient amount of fines. The length of the fibres enables a continuous network to be formed even at low concentrations of

reinforcement fibres. However, a compromise is needed since too long fibres cause fibre flocculation and this leads to a poorer formation. The slenderness of the fibres makes them more flexible, facilitating fibre-fibre contacts and bonds. In contrast to coarse fibres, fine fibres also lead to a more even distribution of load in the fibre network. The fibrils are needed to give strong fibre-fibre bonds between the reinforcement fibres and the weaker pulp.

Hiltunen et al. (2002) studied the reinforcement potential of different chemical pulps for use as reinforcement in TMP-based paper. They found that, when the reinforcement potential of the pulps was ranked by fracture toughness, sulphite pulp had a higher potential than kraft pulp. The reason for this was believed to be a higher degree of bonding and activation of load-bearing fibres promoted by the high fibre swelling of the sulphite pulp.

Mansfield et al. (2004) investigated the reinforcing potential of different softwood kraft fibres for a hardwood pulp. They concluded that the reinforcing potential can be characterized by the fracture toughness of pure softwood sheets.

2.4.4 Production of multilayer handsheets

Over the years, different approaches to produce multilayer handsheets have resulted in a number of formers with their own advantages and disadvantages. Stöckmann (1974a) modified a conventional isotropic handsheet former with a gate that divides the pulp container into two compartments. Figure 13 shows an explanatory sketch of the function of the sheet former. The lower compartment is filled with the bottom-layer pulp. The gate is then closed and the second-layer pulp is added. When the gate is opened and permitting the sheet former to drain, the bottom layer is formed on the wire. The dewatering is interrupted when the water level reaches the gate. The gate is again closed and a third pulp may be added. When the gate is opened to continue the dewatering, the second layer is formed on top of the previous one and drained through that. Additional layers can be added by repeating the procedure. Gentle stirring during the dewatering prevents flocculation and provides some mixing between the layers enhancing the ply bond strength. Stöckmann's sheet former concept was used in several studies (Stöckmann 1974a; Stöckmann 1974b, Bergström and Peel 1979; Erickson 1977).

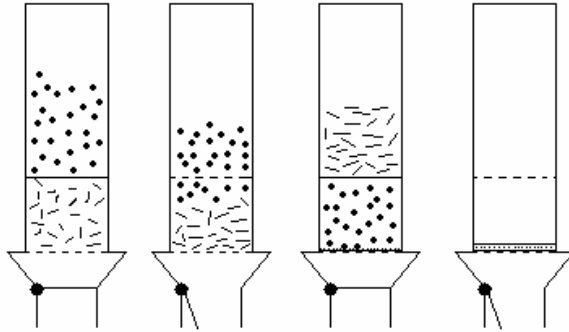


Figure 13. Schematic sketch of the function of a modified handsheet former. Dots and lines represent different pulps. (Redrawn from Stöckmann 1974a).

Bergström and Peel (1979) introduced a slightly different function in the sheet former. To separate the pulps, two plates with drilled holes were used, and one of the plates could be rotated relative to the other. When the holes are lined up, the gate may be moved through the pulp container and when the plate is rotated the gate is closed to flow. Once a layer is dewatered, the plates are lowered and closed and the next pulp is added. The gate is then opened and slowly elevated, and the next layer is dewatered. To hold the formed layers on the wire during the forming of subsequent layers, a valve is opened to permit a small flow through the fibre mat.

Another modification of the conventional isotropic handsheet former, the Pira Plug Flow Former, has been described by Moore (1998). The pulp is added at the top of the former in the ordinary manner. Jets with water and air create a turbulent area in the top of the sheet former and this results in a uniform dispersion of the pulp. Below the turbulent area, at the base of the former, the pulp is allowed to settle evenly, creating a sheet with good formation. Pulp for additional layers may then be added and the degree of interlayer mixing is controlled by the time interval between the pulp additions.

Puurtinen et al. (2003) chose a different approach when developing a multilayer handsheet former. The function is illustrated in Figure 14. The main difference from the previously described methods is the two-sided dewatering. The pulp container can be divided by plates into two or three compartments. Movable fabric frames are mounted vertically at the two ends

of the chamber. The frames are pushed towards each other and the two outer layers are dewatered. When the frames approach the dividing plates, the plates are removed. The frames are then pushed further towards each other and the middle layer is dewatered through the two outer layers.

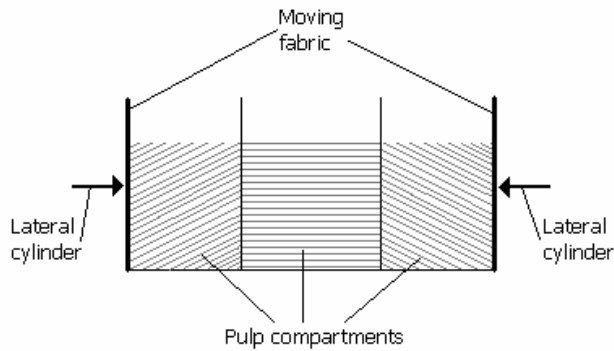


Figure 14. Function of multilayer handsheet former. (Redrawn from Puurtinen et al. 2003).

The dynamic sheet former Formette Dynamique (Sauret 1971), which produces anisotropic sheets, can be used to produce multilayer handsheets. The pulps are added consecutively in the pulp container, or two separate pulp containers can be used alternately. The added layers are dewatered through the previous formed layers. Multilayering in the Formette Dynamique has been reported from studies on both chemical and mechanical pulp (Bristow and Pauler 1983; Tubek-Lindblom and Salmén 2003; Nesbakk and Helle 2003).

3 Experimental

3.1 Materials and methods

3.1.1 *Pulps*

Paper I

Flash-dried, unbleached softwood sulphate pulp and bleached abaca neutral sulphite anthraquinone pulp sheets were used. The pulps were refined separately in an Escher-Wyss conical refiner, with a cutting angle of 60° and a specific edge load of 3.0 Ws/m. The softwood pulp was refined at 240 kWh/ton and had a dewatering resistance of 27 SR. The abaca pulp was refined at 46 kWh/ton and had a dewatering resistance of 20 SR. The refined abaca pulp was dewatered and stored in a deep-freeze before use.

Paper II

Two softwood sulphate pulps, SW1 and SW2, and one hardwood sulphate pulp, HW, were used. They were collected from a local mill after refining. The hardwood pulp was refined at 88 kWh/ton and had a dewatering resistance of 21 SR and SW1 was refined at 115 kWh/ton and had a dewatering resistance 32 SR. SW2 was refined at 128 kWh/ton. The pulps were collected at a concentration of about 3-4% and stored in a cold-storage room before use.

Paper III

Never-dried, bleached softwood sulphate pulp was collected from a local mill, refined at 110 kWh/ton. Bleached abaca neutral sulphite anthraquinone and bleached southern pine kraft pulp sheets were macerated and refined in an Escher-Wyss conical refiner, with a cutting angle of 60° and a specific edge load of 3.0 Ws/m at 45 and 200 kWh/ton respectively. The abaca and southern pine pulps were fractionated on a bow screen, type ST-1, with a standard plate with 150 µm slot width. The dewatering resistances for the pulps were 31.5 SR for softwood and 16.0 SR for both abaca and southern pine.

3.1.2 Commercial papers

Four different types of commercial papers were collected from a local mill. Comm 2, 3 and 4 were produced in a double Fourdrinier machine, where two separately formed layers are combined to a two-layer paper in the press section.

Comm 1

Single-layer, machine glazed paper of a homogeneous mixture of 50% softwood, 40% hardwood and approximately 8% broke and 2% clay. Grammage 60 g/m². The paper was acid-sized.

Comm 2

Two-layer sack kraft paper with softwood in both layers. Total grammage 70 g/m², each layer 35 g/m².

Comm 3

Two-layer paper with softwood in the bottom layer and a homogeneous mixture of 60% hardwood and 40% broke in the top layer. Total grammage 80 g/m², each layer 40 g/m².

Comm 4

Two-layer paper with a homogeneous mixture of 90% softwood and 10% broke in both layers. Total grammage 80 g/m², each layer 40 g/m².

3.1.3 Handsheet preparation

Standard isotropic sheets

Isotropic handsheets with a target grammage of 60 g/m² were produced according to ISO 5269-1:00 in a conventional sheet former.

PFI Sheet Former

Isotropic handsheets were also produced in a PFI Sheet Former, producing quadratic sheets of 22x22 cm. The sheets, with a target grammage of 60 g/m², were produced according to ISO 5269-1:00 except that the sheets were pressed at 224 kPa.

Dynamic sheet former

Anisotropic handsheets with a target grammage of 60 g/m² were produced on a Formette Dynamique sheet former (Sauret 1971) at a rotational speed of 1200 rpm and a nozzle pressure of 2 bar. The sheets were pressed twice in a roll press, starting at 0.6 MPa followed by 1.6 MPa, and dried under restraint in an STFI plate dryer (Htun and Fellers 1982).

LB Multilayer Handsheet Former

Isotropic single-, two-, three- and four-layer sheets were produced in a multilayer handsheet former (Beghello et al. 1996). The pulp container can be divided into four separate compartments. Each compartment is equipped with a propeller to stir the pulp. In Paper II, the forming concentration, stirring frequency and time, and the time for decay of eddies were varied in order to study the operating function of the sheet former. In Paper III, the forming concentration was 0.068 g/l, the stirring frequency 16 Hz, the stirring time 30 s for single-layer sheets and 90 s for multilayer sheets. In the rest of the sheet production, ISO 5269-1:00 was followed.

3.1.4 Test methods

The methods used for the determination of pulp and paper properties are listed in Table 1.

Table 1. Methods used for the determination of pulp and paper properties.

Property	Method	Paper
Air permeance, Gurley	SCAN-P 19:78	I
β - formation	Ambertec Beta Formation Tester	II
Coarseness	STFI Fibermaster (Karlsson et al. 1999)	I, III
Dewatering resistance	ISO 5267-1:00	I, II, III
Fibre length, fibre length distribution	PQM1000 (Heikkurinen and Leskelä 1998)	I
Fibre length, fibre length distribution	STFI Fibermaster (Karlsson et al. 1999)	II, III
Fibre width	STFI Fibermaster (Karlsson et al. 1999)	III
Folding endurance	ISO 5626:93	I
Fracture toughness	SCAN-P 77:95	I, III
Hemicellulose content	TAPPI 249 cm-00, using HPLC	III
Kappa number	ISO 302:04	I, III
Shape factor	STFI Fibermaster (Karlsson et al. 1999)	I, III
Tearing resistance	ISO 1974:90	I, III
Tensile strenght	SCAN-P 67:93	I, II
Tensile strenght	ISO 1924-3:05	III
Tensile stiffness	SCAN-P 67:93	I, II
Tensile energy absorption	SCAN-P 67:93	I
Stretch-at-break	SCAN-P 67:93	II
Thickness	SCAN-P 88:01	I, III
Thickness	ISO 534:2005	II
Water retention value	SCAN-C 62:00	I, III
Wet fibre flexibility	Steadman-Mohlin (Steadman and Young 1978)	I, III
Viscosity	ISO 5351:04	I
Z-directional tensile strength	TAPPI 541 om-89	II, III
Zero-span tensile strength	TAPPI 231 cm-85	I, III

3.2 Summary of the papers

3.2.1 Paper I

- *Abaca as a reinforcement fibre for softwood pulp*

In this study the effects of adding abaca (*Musa Textilis*) fibres to a softwood sulphate pulp were investigated. Abaca fibres were chosen because of their greater fibre length and fibre strength. Properties of the pulps used in the study are listed in Table 2.

Table 2. Properties of the pulps used in the study.

Pulp	Softwood	Abaca
Mean fibre length	2.05 mm	3.20 mm
Coarseness	173 µg/m	155 µg/m
Curl index	16.8 %	22.7 %
Wet fibre flexibility index	37.2	37.1
Water retention value	1.17 g/g	1.26 g/g
Zero-span tensile index	120 Nm/g	155 Nm/g
Kappa number	28.3	7.01
Viscosity	1240 ml/g	925 ml/g
Initial drainage resistance	12.4 SR	17.1 SR
Fibre diameter	25-30 µm ¹	19 µm (6-53) ²
Cell wall thickness	2.2 µm ¹	4.4 µm (1.6-16) ²
Lumen width	10-30 µm ¹	12 µm (1-33) ²

¹ Literature values from (Varhimo and Tourminen 1998; Fellers and Norman 1998)

² Literature values from (Estudillo and Torres 1997)

The beatability of the two pulps was examined. It was observed that to reach a given dewatering resistance, abaca required less refining energy than softwood, as shown in Figure 15. The tensile strength of the refined pulps is shown in Figure 16 and it was observed that at a dewatering resistance in the range 20-25 SR, the two pulps had approximately the same tensile index, while at a higher dewatering resistance abaca had a higher tensile index. Abaca showed a remarkably high initial tearing resistance and, although rapidly decreasing with refining up to about 35 SR, the tear index of abaca was well above that of softwood, as shown in Figure 17.

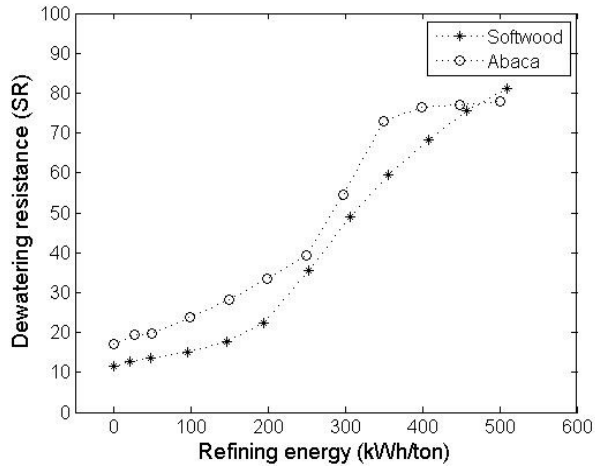


Figure 15. Dewatering resistance as a function of refining energy for softwood and abaca pulps. The pulps were refined in an Escher-Wyss refiner with a cutting angle of 60° and a specific edge load of 3.0 Ws/m.

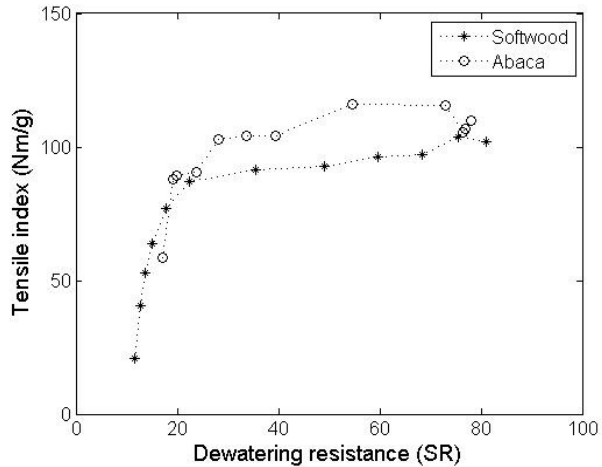


Figure 16. Tensile index as a function of dewatering resistance for softwood and abaca pulps. The pulps were refined in an Escher-Wyss refiner with a cutting angle of 60° and a specific edge load of 3.0 Ws/m.

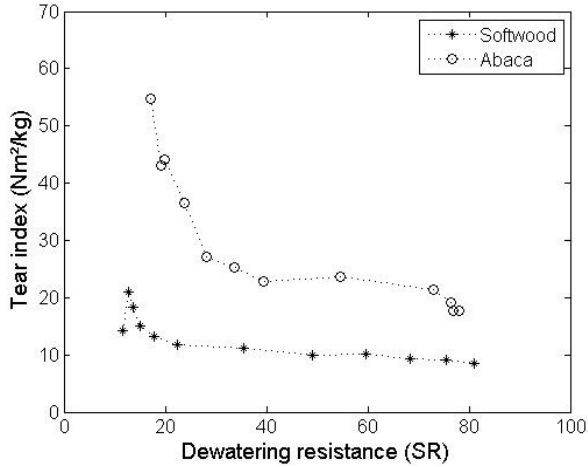


Figure 17. Tear index as a function of dewatering resistance for softwood and abaca pulps. The pulps were refined in an Escher-Wyss refiner with a cutting angle of 60° and a specific edge load of 3.0 Ws/m.

In order to study the effects on paper strength of the addition of abaca, isotropic handsheets with varying abaca content were made in a conventional handsheet former. It was seen that the density of the sheets decreased with the addition of abaca, as shown in Figure 18. This is most likely a result of the low conformability and low collapsibility of the abaca fibres. The decrease in density also indicates a decrease in bonded area and this was probably the reason for the slight decrease in tensile index with the addition of abaca, as shown in Figure 19. While tearing resistance of well-bonded sheets mostly depends on the fibre strength, tearing resistance of sheets with a lower degree of bonding depends on the fibre length. This is reflected in the increase in tear index with increasing abaca content which is shown in Figure 19. As might be expected from the discussion above, the increase in tear index was most significant with the higher additions of abaca in which there was a lower density.

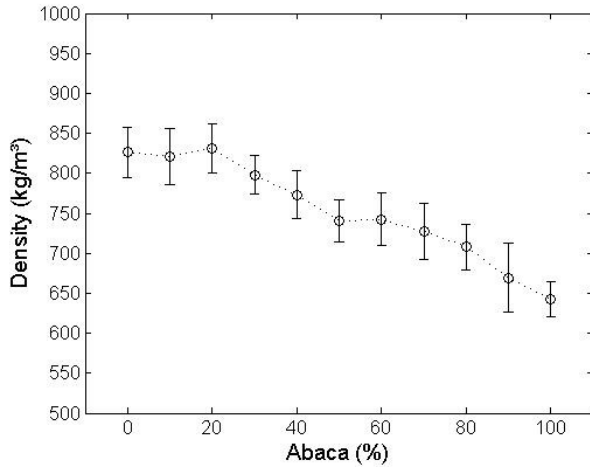


Figure 18. Density for mixed isotropic sheets of abaca and softwood as a function of abaca content.

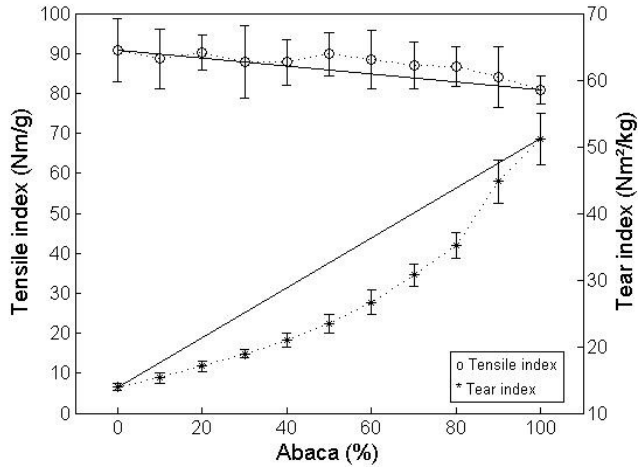


Figure 19. Tensile and tear indices for mixed isotropic sheets of abaca and softwood as a function of abaca content. The solid lines indicate the linear mass fraction additivity.

Moreover, fracture toughness index, folding endurance and air permeance was seen to increase with increasing abaca content, whereas tensile stiffness index and tensile energy absorption showed a slight decrease with addition of abaca.

The most important conclusion of this study is that abaca fibres can be added to a softwood pulp to increase tearing resistance, fracture toughness, folding endurance and air permeance. The tensile strength, tensile stiffness and tensile energy absorption are, however, slightly decreased. Still, it is possible to add up to about 60% abaca without any great loss in tensile strength. As an example, with the addition of 30% abaca, the tear index was increased by 36% while the tensile index was decreased by 8%. These main findings are based on data from isotropic as well as from anisotropic sheets produced in a dynamic sheet former. An increase in the pressure in the press section could compensate for the decrease in density and thus prevent the decrease in the tensile properties. However, to obtain the positive effects of the fibre length of abaca, the density should not be too high.

3.2.2 Paper II

- Handsheet former for the production of stratified sheets

In this paper a handsheet former for the production of stratified sheets, the *LB Multilayer Handsheet Former*, is presented and evaluated. The usability of the sheet former is demonstrated and its performance in relation to conventional handsheet formers is studied. The operating function of the sheet former is optimized and the quality of the sheets produced is analysed. The sheet former was originally developed at Åbo Akademi and has been used in previous studies (Beghello et al. 1996). The basic idea is to create a multilayer sheet former for laboratory use that is easy to handle and has a high sheet producing rate. The sheets produced are to be isotropic, so that paper properties can be studied in the absence of effects of fibre orientation. A certain degree of interlayer mixing should produce sheets with a high ply-bond strength.

The basic design of the multilayer handsheet former is shown in Figure 20 below. The pulp container can be divided into two, three or four compartments using sliding plates. Each compartment has a volume of 15 dm³ and is equipped with a propeller for stirring of the pulp. The former is drained downwards and the sheet is formed on a metallic wire screen supported by a 10 mm thick plate with drilled holes.

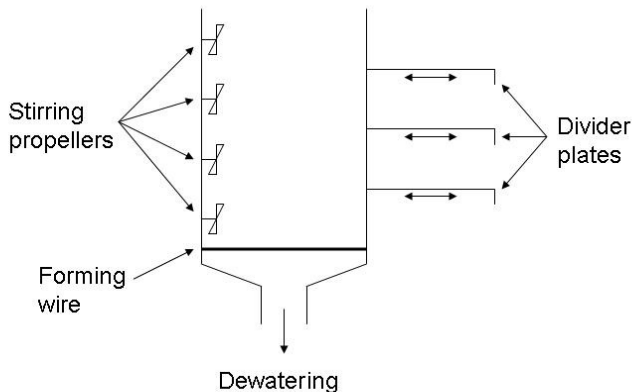


Figure 20. Basic design of the LB Multilayer Handsheet Former.

To start the production of handsheets, water should be added up to a level approximately 50 mm above the wire in order to prevent fibres becoming

stuck on the wire screen. The bottom-layer pulp is then added in the top of the former and the lower compartment is filled with water. The second divider plate is pushed into the former to seal the bottom compartment. The second-layer pulp is added and the compartment is filled with water up to the next divider plate. For additional layers, the procedure is repeated. When the desired number of compartments is filled with pulp, the stirring is started. After stirring has been completed, the divider plates are steadily pulled out in succession from the top to the bottom and the valve to the drainage pipe is opened. To promote further dewatering of the sheet, blotters are placed on top of the formed sheet and a couch-weight is placed on the top. The sheet can then be wet-pressed and dried under standardized conditions.

Single-layer sheets, stratified sheets and multilayer sheets composed of single-layer sheets combined in the press were made in the LB Multilayer Sheet Former. The uniformity of the sheets were analysed and compared to that of sheets made in conventional sheet formers, and to that of commercially produced single-layer and two-layer papers.

The within-sheet coefficient of variation of properties of single-layer and stratified sheets of hardwood is shown in Figure 21. It was seen that for grammage and tensile strength, the uniformity of the sheets seemed unaffected by the number of layers. However, for thickness and tensile stiffness, the variation increased with increasing number of layers in the sheet. Stretch-at-break showed a divergent result with the highest variation in the single-layer sheets.

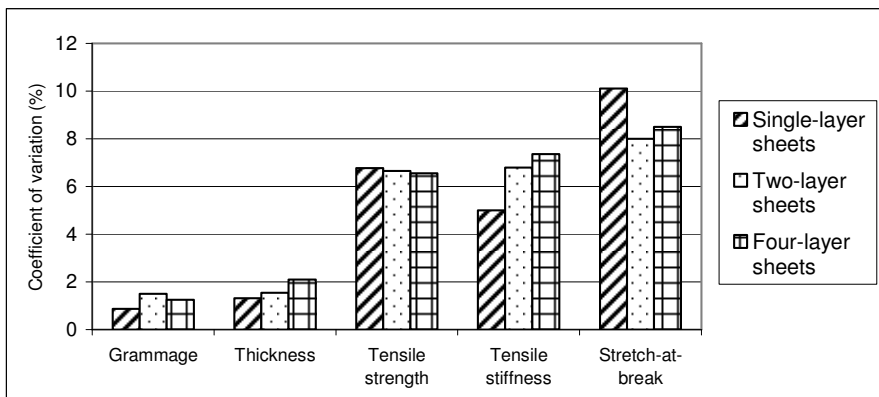


Figure 21. Coefficient of variation of properties of single-layer and stratified sheets of hardwood.

The β -formation index of sheets produced with different forming methods is listed in Table 3. It can be seen that the LB Multilayer Handsheet Former produced sheets with a better formation than the other sheets, except for those produced in the fully automatic PFI Sheet Former.

Table 3. β -formation index for sheets produced with different forming methods. The handsheets were single-layer sheets produced with the forming concentration 0.15 g/l.

Sheet forming method	Fibre composition	β-formation index ($\sqrt{g/m}$)
LB Multilayer Handsheet Former	100% hardwood, HW	0.32
LB Multilayer Handsheet Former	100% softwood, SW1	0.47
ISO	100% hardwood, HW	0.38
ISO	100% softwood, SW1	0.70
PFI	100% hardwood, HW	0.26
PFI	100% softwood, SW1	0.41
Comm 1	50% softwood 40% hardwood 8% broke	0.84
Comm 3	Bottom layer: softwood Top layer: 60% hardwood 40% broke	0.79

Figure 22 shows the within-sheet coefficient of variation in properties of papers made in different handsheet formers and of commercial papers. It was shown that with regard to grammage and thickness, the LB Multilayer Handsheet Former produced the most uniform sheets. Regarding tensile strength, tensile stiffness and stretch-at-break, the variation of the sheets made in the LB Multilayer Handsheet Former was somewhat higher than that of the sheets produced in the ISO former and in the PFI Sheet Former.

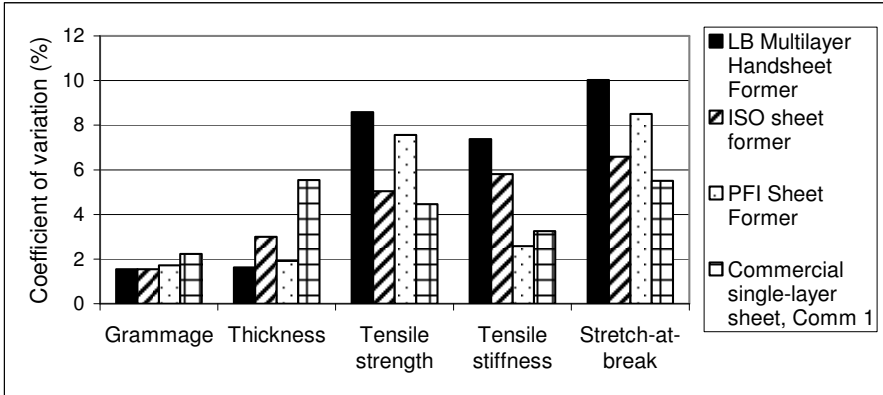


Figure 22. Coefficient of variation for properties of sheets produced by different sheet forming methods. The handsheets were all single-layer sheets produced of hardwood with the forming concentration 0.15 g/l.

The main conclusion from the study is that the LB Multilayer Handsheet Former is a suitable tool for studying the effects of sheet stratification on paper properties. This sheet former is easy to handle and single-, two-, three- or four-layer sheets can be produced efficiently at a high sheet production rate. The sheet former produces isotropic sheets, thus the effects of the fibre orientation are excluded when studying various paper properties. The sheet former produces sheets with good formation, and the variation in paper properties of the sheets remained at a fairly constant level when the number of layers in the stratified sheets was increased. The variation of paper properties of the sheets made in the LB Multilayer Handsheet Former are generally at the same level as of those made in conventional sheet formers. The variation in the sheets can probably be reduced by better alignment of the wire.

3.2.3 Paper III

- *Paper strength evaluation both in homogeneous and in stratified sheets with selected fibres*

In paper III, the effect on paper strength of placing different types of fibre in separate layers, instead of homogeneously mixing the fibres was examined. The aim was to displace the tensile-tear relationship towards higher strength values. Two-layer laboratory sheets were made in the LB Multilayer Handsheet Former and compared to single-layer sheets made from a homogeneous mixture of the two pulps. Fibres with different fibre properties were chosen and selected fibres were from southern pine and abaca and added to a Swedish softwood sulphate pulp as bulk pulp. To intensify the special fibre properties of the two selected fibres, i.e. the fibre length of abaca and the coarseness of southern pine, the amount of fines in the pulps was reduced by fractionation. Properties of the used pulps are listed in Table 4. The composition of the sheets used in the study is listed in Table 5.

Table 4. Properties of the pulps used in the study.

Pulp	Swedish Softwood	Southern Pine	Abaca
Mean fibre length	2.00 mm	2.27 mm	3.56 mm
Fibre width	27.5 μm	30.8 μm	16.2 μm
Coarseness	164.7 $\mu\text{g/m}$	205.6 $\mu\text{g/m}$	146.2 $\mu\text{g/m}$
Shape factor	85.1 %	84.5 %	80.9 %
Wet fibre flexibility index	65	58	61
Water retention value	1.98 g/g	1.58 g/g	1.39 g/g
Kappa number	2.5	0.53	9.7
Hemicellulose content	18.01 %	17.57 %	13.05 %
Drainage resistance	31.5 SR	16.0 SR	16.0 SR
Zero-span tensile index	126.4 Nm/g	114.8 Nm/g	156.3 Nm/g
Fibre wall thickness	2.9-6.2 μm^3	5-10 μm^3	1.6-15.8 μm^2

²Literature value from (Estudillo and Torres 1997)

³Literature values from (Karlsson 2006)

As indicated by fibre width, coarseness and fibre wall thickness, the most collapsible fibres should be the Swedish softwood fibres, followed by the southern pine fibres. The smaller fibre width and possibly higher fibre wall thickness of the abaca fibres indicated that they, despite their low coarseness, should be less collapsible. The wet fibre flexibility index indicates the conformability of the fibres, whereas the water retention value indicates the swelling ability, with a high degree of swelling promoting fibre-fibre bonding. Thus, the results shown in Table 4 above suggest that softwood fibres should

form a dense network with a high bond density, while networks of southern pine and abaca fibres should be less dense and exhibit a lower bond density.

Table 5. Sheet IDs and composition of the sheets used in the study.

Sheet ID	Pulp(s)	Nr of layers	Target grammage (g/m ²)
S30	Softwood	1	30
S60	Softwood	1	60
SP30	Southern Pine	1	30
SP60	Southern Pine	1	60
A30	Abaca	1	30
A60	Abaca	1	60
S+SP	Softwood and Southern Pine	1	60
S+A	Softwood and Abaca	1	60
S/SP	Softwood and Southern Pine	2	60
S/A	Softwood and Abaca	2	60

The tensile index was higher in the mixed sheets than in the stratified sheets, as shown in Figure 23. The mixed sheets with abaca had a higher tensile index than those with southern pine, while the two different kinds of stratified sheets had approximately the same strength. The tensile index of the pure softwood sheets was at the same level as that of the mixed sheets, while that of the pure southern pine and abaca sheets respectively was somewhat lower than that of the stratified sheets. Thus, the less conformable additive fibres do not seem to impair bonding between the softwood fibres. It is suggested that the load-bearing capacity of the less collapsed southern pine and abaca fibres are activated to a greater extent when they are mixed with softwood fibres. In the network together with the more flexible and conformable softwood fibres, the number of fibre-fibre contacts is increased, increasing the number of bonds in the sheet. Moreover, the fines in the softwood pulp probably contribute to the bonding of the abaca and southern pine fibres. With the higher degree of activation of the southern pine and abaca fibres, their individual fibre strength, indicated by the zero-span tensile index, should have a positive effect on the tensile strength of the sheets.

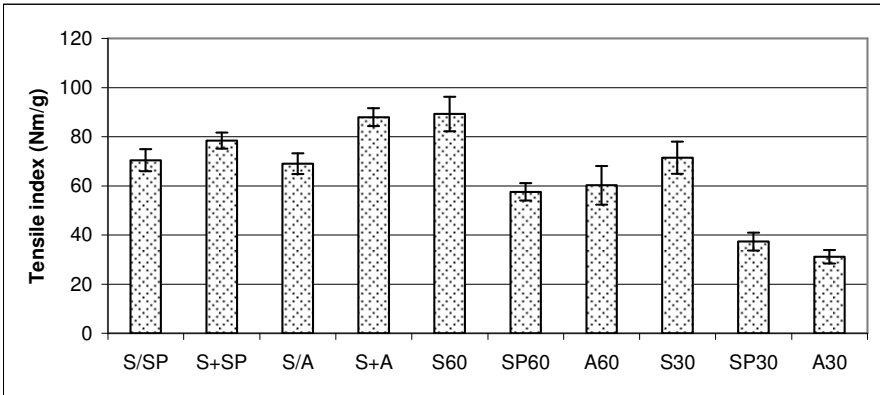


Figure 23. Tensile index for the single-layer and the stratified two-layer sheets. Sheet IDs are given in Table 5.

Regarding tearing resistance, the relation between the mixed and stratified sheets was reverse, as shown in Figure 24. The stratified sheets showed a higher tear index than the mixed sheets. Furthermore, the pure abaca sheets had a remarkably high tear index resulting in a high tear index for both the mixed and the stratified sheets containing abaca. Tearing resistance is, to a high degree, promoted by fibre length and the results clearly shows that the long abaca fibres contributed to a high tear index. Tearing resistance has been shown to decrease with increasing fibre-fibre bonding (Yu 2001) and the lower tear index for the mixed sheets is most likely a result of a higher bonding level.

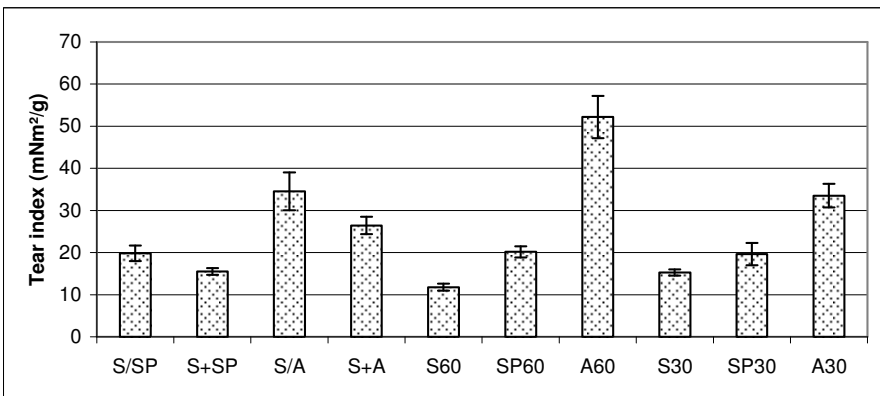


Figure 24. Tear index for the single-layer and the stratified two-layer sheets. Sheet IDs are given in Table 5.

The effect of stratification on the tensile-tear relationship is shown in Figure 25. It was seen that by placing the additive fibres in separate layers, rather than by making homogeneous sheets of the mixed pulps, the relation was shifted towards a higher tear index, while the tensile index was decreased.

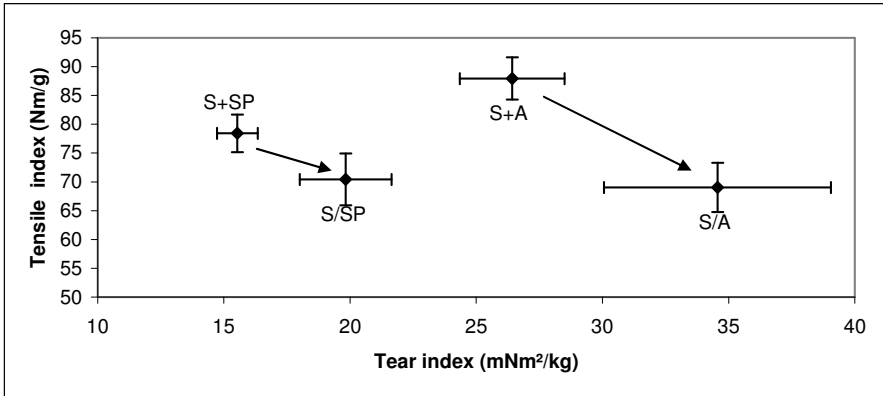


Figure 25. Tensile index against tear index for the mixed and stratified sheets. Sheet IDs are given in Table 5.

The main conclusion from this study is that by making sheets with one layer of long fibres and a low degree of bonding, and a second layer with well-bonded fibres, the tensile-tear relationship was shifted towards a higher tear index, however with a decrease in tensile index, compared to making sheets of a homogeneous mixture of the two pulps.

Conclusions

- Abaca pulp requires less refining energy than softwood pulp to reach a given tensile strength.
- Abaca pulp has a remarkably high tearing resistance.
- Abaca fibres can be added to a softwood pulp to increase tearing resistance, fracture toughness, folding endurance and air permeance.
- It is possible to add up to about 60% abaca without any great loss in tensile properties caused by a decrease in density.
- The LB Multilayer Handsheet Former can be used for studying properties of stratified sheets.
- The LB Multilayer Handsheet Former is easy to handle and produces isotropic single-, two-, three- or four-layer sheets.
- The LB Multilayer Handsheet Former produces sheets with good formation and good uniformity in paper properties compared to conventional sheet formers and commercially produced sheets.
- By stratifying a sheet, so that fibres with a high tear index and fibres with a high tensile index are placed in separate layers, rather than by making sheets of a mixture of the pulps, it was possible to increase the tear index of the resulting sheet by approximately 25%, whereas the tensile index was decreased by 10-20%.
- By mixing less collapsible and less conformable fibres with fibres with higher collapsibility and conformability, a synergism in tensile index was obtained, i.e. the mixed sheets had a higher tensile index than that predicted by the linear mass fraction additivity.

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Some aspects on strength properties in paper composed of different pulps

For paper producers, an understanding of the development of strength properties in the paper is of uttermost importance. Strong papers are important operators both in the traditional paper industry as well as in new fields of application, such as fibre-based packaging and light-weight building material. In this study, two approaches of enhancing paper strength, reinforcement and multilayering, were addressed. In specific, the effects of adding abaca (*Musa Textilis*) as a reinforcement fibre for softwood pulp were investigated. Moreover, a handsheet former for the production of stratified sheets, the *LB Multilayer Handsheet Former*, was evaluated. The LB Multilayer Handsheet Former was then used to study the effects of placing selected fibres in separate layers, rather than by making homogeneous sheets from a mixture of the pulps.

Handsheets of a softwood sulphate pulp with the addition of abaca fibres were made in a conventional sheet former. It was seen that the addition of abaca fibres increased the tearing resistance, fracture toughness, folding endurance and air permeance. Tensile strength, tensile stiffness and tensile energy absorption, however, decreased somewhat. Still it was possible to add up to about 60% abaca without any great loss in tensile strength. As an example, with the addition of 30% abaca, the tear index was increased by 36%, while the tensile index was decreased by 8%.

It was shown that the LB Multilayer Handsheet Former is suitable for studying the effects of stratification of paper. The sheet former produces sheets with good formation and the uniformity of the sheets, evaluated as the variation of paper properties, is retained at a fairly constant level when the number of layers in the stratified sheets is increased. The uniformity of the sheets produced in the LB Multilayer Handsheet Former are generally at the same level as of those produced in conventional sheet formers.

Homogeneous and stratified sheets were produced in the LB Multilayer Handsheet Former and it was found that by stratifying a sheet, so that a pulp with a high tear index and a pulp with a high tensile index are placed in separate layers, it was possible to increase the tear index by approximately 25%, while the tensile index was decreased by 10-20%.